SWINBURNE UNIVERSITY OF TECHNOLOGY

WORKPLACE ANALYSIS FOR REGIONAL PAIN SYNDROME

THE DEVELOPMENT AND APPLICATION OF POSTURE MEASUREMENT MODEL AND CERVICAL ASSESSMENT TOOLS FOR REDUCING THE RISK OF REGIONAL PAIN SYNDROME

by

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ABSTRACT

Work-related musculoskeletal disorders are widespread in industrialised countries and represent a serious work-related health concern. Work-related musculoskeletal disorder is an umbrella term used to describe a wide range of *specific* and *non-specific* complaints. It includes *regional pain syndrome* (RPS) and *fibromyalgia* (FM), which are regional and general chronic non-specific musculoskeletal pain syndromes, respectively. Non-specific pain syndromes are common in the general population. Sufferers experience significant chronic pain and discomfort. Unfortunately, a definitive aetiology for these syndromes is still unclear. Knowledge about causative factors would be very helpful in assessing risks associated with the onset of these pain syndromes.

It is believed by rheumatologists that chronic non-specific musculoskeletal pain syndromes are caused by dysfunctional pain modulation. Augmentation of pain stimulus, via mechanisms of peripheral and possibly central sensitisation, are believed to play a critical important role in the pain manifestations associated with RPS and FM. However, this information has not been effectively conveyed to other disciplines.

The ergonomics community has not recognised the potential neurogenic basis for chronic musculoskeletal pain. Hypersensitivity of the pain system in chronic musculoskeletal pain, including the dorsal horn cells in the central nervous system, has not been greatly discussed by this discipline. In addition, the rheumatology and pain physiology fields have not investigated to a great extent the potential contribution of workplace ergonomic risk factors to the onset of non-specific pain syndromes, including RPS and FM. Consequently, it is not clear how workplace ergonomic exposures may act as aetiological factors in chronic musculoskeletal pain.

There is significant opportunity for the disciplines of ergonomics, rheumatology and pain physiology to combine knowledge when examining the associations between workplace ergonomic risk factors, dysfunction of the pain system and non-specific musculoskeletal pain.

This thesis uses knowledge from these different research fields to explore the relationship between the specific ergonomic risk factors of poor and static working posture and the development of RPS and FM characteristics. The literature is initially

examined for possible aetiological factors of RPS and FM. Putative pathophysiological peripheral and central pain mechanisms involved with RPS and FM are reviewed.

Research conducted in this thesis showed that exposure to poor and static working postures, particularly of the cervical spine region, increased pain sensitivity and self-reported pain in healthy people. Furthermore, it was demonstrated that the work action characteristics of a task significantly influenced pain sensitivity. The work action characteristics of the neck were varied during a computer based work task and this intervention significantly changed the amount of pain sensitivity and self-reported pain. Hence, the postures and actions of the neck can be very important in changing how the pain system modulates pain. Long-term exposure to the postures and actions described in this research increased the risk of RPS developing and, therefore, should not be undertaken as part of daily work. It was concluded that pathophysiological pain mechanisms should be included as risk factors for chronic musculoskeletal pain.

This research added to the limited understanding of the relationship between ergonomic postural risk factors and change in pain sensitivity. As well, this research supported the measurement of pain sensitivity in ergonomic work investigations, a measurement that is not normally used by ergonomists in workplace investigations. More research is needed to inform the development of better ergonomic guidelines (including better workplace analysis tools), with the ultimate goal of decreasing the risk of development of non-specific musculoskeletal pain.

A new posture measurement system was developed specifically for this research. This tool assisted in understanding the postural and action characteristics of the computer task. This system utilised an electromagnetic tracking system to measure the motion and posture of participants. A computer application was developed that applied kinematic transformations to convert raw data from the tracking system to meaningful postural data. This custom computer application assessed the actions of the measured task based on a pre-determined motion-time standard, and displayed the results both textually and through animation. As motion-time standards are based on manual assessment methods, the new posture measurement system and computer application represented a significant advancement for work action analysis. There is potential for this advanced tool to assist ergonomists in understanding the posture and work action characteristics of a work task.

In this thesis, particular attention was also paid to cervical spinal factors. The concept of 'spinal dysfunction' and its importance in the aetiology of RPS and FM was explored. A new device was developed in this thesis for the measurement of cervical stiffness and mechanical pressure pain, to assess cervical spine function. This device was used in an experiment to explore cervical spinal stiffness and pain in both FM patients, chronic neck pain patients, and healthy participants. Results from the pain measurements, and other clinical measures, supported the hypothesis that the symptomatic participants had dysfunction of the axial musculoskeletal system in the cervical spine.

The conclusion from this research was that abnormalities of spinal function and aberrant pain modulation mechanisms in the symptomatic participants (possibly including central pain factors) may be associated with clinical features characteristic of RPS and FM. Consequently, spinal dysfunction is possibly a factor involved in the aetiology of chronic non-specific musculoskeletal pain syndromes.

DECLARATION

This is to certify that

(i) the thesis comprises only my original work,

(ii) due acknowledgment has been made in the text to all other material used,

Adrian Lindsay Morphett

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First and foremost I would like to thank Michelle my wife and Edwin my son for their complete support and commitment to me and to my goal of finishing this PhD. This PhD has taken a considerable amount of time from both of our lives and has stopped Michelle from taking life options that she may otherwise have wanted to pursue. In this regard, she has been beholden to the PhD as much as I have. Without her love and support this PhD would not have been possible.

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LIST OF ABBREVIATIONS

A/D ..... Analog To Digital
ACR ..... American College of Rheumatology
AL ..... Anatomical Landmark
ANOVA ..... Analysis of Variance
App. ..... Appendix
BPDF ..... Body part discomfort frequency
BPDFS ..... Body part discomfort frequency severity
BPDS ..... Body part discomfort severity
C ..... Cervical vertebra
Ch. ..... Chapter
CI ..... Confidence Interval
CNS ..... Central nervous system
CP ..... Control Point
EMG ..... Electromyography
Eq. ..... Equation
ETS ..... Electromagnetic Tracking System
F/E ..... flexion/extension ROM
FD ..... Force-Displacement
Fig. ..... Figure
FIQ ..... Fibromyalgia Impact Questionnaire
FM ..... Fibromyalgia
FWAP ..... Fine-detailed Work Action and Posture
GRS ..... Global Reference System
HTM ..... High-threshold mechanoreceptors
ICC ..... Intraclass Correlation Coefficient
IASP ..... International Association for the Study of Pain
JCS ..... Joint Coordinate System
β ..... JCS angle abduction/adduction
α ..... JCS angle flexion/extension
γ ..... JCS angle rotation
Lat flex ..... lateral flexion ROM
LSRS ..... Local Segment Reference System
LTM ..... Low-threshold mechanoreceptors
m/s ..... Metres per second
Mins ..... Minutes
Mm ..... Millimetres
MOD ..... MODAPTs time unit
MODAPTS ..... MODular Arrangement of Predetermined Time Standards
Ms ..... Milliseconds
M-TCM ..... Modified-Tissue Compliance Meter
N ..... Newton
NA ..... Not Applicable
NDI ..... Neck Disability Index
No ..... Number
NORM ..... Asymptomatic participants
NP ..... Neck pain sufferers
NS ..... Not significant
PMTS ..... Predetermined Motion-Time Standard
PNS ..... Peripheral nervous system
POMS ..... Profile of Mood States
PPT ..... Pressure Pain Threshold
Quad ..... Quadrant
R ..... Pearson's correlation coefficient
r^2 ..... Coefficient of Determination
RA ..... Rheumatoid Arthritis

RMS .....Root Mean Square
ROM ..... Range of Motion
Rot.....rotation ROM
RPS .....Regional Pain Syndrome
RSI .....Repetitive Strain Injury
S ..... Seconds
SD .....Standard Deviation
Sec. .....Section
SP ..... Substance P
STAI-S ..... State-Trait Anxiety Inventory (STAI-S)
T ..... Thoracic vertebra
Tab. ..... Table
TCM..... Tissue Compliance Meter
TeP .....Tender Point
Total PPT .....Sum of Pressure Pain Thresholds
Total ROM ..... Sum of Range of Motions
VAS.....Visual Analog Scale
VDT ..... Visual display terminal

CHAPTER 1

INTRODUCTION

1.1 POSTURE AND WORK ACTIONS, SPINAL DYSFUNCTION AND REGIONAL PAIN SYNDROME

Musculoskeletal disorders are widespread in many industrialised countries [1]. Sufferers of these disorders experience high personal life impacts [2]. Significant economic and social costs are also associated with these disorders – they are a very serious work-related health concern in the industrialised world [3,4]. Despite the very high personal, social and economic impacts, knowledge regarding pathogenesis has been illusive [5-10].

Work-related musculoskeletal disorders are by definition a subset of musculoskeletal disorders, that arise out of occupational ergonomic exposures [11]. They are "work-related" when work activities and work conditions significantly contribute to their development or exacerbation, but are not the only determination of causation [12]. Generally, two broad divisions are described under the umbrella term work-related musculoskeletal disorders: specific disorders that could be clinically defined as discrete disorders of soft tissues (including nerves, tendons, muscles, and supporting structures of the body [13]), as well as less well standardised conditions including non-specific pain syndromes, not attributable to known pathology [1,8,10,14-16]. From the rheumatology literature, the term "regional pain syndrome" (RPS) has been used [2,17-25], amongst many other titles, for non-specific pain syndromes when they are chronic, present in one area of the musculoskeletal system and there is no obvious pathological cause for the diffuse musculoskeletal pain. RPS was the term used in this thesis for non-specific work-related musculoskeletal disorders.

Fibromyalgia syndrome (FM) is a clinical pain syndrome that has as its main features widespread diffuse musculoskeletal pain, generalised hyperalgesia and allodynia, and often psychological distress [26-29]. It has been proposed that FM and RPS are related disorders [20,21,24,28,30,31] and that they share similar pathophysiological

mechanisms [21,24,24,31-34], but to different degrees [34]. However, many factors have been reported as the cause of muscle pain and allodynia in FM and RPS, and may not be the same in all persons [35]. Hence, the association between these two pain syndromes is unclear.

Generally, more research has been conducted into FM, unlike RPS which has not received the same level of attention from researchers [24]. Hence, there is a requirement for better understanding about the pain syndrome RPS and the pathological steps by which this pain syndrome may develop [24].

The increased pain sensitivity in FM and RPS patients (characterised by primary and secondary hyperalgesia, and allodynia) suggests that the pathophysiology of these syndromes could include hyperexcitability of the pain pathways. Peripheral mechanisms have been identified in both RPS [36-45] and FM [46-51] using various tests. Central hyperexcitability has also been observed in the central nervous system, most likely involving the dorsal horn neurons and/or supraspinal neurons [52,53]. The increased central excitability of the nociceptive system is believed to be an aetiological factor of FM and to some extent RPS [17,33,54-60], however the involvement of central mechanisms in RPS remains unclear; peripheral factors may be more prevalent [43,44].

The dorsal horn neurons of the spinal cord are representative of many complex and integrative systems [61]. They exhibit an ability to increase in excitability as a result of sustained afferent stimulus from unmyelinated afferent nociceptors [62]. This phenomenon is called central sensitisation and manifests as a long-term increase in excitability [63-67]. Clinically, central sensitisation manifests as primary and secondary hyperalgesia, and allodynia [68].

Central sensitisation alters the sensory processing in the dorsal horn neurons and may convert previously subthreshold afferent inputs to suprathreshold [69,70]. Under these circumstances, mechanoreceptive afferents that normally signal non-noxious stimulus may gain access to the pain system and begin to cause pain, something they never normally do. In addition, the descending pain modulatory system from supraspinal regions can influence the transmission of pain signals at the dorsal horn level [71]. These two phenomena, central sensitisation of nociceptive neurons in the dorsal horn and disturbed function of the descending modulatory pain pathways, are the main

mechanisms for pain hypersensitivity [72-74]. They are thought to be one of several proposed mechanisms that may contribute to the pathogenesis of the pain hypersensitivity in FM and RPS [75-77]. However, the definitive aetiology of FM [47,78,79] and RPS [17,44,45] is unknown and risk factors that may alter the function of the dorsal horn neurons remain unclear. Knowledge regarding causative factors of RPS and FM would be of benefit to patients with chronic musculoskeletal pain.

FM and RPS pose a challenging problem to ergonomic research. Ergonomic guidelines frequently state that static postures [80-86] and repetitive actions [1,11,81,87-89] are contributory factors to musculoskeletal discomfort and pain. However, many conclusions are based on associations and suggestions [90]; specific ergonomic guidelines for FM and RPS do not exist. Furthermore, in the ergonomic and occupational health literature changes in pain sensitivity are rarely described with regards to RPS. The putative pathophysiological pain mechanisms underlying these syndromes are not discussed. Hence, there exist few investigations exploring the association between ergonomic risk factors and changes in pain sensitivity.

The rheumatology and pain fields also have not extensively investigated the putative association between ergonomic risk factors and features of RPS and FM. Workplace ergonomic exposures that may act as aetiological factors in chronic musculoskeletal pain syndromes remain unclear [91,92]. Specific guidelines regarding ergonomic workplace factors and hypersensitivity of the peripheral and/or central pain system (which may manifest as tenderness, allodynia and referred tenderness and pain) are presently at their very early stages. Prospective studies are now needed to explore the association between specific workplace risk factors, such as posture and repetitive actions, and pain variables.

It is likely that dysfunction of spinal structures is associated with the pathogenesis of RPS and FM [17,20,21,32,93-100]. Patients report that the axial skeleton, shoulder and pelvic girdles are the most common areas of pain [20,21,101,101]. It is very unusual for FM and RPS patients not to have cervical and upper limb pain. Dysfunction of axial structures, or spinal dysfunction, may be characterised by abnormalities of deep spinal structures, including the intervertebral discs, spinal muscles and ligaments, and the zygapophysial joints [102,103]. Hypothetically, spinal dysfunction could result in a strong and prolonged nociceptive afferent barrage that may be sufficient to induce a

persistent hyperexcitability of the spinal cord neurons, or central sensitisation [20,96,104-107]. Abnormalities of spinal function and a change in the pain-processing function of the central nociceptive system may associate with features characteristic of RPS and FM [20,94,108].

However, the relationship between spinal dysfunction and clinical features of RPS and FM has not been extensively investigated because an objective method of *in vivo* assessment for spinal dysfunction does not exist [109-111]. It has been hypothesised that abnormal spinal musculoskeletal stiffness is associated with dysfunction of spinal structures [102,103,112,113] and several mechanised spinal stiffness measurement devices have been developed to explore this hypothesis [102,114-119]. However, these devices are not applicable to the posterolateral aspect of the cervical spine and do not provide for measurement of tenderness. Presently, there does not exist a method or instrument that may be used for the detection of abnormal musculoskeletal stiffness in the cervical spine, which may be indicative of spinal dysfunction. Further, no stiffness measurement devices presently measure pain sensitivity, which is a principal variable associated with musculoskeletal pain syndromes.

In summary, the relationship between the occupational environment and RPS and FM has not been extensively studied. There are few ergonomic investigations that recognise the potential neurogenic basis of RPS and FM. Only a small number of prospective studies have been undertaken to investigate the relationship of specific occupational risk factors and clinical features characteristic of RPS and FM. Ergonomic exposures have not been investigated extensively as risk factors for RPS and FM. In addition, spinal dysfunction may be an important pathophysiological factor in the aetiology of RPS and FM. However, this association has not been extensively investigated because a reliable and objective method of assessment for spinal dysfunction does not exist. There exists a need for research exploring the hypothetical associations between 1. ergonomic risk factors and FM and RPS and, 2. spinal dysfunction and FM and RPS. These putative associations are investigated in this thesis.

1.2 RESEARCH GOALS

The major goals of this thesis are:

1. **Develop an instrument-based posture action measurement and analysis system (Ch. 3).**

2. **Use the new postural analysis system to explore the relationship between the ergonomic factors of poor posture and repetitive actions and the development of clinical features characteristic of RPS (Ch. 4).**

3. **Explore the relationship between dysfunction of cervical spine structures and clinical features of RPS and FM (Ch. 6).**

1.3 THESIS OVERVIEW

1.3.1 CHAPTER 2 – REVIEW OF THE LITERATURE

Chapter 2 discussed the foundation for the thesis topic, that the increased pain sensitivity in FM and RPS patients suggest hyperexcitability of the pain pathways. Peripheral mechanisms have been identified in both RPS and FM. Central mechanisms have also been observed most likely involving the dorsal horn neurons and/or supraspinal neurons. The increased central excitability of the nociceptive system is believed to be an aetiological factor of FM and to some extent RPS. However, the definitive aetiology of FM is unknown and risk factors that may alter the function of the pain system remain unclear. Other pathogenetic factors of RPS and FM are reviewed.

The ergonomic literature was also reviewed regarding risk factors for work-related musculoskeletal disorders. Postural work factors are identified as an important risk factor in the development of these disorders. A positive relationship has been shown to exist between exposure to postural work risk factors and disorder development. However, it is now recognised that the nature of work-related musculoskeletal disorders is complex and multifactorial. The pathophysiological mechanisms behind these disorders remains unclear. In particular, for regional pain syndrome (which is a non-specific work-related musculoskeletal disorder) altered pain processing mechanisms

have been suggested as a pathophysiological factor for the hyperalgesia and allodynia seen in some patients.

A hypothetical model was also reviewed encompassing dysfunctional pain mechanisms in RPS and FM. This hypothesis was explored because it partly presents a pathway for the development of increased pain sensitivity as a result of ergonomic risk factors. Aspects of this model mere investigated in this thesis.

1.3.2 CHAPTER 3 – FWAP-LINK: POSTURE AND ACTION MEASUREMENT SYSTEM

The basis of the first goal of this thesis, advancement and development of a posture and action measurement system, is discussed in this chapter.

A manual workplace posture and action measurement code was selected for development. The 'Fine-detailed Work Action and Posture' (FWAP) code records the postures and actions of the body while undertaking a specific task. This record can then be analysed to investigate the occurrence and duration of static postures, and the repetitiveness of actions required to complete the task.

The FWAP manual code was combined with electromagnetic tracking technology and computer animation to assist with posture measurement and analysis. Kinematic geometry converted the raw data from the electromagnetic tracking sensors to anatomically meaningful postural information. This new advanced posture measurement system was called the '*FWAP-Link'* system. App. A reviews the specifics of the FWAP-Link system.

FWAP-Link was incorporated with the commercially available computer program 'FWAP for Windows©'. The FWAP-Link system provided a new method for analysing motion capture data from electromagnetic tracking technology and, with the help of computer animation, converted this to a 'FWAP for Windows©' format.

1.3.3 CHAPTER 4 – THE ASSOCIATION OF POSTURE AND PAIN

This chapter investigates the association between the ergonomic risk factors of poor posture and work actions and the development of RPS characteristics, which is goal of this thesis.

Fifteen healthy females participated in two simulated work sessions, where they were required to undertake computer-based tasks in positions of poor posture. The sessions were of four hour duration and were conducted one week apart. The two sessions did not differ except that in one session the posture of the head and neck were static throughout (neck-static), and in the other session the head and neck were required to move substantially once every minute (neck-mobile). Changes in the function of the cervical spine and musculoskeletal system were measured using self-reporting instruments, passive cervical range of motion, and cervical and musculoskeletal PPT measurements. The FWAP-Link system measured the postures and actions of the participants with six electromagnetic sensors.

The posture of the participants did not vary considerably between or within the two measurement sessions, except at the once a minute postural alteration events in the neck-mobile session. The neck-static posture session led to significantly increased pain sensitivity, than in the neck-mobile session. This was observed at locations both within and at some sites remote from the cervical spine. There was also a significant change in pain sensitivity between the start and end of the measurement sessions at most measured locations. The PPT results suggested a change in pain sensitivity that involved peripheral mechanisms, and possibly also central mechanisms although this was unclear.

There was also a change in ROM in some measured planes, although this was not significant. Self-reports of pain were also significantly higher with a neck-static rather than a neck-mobile posture.

The results of this investigation supported the hypothesis that ergonomic risk factors can influence pain sensitivity. The ergonomic risk factors of static and constrained postures, particularly of the cervical spine, combined with repetitive actions of the arm were associated with an increase in the excitability of the pain system. Increased excitability of the nociceptive system, possibly including central mechanisms, is believed to be an aetiological factor of RPS. Therefore, long-term exposure to ergonomic risk variables that increase pain sensitivity, as a consequence of central pain changes, could be a factor associated with the onset of RPS. More research is needed to better understand these associations. The ergonomics community should consider

pathophysiological pain mechanisms when examining risk factors of chronic musculoskeletal pain.

1.3.4 CHAPTER 5 – MEASUREMENT OF CERVICAL RANGE OF MOTION

Passive cervical range of motion (ROM) measurement is reviewed. Passive cervical ROM is commonly measured by manual practitioners to assess the function of the cervical spine. They believe that reduced cervical ROM may be indicative of dysfunction in the neck.

A new instrument based ROM measurement system was developed and used to measure cervical ROM in asymptomatic participants. The reliability of the new system was assessed and comparisons were made between the new device and another ROM measurement device. Intra and inter-examiner reliability was high and the new instrument based system compared well with the more commonly used ROM device.

1.3.5 CHAPTER 6 – CERVICAL SPINE FUNCTION IN CHRONIC MUSCULOSKELETAL PAIN SYNDROMES

Goal three of this thesis, the supposition that in FM patients and patients with chronic neck pain there is dysfunction of the cervical spine, was investigated. Spinal dysfunction may be an important factor in the aetiology of chronic musculoskeletal pain syndromes, including RPS and FM. Therefore, detection of spinal dysfunction may be of benefit to these patients.

A newly developed neck musculoskeletal stiffness measurement device was applied to three participant groups: FM patients, patients with chronic neck pain and asymptomatic participants. Other clinical measurement variables were also assessed: cervical range of motion, self-reporting instruments and pain sensitivity. The discriminate ability and reliability of each assessment tool over short and medium terms was determined.

The cervical stiffness measurement device had poor reliability and discriminate ability and was not was not suitable for assessment of dysfunction in the cervical spinal. ROM and PPT measurements had good reliability and discriminate ability. The PPT, ROM and self-reporting instrument results were significantly different in the patient versus

healthy participant groups, and supported the hypothesis that in the patient groups there existed dysfunction in the cervical spine.

CHAPTER 2

REVIEW OF THE LITERATURE

2.1 WORK-RELATED MUSCULOSKELETAL DISORDERS

2.1.1 POSTURAL RISK FACTORS

Work-related musculoskeletal disorders are widespread in many countries, with high costs and impact on quality of life [1]. These disorders are a serious work-related health concern to industrialised nations [3,4], with respect to health, productivity and associated costs [5,12] and they continue to present major challenges in virtually all industry sectors [120].

The following occupational ergonomic stressors are commonly cited in the ergonomic literature as likely risk factors for work-related musculoskeletal disorders.:

- non-neutral body postures (either dynamic or static),
- rapid work pace and repetitive motions,
- forceful exertions,
- vibration, and combinations of some or all of these factors [1,11,80,81,87-89,121-123].

A positive relationship has been shown to exist between exposure to these physical work risk factors and disorder development [12]. In particular, constrained and awkward working postures are described as one of the most important factors associated with the development of work-related musculoskeletal disorders [80-86]. Indeed, there is strong evidence of a causal relationship between postural work factors and musculoskeletal disorders [13]. In combination with high levels of static contraction and prolonged static loads, poor working postures of neck and shoulder convey increased risk for neck/shoulder musculoskeletal disorders [13].

Postural factors are important as they contribute greatly to mechanical load placed on the musculoskeletal system [82]. Constrained body postures and any deviations from neutral postures are the most frequent form of static muscular effort [85,124,125].

(Constrained postures are usually characterised by restriction of free movements and long-lasting static postural efforts [126,127]). Static and non-neutral constrained body postures can lead to prolonged muscular efforts [85,124,125], which can cause long-lasting contraction of the muscles, muscular fatigue, discomfort and pain [81,126,128-131] and, eventually, the development of work-related musculoskeletal disorders [124,132-134].

Long-term exposure to postural risk factors, and other factors listed above, is commonly cited as contributing to the genesis of work-related musculoskeletal disorders via ergonomic biomechanical stress models. These models are based on the concept that repeated exposure leads to micro-trauma in tissues [11] and that, over time, the exposure to biomechanical stress leads to an unhealthy tissue response, which results in symptoms and/or impairment, and pathology [11,12,135]. This focus on biomechanical stress and the resulting tissue damage has meant that the study of work-related musculoskeletal disorders has traditionally focused on specific pathology in the muscles, tendons, ligaments, cartilage, bones, nerves and joints [11].

However, the complex mechanisms involved in the pathogenesis of work-related musculoskeletal disorders is generally not addressed in the ergonomic literature [5,32,123,136-138] and the pathophysiology of development is understood incompletely [5-10]. Little is known about the relative importance of postulated ergonomic risk factors, and even less about their potential interaction effects [80,123,136]. The ergonomic literature supplies general and routine advice regarding work-related musculoskeletal disorders, but does not provide specific guidelines and examples [139,140]. There does not exist a well-defined specific and quantitative relationship between exposure, capacity and disorders [7,81,90,141,142]. A clearer understanding of the underlying pathogenesis is essential [11,81] so that better guidelines can be developed to reduce the incidence of work-related musculoskeletal disorders [123].

In addition, it is now recognised that the nature of work-related musculoskeletal disorders is complex and multifactorial [1,5,9,10,137,143] and that the biomechanical model does not adequately explain the aetiology of all work-related musculoskeletal disorders. Increasingly, work organisation and psychosocial factors are also being seen as significant causal factors for work-related musculoskeletal disorders [144,145]. Psychosocial factors include stress and social, organisational, behavioural, environment

factors [12,87,121,146] and neurotic perfectionism [122]. Unfortunately, while psychosocial factors are now often associated with work-related musculoskeletal disorders [147], the role of these factors in the development of work-related musculoskeletal disorders remains poorly understood [13,148,149] and under researched [122]. These factors are outside the realm of this thesis, however they warrant further attention in the future.

As noted above, while it is widely accepted that postural factors are one of the most important ergonomic risk factors associated with the onset of work-related musculoskeletal disorders, literature and research dealing specifically with working postures is uncommon; knowledge has been elusive [82]. This is most clearly demonstrated by the lack of information about the relationship between posture, repetitive actions and the risk of injury [90,140,150,151]. Adequate exposure assessment methods for postural stress and repetitive motion are not yet available, and there are few existing criteria for defining appropriate working postures and safe postural exposures [150,151].

More work is required to elucidate the pathomechanisms of work-related musculoskeletal disorders, particularly for the risk factor of poor and static working postures.

2.1.2 CLASSIFICATION

Work-related musculoskeletal disorders are by definition a subset of musculoskeletal disorders, that arise out of occupational ergonomic exposures [11]. They are "work-related" when work activities and work conditions significantly contribute to their development or exacerbation, but are not the only determination of causation [12]. Many other contributing factors may play a role in the development or persistence of the disorder [152]. "Work-related" also distinguishes from "occupational" disorders, where there is a clear cause-and-effect relationship between hazard and disease [1,152].

A profusion of terms has been used previously for work-related musculoskeletal disorders [153]. Many have caused controversy and confusion regarding diagnostic criteria and terminology [10]. Some terms that have been used include *regional pain syndrome* [1,17-19,22,24,33,135,154], *regional soft tissue pain* [21], *non-specific upper limb disorder* [30], *non-specific diffuse forearm pain* [155], *chronic regional muscular*

pain [2], *regional musculoskeletal disorders* [81,156], *regional musculoskeletal pain disorders* [25], *refractory cervicobrachial pain syndrome* [54,97], *work-related upper limb musculoskeletal disorders* [24,90], *work-related musculoskeletal disorders* [10-12,121], *disorder of occupational overuse or stress* [143], *non-specific work-related upper limb disorders* [122], r*epetitive strain injury* (RSI) [157] and the term that replaced RSI, *Occupational Overuse Syndrome* (OOS) [24,158].

For many of these titles, agreed diagnostic criteria did not exist or were not standardised [1], and consequently many of these conditions were poorly characterised [156]. The lack of universally agreed criteria has hampered investigation and analysis of risk factors of upper limb musculoskeletal disorders [14,30].

More recently, different research groups have attempted to provide classification variables for these disorders. Generally, two broad divisions are described under the umbrella term work-related musculoskeletal disorders: specific disorders that could be clinically defined as discrete disorders of soft tissues (including nerves, tendons, muscles, and supporting structures of the body [13]), as well as less well standardised conditions including non-specific pain syndromes, not attributable to known pathology [1,14-16,30,81,135,155].

Some groups have defined criteria for specific clinical disorders. For example, Ohlsson et al. [159,160] introduced a standard set of criteria for symptoms and signs for specific clinical diagnoses of the neck and upper limbs. This was extended by Juul-Kristensen et al. [161] to include the following clinical diagnoses via clinical examination: tension neck syndrome, cervicalgia, cervical syndrome, trapezius myalgia, thoracic outlet syndrome, frozen shoulder, supraspinatus tendinitis, infraspinatus tendinitis, bicipital tendinitis, acromioclavicular syndrome, lateral epicondylitis, medial epicondylitis, pronator syndrome, radial tunnel syndrome, cubital syndrome, peritendinitis, carpal tunnel syndrome, ulnar nerve entrapment at the wrist, overused hand syndrome and deQuervain's disease.

Sluiter et al. [15] introduced similar clinical diagnostic criteria for eleven specific disorders, and one non-specific disorder, all of which fell under the umbrella title of work-related musculoskeletal disorder. Of the specific disorders the following were described in great detail: radiating neck complaints, rotator cuff syndrome, epicondylitis

- lateral and medial, ulnar nerve compression at the elbow: cubital tunnel syndrome, radial nerve compression: radial tunnel syndrome, flexor-extensor peritendinitis or tenosynovitis of the forearm-wrist region, deQuervain's disease, carpal tunnel syndrome, ulnar nerve compression at the wrist: Guyon canal syndrome, raynaud's phenomenon (vibration white finger) and peripheral neuropathy associated with hand-arm vibration and, osteoarthrosis of the distal upper-extremity joints. However, Sluiter et al. explained that in most cases work-related musculoskeletal disorders cannot be classified into specific diagnostic categories. They defined another disorder titled as non-specific upper-extremity musculoskeletal disorders to capture such disorders. Sluiter et al. [15] included "tension neck syndrome" as a non-specific disorder.

Harrington et al. [155] used a Delphi approach by bringing together expert healthcare professionals from various disciplines to establish consensus on case definitions for common work related upper limb pain syndromes. Consensus for definition and diagnostic criteria was agreed on for seven specific disorders of the upper limb. These were similar to the criteria provided by Sluiter et al. [15] and Ohlsson et al. [159]. As well, the consensus group defined diagnostic criteria for one non-specific disorder, non-specific diffuse forearm pain.

Another group, Helliwell et al. [30], sought to define epidemiological criteria for upper limb musculoskeletal disorders. They combined data from health clinics to establish classification criteria for seven soft-tissue disorders of the upper limbs. The definitions and diagnostic criteria that were established were similar to those developed earlier by Harrington's et al. [155] consensus approach. Classification criteria for two non-specific disorders were also described including fibromyalgia and non-specific upper limb disorders.

2.1.3 REGIONAL PAIN SYNDROME

Common to Sluiter et al. [15], Harrington et al. [155] and Helliwell et al. [30] classification criteria described above, the criteria for non-specific work-related musculoskeletal disorders included pain in the hand, wrist, forearm or neck in the absence of one of the specific disorders discussed above. Sluiter et al. [15] discussed that pain is a major symptom in this particular disorder, and is often chronic. Other features described by Harrington et al. [155] included loss of function, weakness,

cramp, muscle tenderness, allodynia or slowing of fine movements, but these were not defining criteria. Of interest, Helliwell et al. [30] noted some positive indicators for diagnosis, including an increased number of tender points in this disorder.

From the rheumatology literature, the term "regional pain syndrome" (RPS) has been used in some previous investigations rather than non-specific work-related musculoskeletal disorders. Regional pain syndrome has the same criteria to those described above in to Sluiter et al. [15], Harrington et al. [155] and Helliwell et al. [30] reports, but has been further elaborated in the rheumatology literature to highlight the pain aspect to the disorder. Diagnostic features of RPS can also include a female preponderance, fatigue, sleep disturbances, paresthesia, decreased pain threshold, emotional distress, anxiety and depression [17,21,135]. The dominant symptom described in these reports is chronic soft tissue pain involving one or limited contiguous sites for three months or more [21,23]. A spinal component in the pain distribution is common. Tender points are present in the reported painful sites [21,23,33,107,162,163]. Other regions are reported as asymptomatic and pain free with normal tender points [33,107]. Chronic pain has been defined as pain which persists past the normal time of healing, and in most cases three months is the point of division between acute and chronic pain [164].

The term regional pain syndrome (RPS) has been used by Littlejohn and colleagues [17-20] and others [2,21-25] in the rheumatology literature to describe non-specific work-related musculoskeletal disorders. RPS in this thesis was regarded as the second group of work-related musculoskeletal disorders that were classified in the absence of specific disorders (as discussed above). Although considerably varied terms have been used previously for non-specific work-related musculoskeletal disorders [30], regional pain syndrome was applied in this thesis due to attention given to the pain system. RPS in this thesis was regarded as a "work-related" disorder as this thesis also explored physical work exposures. Hence, for this thesis, RPS fell under the umbrella term work-related musculoskeletal disorder.

Sluiter et al. [15] described possible international classification of disease (ICD) codes (ICD-9-CM codes) for what the authors termed non-specific upper extremity disorders: "diffuse pain" for regional neck pain (ICD-9 723.1,3,5,7,8,9), "pain in shoulder" for non-specific shoulder pain (ICD-9 719.41,51, 726.0, 729.89), "no unique symptoms"

for non-specific elbow pain (ICD-9726.39) and, finally, "varying with underlying disorder" for non-specific pain in the forearm, wrist or hand (ICD-9 719.43,44, 719.5). However, [16] argued that of the ICD codes most are not suitable for musculoskeletal disorders, aside from "soft tissue disorders relate to use, over use and pressure" (ICD-M70). For RPS, the ICD-10 code most likely to apply would be M70.9 unspecified soft tissue disorder related to use, overuse and pressure. This code fits within the ICD-10 codes of M70, which is Soft tissue disorders related to use, overuse and pressure.

2.1.4 PREVALENCE

Work-related musculoskeletal disorders form a major proportion of registered and/or compensable work-related diseases in many countries [1,9,165]. In Victoria, Australia, during the ten years between 1994 and 2004, there was an average number of 18,824 work-related musculoskeletal standard claims per year (not including travel to and from work, more than ten days compensation and/or costs greater than AUD $459) [166]. These claims were the largest proportion of injuries compared with other natured afflictions representing an average of 58.2% of all claims [166]. These figures were relatively consistent throughout this ten year period, indicating that the situation did not improve. Australia-wide, musculoskeletal disorders (both acute and chronic) accounted for 76,000 claims in the year 2003, representing 43% of all disease-related claims made [167]. These were the most common condition cited for workers compensation claims. Unfortunately, official figures do not discern between injuries with an explicit diagnosis and those without [12,30,90]. Nevertheless, it is well known that injuries attributable to non-specific musculoskeletal pain form a major component of musculoskeletal disorder complaints and are probably more common than specific clinical disorders [12,30,90,135].

The significant challenge of musculoskeletal disorders in the workplace is also evident in other industrialised nations, where, like Australia, they are still the leading cause of occupational-related injuries [29,92,168-171]. However, these prevalence rates are only estimates of the true cost and nature of musculoskeletal disorders [12,121,135], because compensable claims are restricted to the most severe incidents [121] and to those patients that are able to make lodge a claim [1,135]. Therefore, they only account for a portion of the true total incidence of musculoskeletal disorders and the actual prevalence may be considerably larger than the official figures [121,135].

However, it is difficult to separate musculoskeletal disorder statistics gathered by the relevant governing bodies in Australia regarding specific and non-specific disorders. This problem is not specific to Australia. Palmer [135], for example, reported in the UK it was likely that the majority of UK cases (approximately 50%) were due to non-specific regional pain syndromes, but that the actual figure was unknown. This view has also been reported by others [9].

Chronic regional pain prevalence (not necessarily work-related) in the general American population is similar in both sexes across all age groups at 20.1% [26,172]. At ages 18-29, chronic regional pain is found in approximately 15% of the population and almost 30% in higher ages groups up to 80 [172]. Of the general Swedish population, 15-20% report obvious pain in the neck, shoulder, arm, lower back or legs [2]. In Europe, community-based surveys indicate a prevalence of 4-20% for pain at specific sites in the neck and upper limb and a lifetime prevalence of 60% [14]. In the UK population, Croft et al. [173] reported prevalence rates of 11% for chronic widespread pain, regional pain at 43% and no pain 44%.

2.2 FIBROMYALGIA (FM)

2.2.1 DESCRIPTION

Fibromyalgia syndrome (FM) is a clinical pain syndrome that has as its main features widespread diffuse musculoskeletal pain, generalised hyperalgesia and allodynia, decreased pain threshold, tenderness elicited from application of pressure at specific anatomic sites and often psychological distress [26-29]. Other common symptoms include sleep disturbance [174,175], fatigue, psychological complaints, morning stiffness [27,101], subjective swelling and headaches [176]. Less common symptoms may include irritable bowel syndrome, sicca symptoms and Raynaud's phenomenon [101]. Widespread pain, aching and generalised tenderness are the core complaints of FM, the pain is poorly circumscribed and deep [27,176], and localised mainly to the deep somatic system [48,177], particularly in the muscles [51,77]. The pain is present during muscular rest and is more or less continuous [77]. The axial skeleton, shoulder and pelvic girdles are the most common areas of pain, and it is very unusual for FM patients not to have cervical or low back pain [106,176]. FM patients demonstrate

allodynia and hyperalgesia from application of pressure to the musculoskeletal system [57].

In 1990, the American College of Rheumatology (ACR) endorsed the Wolfe et al. [101] criteria for the classification of FM. These criteria included the presence of widespread pain for more than three months and eleven or more out of eighteen (nine bilateral) symptomatic tender points (TeP). This criterion yields a sensitivity of 88.4% and a specificity of 81.1%.

Despite extensive research, a definitive aetiology of FM is still lacking [34,78,79,178], although it is becoming increasingly evident that aberrant central and possibly peripheral pain mechanisms are involved in the pathogenesis of this pain syndrome. FM has been described as a 'pain amplification syndrome' due to a disorder of the mechanism of pain modulation [106]. Pathophysiological peripheral and central mechanisms that may be involved in the pain hypersensitivity and tenderness of FM are discussed in Sec. 2.4.

2.2.2 FM – PREVALENCE

Chronic widespread pain occurs in approximately 10-11% of the population [26,179]. In southern Sweden, chronic pain (> 3 months) has been reported at a prevalence of 53.7% [180]. FM is one of many chronic pain syndromes and the prevalence of this debilitating syndrome is high in the general community – higher even than rheumatoid arthritis [181]. In North American [179] and European [181] general populations FM has been reported at an occurrence of 3.4% in women and 0.5% in men, averaging to 2%. FM in females has been reported to be as high as 10.5% in the general population [182]. FM symptoms are considerably more prevalent in women than men; women are ten times more likely to have 11 sensitive TePs [172] and FM exists significantly more in women (80-90%) than in men [31].

2.2.3 FM AND RPS – RELATED DISORDERS?

Commonly, FM appears to gradually develop during adult life, such that patients often find it difficult to say when the syndrome began [183]. Over time, there is an increase in tenderness, psychological distress and the symptoms of FM as pain goes from no pain, to transient pain, to chronic regional pain, to chronic widespread pain and finally to FM

[184]. Various initiating factors of generalised FM have been reported. Many patients (60% [176]) cannot recall a single initiating 'event', although some report infection, and surgery as possible contributory factors. Symptom onset is sudden in about 33% of patients and initially may be localised [176].

However, in the majority of FM cases patients reported that the generalised pain was preceded by chronic localised pain usually in the musculoskeletal system [31,35,72,73,92,185,186]. For example, Bengtsson et al. [187] reported that 87% of FM patients had initial localised symptoms before. In another unpublished study of 191 FM patients, Henriksson [188] reported that 80% of patients had initial localised symptoms. In a six year follow-up study, Yunus et al. [189] reported that 44% of patients with RPS had extended symptoms to qualify for generalised FM. Inanici et al. [23] reported that 35% of RPS patients developed FM after a period of 5.9 years.

Often there is a spinal aspect to the initial pain complaints. Muller et al. [93] reported that 70% of FM patients described initial manifestations in a single localisation in the lumbar and cervical spinal regions with an average duration of seven years before the onset of generalised FM. Lapossy et al. [98] showed that 25% of patients (predominantly women with chronic low back pain) developed FM after a long period of time. Buskila et al. [78] reported that of patients who suffered a single event cervical spine injury, 21.6% patients subsequently developed FM in an average of 3.2 months after the initial cervical injury.

These studies support the notion that in the onset of FM, initial chronic localised pain (including that seen in RPS) could be an important causal factor. Pain distributions that include a spinal component also appear to be an important factor. This is discussed further discussed and investigated in Ch. 6.

Investigations into FM and other pain syndromes reveal that there may be a continuum between different pain status groups. Forseth et al. [186] conducted a five year prospective study of self-reported musculoskeletal pain in the general population and categorised participants into four pain status groups: non-chronic pain, chronic regional pain, chronic multifocal pain and chronic widespread pain (including FM). Results showed that these four groups represented a continuum of pain severity; FM was regarded as the severe end of this continuum. They [186] found that because the process

of deterioration began with localised pain in the patients and ended with generalised pain, self-reported pain of any severity conferred a risk for deterioration and developing FM.

Other investigations have reported similar results. Granges and Littlejohn investigated fit and unfit controls compared with FM patients and showed a continuum between these participant groups for pain measurements [57]. In anther study by the same group [33], RPS, FM and control patients showed an overlapping of pain symptoms between the participant groups.

Carli et al. [34] conducted similar work and investigated pain sensitivity in five different chronic pain groups, including FM. Self-reports of stiffness and present pain intensity increased concomitantly with an increase in TeP point count and pain extent. For patients affected by chronic diffuse musculoskeletal pain, results showed that as the extent of pain and the number of TePs increased the pain thresholds to superficial and deep stimuli decreased and psychological test scores decreased. Carli et al. [34] showed that the reactivity of the nociceptive system was modified in all participant groups, but to different degrees.

Inanici et al. [21] investigated clinical and psychological features of RPS and FM patients, and compared results to controls. The study showed a significant overlap between the pain groups, with RPS and FM patients sharing many clinical and psychological features. Based on the results of the study and the significant overlap in results between the pain groups, the authors proposed that RPS and FM may represent different subsets of the same condition.

This study and others described above have led some authors to propose that RPS and FM are possibly related disorders [20,21,24,28,30,31]. It is possible that these pain conditions share similar pathophysiological mechanisms [21,24,24,31-34] but to different degrees [34].

However, many factors have been reported as the cause of muscle pain and allodynia in FM and RPS, and may not be the same in all persons [35]. Several studies have shown that there are varied and possibly multiple mechanisms operating at the same time, at both a peripheral and central level, making a clear association between FM and RPS unclear. This is discussed further below in Sec. 2.4.5.3.

2.3 PAIN SUMMARY

A review of aspects of the human pain system relevant to this thesis are explored in this section. In particular, mechanisms of pain hypersensitivity (including peripheral and central mechanisms of sensitisation) are reviewed as these mechanisms are believed to be important factors in the pathophysiology of RPS and FM.

2.3.1 PAIN DEFINITION

The International Association for the Study of Pain (IASP) has defined pain as "An unpleasant sensory and emotional experience associated with actual or potential tissue damage, or described in terms of such damage" [164]. The IASP elaborate on this definition by acknowledging the subjective experience of pain, and that it is an emotional experience based on learned life experiences. Furthermore, the IASP recognise that in many cases people report pain in the absence of tissue damage or any likely pathophysiological cause. In these cases there is usually no way to distinguish their experience from that due to tissue damage taking the persons subjective report. Hence, if the pain is reported as the same as that caused by tissue damage, it should be accepted as pain.

Nociception comprises the neuronal events that are associated with the detection of tissue-threatening stimuli and with the central nervous processing of the information of these stimuli and transmission to the cerebral cortex where its effect and location are consciously interpreted [190,191]. *Nociceptors* are receptive endings that are activated by noxious (tissue-threatening) stimuli and distinguish between innocuous and noxious events. Excitation of *nociceptive neurons* result in the elicitation of the subjective sensation of pain in the conscious human [190].

Two distinct types of pain have been described. *Physiological* pain is the normal defensive response or mechanism when a noxious stimulus is applied that may threaten to damage normal tissue [53,192,193]. Physiological pain is highly localised and transient if no tissue damage occurs. In contrast, c*linical* or *pathological* pain occurs following tissue or nerve damage and ongoing discomfort and abnormal sensitivity occur. There are several pathological features of clinical pain: spontaneous pain that may be dull, burning, or stabbing; exaggerated and prolonged pain in response to

noxious stimuli (hyperalgesia); pain produced by stimuli that would never normally do so (allodynia: reduced pain threshold); and, referred pain that is a spatial spread of pain to uninjured tissue [67,69,192-194]. Clinical pain represents an increase in the sensitivity of the sensory system, the phenomenon of *nociceptive sensitisation*, and indicates that the pain system is not fixed or immutable but rather dynamic and flexible [70].

Tissue injury provokes two kinds of modifications in the responsiveness of the pain system. *Peripheral sensitisation*, a reduction in the threshold of nociceptor afferent peripheral terminals, and *central sensitisation*, an activity-dependant increase in the excitability of spinal neurons. Together these changes contribute to post-injury pain hypersensitivity, which manifests as an increase in the response to noxious stimuli and a decrease in the pain threshold, both at the site and surrounding normal tissue [65,66]. *Acute* pain typically results from soft tissue injury or inflammation and serves to protect an injury by allowing it to repair and heal undisturbed. *Chronic* pain can be a sustained sensory abnormality occurring from ongoing peripheral pathology or it can be autonomous, independent of the trigger that initiated it [53,194]. In the latter case it is the changes in the nervous system that have become the pathology and can persist for years or decades after all possible tissue healing has occurred [53,67].

2.3.2 PERIPHERAL NERVOUS SYSTEM (PNS)

Two types of afferent nerves respond to noxious stimulus, the A-delta ($A\delta$) the C-fibre nociceptor (C), also respectively termed Group III and Group IV nociceptors in deep tissues such as muscles and joints. Nociceptors are classified by the speed with which they transmit information along their axons and also their cross-sectional diameter. The $A\delta$ afferents are myelinated nociceptors that have a conduction range of approximately 2-20m/s; these nociceptors respond maximally to mechanical and thermal noxious stimulus. Some myelinated nociceptors respond only to noxious mechanical stimulus, the $A\delta$ high-threshold mechanoreceptors (HTMs). The $A\delta$ mechanothermal nociceptors respond to thermal as well as mechanical noxious stimulus. Afferent input from these nociceptors is perceived as a sharp tingling, prickling sensation. The $A\delta$ afferents generate a fast excitatory potential in the spinal cord neurons.

The C-fibre nociceptors are the most common peripheral afferent in the peripheral nervous system. They are unmyelinated and conduct at a slow rate of less than 2m/s. The major class of the C-fibre afferents in the cutaneous region is the C-polymodal nociceptor, so named because it responds to chemical, mechanical and thermal noxious stimulation. Noxious information from these nociceptors is perceived as an intense prolonged and dull burning sensation [71].[195] The C-fibre nociceptor can generate an excitatory potential in the spinal cord neurons much longer than the Aδ afferents (only a few milliseconds), lasting up to 20 seconds [64,192].

The Aβ low-threshold mechanoreceptive afferents are large myelinated nerves that do not normally respond to noxious stimulation. Hence most Aβ afferents are not classified as nociceptors. Instead they are excited normally by mild mechanical stimuli, such as light touch in the cutaneous region. They also respond to non-nociceptive deep sensors such as proprioceptors (the Golgi tendon organ afferents, muscle spindle afferents and joint afferents that normally respond to innocuous joint positions and movements) [58,71,196,197].

2.3.2.1 PERIPHERAL SENSITISATION

Both the Aδ and the C-fibre nociceptors demonstrate an ability to sensitise. *Repeated stimulation can sensitise these nociceptors,* which results in a lowering of the stimulation threshold and prolonged and enhanced response to stimulation [61]. C nociceptors frequently develop an ongoing background discharge after sensitisation. This can occur in response to tissue damage and the consequent inflammatory response [194] and can have consequences for the second order neurons in the spinal cord [53,71,195].

2.3.2.2 MUSCULOSKELETAL PAIN

Pain signals from the musculoskeletal system, particularly from the C-fibre afferents, are effective drivers of central pain sensitivity changes. Increased central pain sensitivity is involved in chronic musculoskeletal pain syndromes and, therefore, mechanisms of musculoskeletal pain are explored in this section. Musculoskeletal pain from muscles and joints, in the context of experimental investigation, are discussed further Ch. 4.

The peripheral pain system can be divided into three functional groups: the skin, the deep somatic (musculoskeletal) and the visceral. Pain arising from the skin is normally sharp and well localised and serves well the function of rapid removal or escape from a noxious and potentially tissue-damaging stimulus. However, pain from the deep structures is not as well localised [198] and normally serves to immobilise the structure to prevent further damage [71]. Since pain from deep structures constitutes the majority of pain treated by clinicians, deep pain is of greatest clinical importance [199].

In the *muscles* there exist two types of afferent fibres responsible for transmitting nociceptive impulses: the thin myelinated (group III or A-delta) and the unmyelinated (group IV or C) fibres. Group I and II fibres (A β) are large myelinated fibres with fast transmission speeds that relay information from muscle spindles and tendon organs; they do not transmit noxious impulses and so are not classified as nociceptors [200]. The peripheral terminal endings of most afferent muscle nociceptor fibres are free nerve endings partly covered in Schwann cells [190,197] that are scattered throughout skeletal muscle, with particular dense concentration at tendons, fascia and aponeuroses [200]. Most free nerve endings are at walls of arterioles, surrounding connective tissue, between muscle fibres or in tendons [190,201]. The most common type of nociceptor is the unmyelinated group IV that typically terminates in free nerve endings. The free nerve endings form as much as 75% of sensory innervation of skeletal muscle [201].

Similarly to cutaneous polynomial modal nociceptors, muscle nociceptors can respond to multiple types of noxious stimulus, whereby some may respond to a single chemical substance while others respond to a variety of chemical, mechanical and thermal stimuli [200]. The typical nociceptor is polymodal and responds to both noxious local pressure and certain chemicals (both arterial or intramuscular); there are also nociceptors that are activated by only one type of noxious stimulus (mechanical or chemical) [190]. Receptive endings are classified as low-threshold mechanoreceptors (LTM) (respond to weak innocuous mechanical stimuli) and high-threshold mechanoreceptors (HTM) that require strong mechanical stimulation (noxious local pressure) to be activated. Many units have two receptive fields and can be activated from two separate areas in the muscle. Units have also been found that have receptive fields in deep tissues and another in the skin distal to the deep field. Branched afferents are rare but may reduce the spatial resolution, hence contributing to the diffuse nature of muscle pain.

Muscle pain can be experienced by several mechanisms. Some of these are reviewed here: *acute trauma* and strong mechanical forces will activate muscle nociceptors mechanically and disrupt blood vessels and muscle fibres. Chemicals released from the blood, disrupted muscle fibres and also the axon reflex will activate nociceptors. The immediate pain of acute trauma can be explained by direct mechanical activation of muscle nociceptors, and the ensuing tenderness is due to sensitisation of the receptors by numerous chemicals released from the damaged tissue and/or blood. Sensitisation of HTM mechanonociceptors receptive endings may occur, which will lower the mechanical threshold and they will begin to respond to innocuous mechanical stimuli such as touch or innocuous deformation of the muscle [197]. In an inflamed muscle, the pain is likely mediated predominantly by group III units whereas the tenderness is probably caused by sensitisation of nociceptive receptors that may be due mainly to group IV afferents [197].

Ischemia: interruption of blood supply to a resting muscle does not cause pain, but if the *muscle is forced to contract under these conditions*, ischemic pain quickly develops [190]. Only a small proportion of muscle nociceptors respond to this condition, but respond strongly and severely to the detriment of muscle contractile performance, suggesting that they are highly specialised. Ischemic pain is likely conducted by C-fibre (group IV) afferents [197]. Ischaemic muscle pain is believed to be, at least in part, due to accumulation of metabolites, including histamine, serotonin, potassium, bradykinin and others [190,200,202]. These metabolites are particularly effective stimulants of skeletal muscle nociceptors. Bradykinin has been shown to have an excitatory and strong sensitising effect on muscle nociceptors [190]. Bradykinin is released when pathological deviations from the normal environmental conditions occur. It is released from plasma proteins during ischemia [190]. It has been speculated that an ischemia-induced decrease in muscle pH releases bradykinin and other chemicals, which sensitise the muscle nociceptors so that they respond to the force of contraction [190]. Therefore, muscle contractions under ischemic conditions may sensitise and activate muscle nociceptors [190]. *A sensitised muscle nociceptor will become responsive to innocuous mechanical stimuli* (e.g., stretch, contraction or local pressure). Tenderness can be explained by activation of sensitised nociceptors by weak mechanical stimuli [190]. This type of pain disappears quickly from cessation of contractions and restoration of circulation [200].

Pain from the musculoskeletal system is normally ill-localised. This may be due to second order neurons in the dorsal horn almost always having additional input from neighbouring nociceptors in tendons, ligaments and joints [198] and/or it could be due to the fact that afferent fibres from a given muscle are distributed to many spinal segments making localisation difficult [197]. In addition, the dorsal horn neurons that receive nociceptor afferent input from deep tissues are *strongly modulated by the antinociceptive modulation system from supraspinal structures*. This may be another factor that contributes to the poor localisation of muscle pain [197]. The dorsal horn cells and the antinociceptive system are discussed respectively in Sec. 2.3.3.1 and 2.3.3.4.

The *joints* are extensively innervated by A and C-fibre afferents and respond maximally to mechanical deformation [203]. Afferent fibres are predominantly group II and group IV types [201]. In an inflamed joint, patients do not normally experience continuous 'spontaneous' pain but rather pain is experienced predominantly and most severely when the inflamed site is mechanically stimulated by being moved or touched [204]. Injection of pain producing substances causes swelling, increases in temperature and increases of afferent fibre activity [205]. Induction of inflammation in a joint results in a marked increase in sensitivity of both A-delta and C-fibre nociceptors with increased background activity [196,205,206] and the nociceptors become hypersensitive by responding to innocuous stimuli and increased response to noxious stimuli [204]. In a normal joint, pain is produced by movements of the joint in excess of the normal range, however in an inflamed joint even minimal movements can be painful by activation of sensitised nociceptors [196,205,206]. These outcomes have implications for joint range of motion assessments; this is discussed in Ch. 5 with regards to cervical range of motion.

It is also possible that activation of non-nociceptors afferents can cause pain in an inflamed joint [58,204]. Activity in the Aβ non-nociceptive low-threshold afferents may also contribute to the generation of pain by gaining access to the pain pathways [204]. Kramis et al. [58] suggested that in a sensitised central pain system, non-nociceptive proprioceptive afferents may 'obtain access' to the pain pathways and generate pain, probably via sensitised wide-dynamic dorsal horn neurons. Spinal neurons, both wide-dynamic range and nociceptor specific (discussed in Sec. 2.3.3.1),

can sensitise to input from articular afferents under influence of inflammatory processes [207]. In addition, the spinal neurons display enhanced reactions to non-inflamed parts of their receptive fields and some neurons show enlargement of their total receptive fields. Therefore, spinal mechanisms may also participate in the sensitisation process seen in inflamed joints [207]. Central spinal mechanisms are discussed below.

2.3.3 CENTRAL NERVOUS SYSTEM (CNS)

As will be discussed in Ch. 6, Sec. 6.6.2 and Ch. 4, Sec 4.6.8, mechanisms of central hypersensitivity are important factors in the pain manifestations related to chronic musculoskeletal pain syndromes. Central sensitisation and dysfunction of the descending pain modulation are the main mechanisms of central hyperexcitability. Wind-up is also an important mechanism of central hyperexcitability, because it may be a triggering factor for central sensitisation. These phenomena manifest in the dorsal horn neurons in the spinal cord and are discussed below. It is important to begin any discussion of the central nervous pain system by first exploring the function of dorsal horn neurons.

2.3.3.1 THE DORSAL HORN CELLS

The dorsal horn region of the spinal cord is representative of many complex and integrative systems that modulate and transmit afferent information. Four functional components converge at these neurons: central terminals of primary afferents, neurons of ascending systems, local-circuit interneurons and axonal terminals of descending systems [61].

The peripheral afferent nociceptors synapse directly with second order neurons in the dorsal horn region of the spinal cord. The C-fibre afferent constitutes the majority of afferents in the dorsal horn [208]. As the afferents approach the spinal cord, the myelinated and small unmyelinated axons become segregated. The afferents bifurcate into ascending and descending branches that extend for one or two segments beyond the level of the parent axon entry. After coursing in spinal tracts, the primary afferents either enter or send a collateral branch into the adjacent dorsal horn. There, they give rise to an extensive and highly branched terminal field.

The nociceptors terminate in the dorsal horn in a highly ordered way in segregated layered regions, the 'laminae'. The Aδ terminate in laminae I and V and C-fibres in lamina II and possibly lamina I [53,71]. The low-threshold mechanoreceptors terminate predominantly in laminae III and IV. Most dorsal horn neurons receive convergent input from numerous primary afferents, often of different types including nociceptive and non-nociceptive afferents [71]. The result is a receptive field several times larger than those of peripheral afferent nociceptors, particularly in lamina V. In deeper lamina, nociception projection cells show even greater convergence, and the input to these deep-lying neurons is often bilateral and they may respond from deep tissues such as muscle and viscera afferents.

A variety of neurons exist in the dorsal horn and can be broadly classified as: projection neurons – relay the nociceptive information to higher processing centres; excitatory interneurons – relay nociceptive input between laminae of the spinal cord to projection neurons, to other interneurons or motor neurons (for spinal reflexes); and, inhibitory neurons – contribute to the control of nociceptive transmission. The projection neurons can be further classified: *nociceptive specific* (NS) neurons which, as the name implies, synapse only with Aδ and C nociceptors; and the *wide-dynamic range* (WDR) neurons which receive input from nociceptors and low-threshold mechanoreceptive afferents (Aβ) [71,196,209]. The nociceptive-specific neurons are found in lamina I and, to a lessor extent, in laminae IV and V [209].

The wide-dynamic range neurons are the most common cell in every lamina [209]. Their receptive fields are normally larger than those of the primary afferents [210]. They exhibit a gradient of sensitivity: at the centre of the receptive field all stimulus types are effective, including weak mechanical stimuli. At the periphery of the receptive field, only noxious stimuli excite the neurons [210]. The graded receptive field of the dorsal horn neurons is believed to be an important factor in central phenomena including hyperalgesia and secondary hyperalgesia. These are important pain manifestations in chronic musculoskeletal pain, and are discussed in more detail below (see Sec. 2.3.3.3).

Afferent nociceptor input, after complex active processing, is transferred in the dorsal horn directly or via the brainstem relay to the thalamus and then the cortex where the

sensation of pain is generated. Parallel outputs from the dorsal horn go to the ventral horn and activate flexor motor neurons generating a withdrawal reflex [53].

In the dorsal horn, a small proportion of neurons are nociceptor specific to afferent input from muscle nociceptors. Some dorsal horn neurons also receive nociceptive input from both deep and cutaneous receptive fields [211]. However, the great majority of dorsal horn cells with nociceptor afferent input from the deep somatic tissues receive input from various tissues such as muscle, tendons, ligaments and joints [211]. The high-threshold mechanosensitive neurons (HTM: nociceptor input from deep tissue nociceptors) and low mechanical threshold neurons (LTM: exclusive input from deep tissue afferents that respond to innocuous stimuli) have been used to classify dorsal horn cells that receive input from deep tissues [211]. The convergent afferent input from neighbouring nociceptors in various deep tissue may contribute to the diffuse, poor localised nature of deep pain [198]. Furthermore, the multiplicity of the receptive fields of many dorsal horn neurons with input from deep tissues may add to the diffuse nature of deep pain and could form the basis of the spread or referral of deep pain to other deep tissues [197].

2.3.3.2 WIND-UP

'Wind-up' was first observed by Mendall and Wall [62] who noticed that low frequency input from afferent nociceptors, particularly C afferents, produced a progressive increase in the excitability or amplitude of response of the dorsal horn neurons. Wind-up generates a progressive increase in action potential discharges of dorsal horn neurons [64,212,213]. C-fibres in muscles and the deep tissues are more effective at initiating wind-up than cutaneous C-fibre afferents [214]. Wind-up requires a very low frequency input to elicit it and manifests only during the train of repetitive inputs [64]. Stimulus frequencies of once every three seconds or greater will initiate wind-up [49,213]. This critical frequency appears to mimic the natural frequency of peripheral C nociceptors that discharge at about once every 2-3 seconds at stimulus intensities likely to be minimally painful [49].

Once wind-up has been produced in wide-dynamic range neurons by repetitive stimulation of C-fibre stimulation, the enhanced C-fibre mediated response can subsequently be maintained by very low frequency C-fibre stimulation, one stimulus

every ten seconds [49]. This suggests that once wind-up occurs, a sensitised state can be maintained by extremely low frequencies of tonic peripheral input from nociceptors [49].

It is possible for a central summation of afferent stimulus, or wind-up, to occur in the absence of spiking activity. This subthreshold change in excitability of spinal cord cells represents the possibility for subsequent excitability alterations that may be hidden, in the sense that no action potential discharge is evoked [213]. This may result in a prolonged alteration in the properties of the spinal neurones, such that they respond to normal afferent inputs in an exaggerated fashion, and yet this change in excitability may be hidden [213].

Wind-up has been described as a *homosynaptic* event as it only involves the same synaptic input that has transmitted the conditioning stimulus and does not involve sensitisation of other synaptic inputs to the same neuron [215,216].

2.3.3.3 CENTRAL SENSITISATION

The phenomenon of central sensitisation contributes much to our understanding of pain manifestations in chronic pain syndromes, including RPS and FM. It is believed that this mechanism of central hyperexcitability is equally, if not more, responsible for many common chronic musculoskeletal pain syndromes compared with peripheral mechanisms.

Central sensitisation has been defined in the literature as an enhanced responsiveness of nociceptive neurons in the CNS to their normal afferent input [217]. Central sensitisation is a prolonged alteration in the response properties of nociceptive transmission neurons, whereby there is a long-term increase in excitability, outlasting any nociceptive afferent input or requires a low-level peripheral drive to maintain it [198,218-220].

Central sensitisation is expressed behaviourally as a prolonged pain threshold reduction, an increased responsiveness at the spinal cord to afferent inputs, an expansion of the peripheral receptive field of dorsal horn neurons [63-67] and the development of new receptive fields [198,221]. Central sensitisation may be produced as a result of activity generated by C-fibre afferent nociceptors at the time of an injury and as a result of the

activity produced later in C-fibre afferents from inflammatory responses at the injury site [53,65,68,69]. Activity in cutaneous and muscle C-fibre afferents can evoke central sensitisation [63,65,214,215], although muscle afferents producing much longer-lasting effects. Electrical stimulation of skin afferents for 20 secs produced several minutes of central hyperexcitability, whereas activation of muscle afferents for the same period will produce a central effect for up to an hour [66].

Central sensitisation alters sensory processing in the spinal cord; large myelinated low-threshold afferents that respond to light innocuous stimuli begin to produce pain, something they never do under normal circumstances [63] (see Figure 2-1). This may explain how low-intensity, innocuous stimuli can produce pain in a clinical pain syndrome [63,65,66]. Central sensitisation manifests clinically as allodynia (lowered pain threshold where a normally non-noxious stimulus is perceived as painful), primary hyperalgesia (tenderness or increased responsiveness to a noxious stimulus at the site of injury), and secondary hyperalgesia (tenderness in the normal tissue surrounding an injured site) [68]. Central sensitisation is believed to occur from chemical imbalances in the dorsal horn. The process of wind-up is believed to rely on a similar process and as a result may contribute to the establishment of a neurochemical imbalance that is important for central sensitisation. N-methyl-D-aspartic (NMDA) acid, Mg^{2+}, Ca^{2+}, substance P, neurokinin A and other neurochemicals are believed to play a role in both wind-up and central sensitisation [64,194].

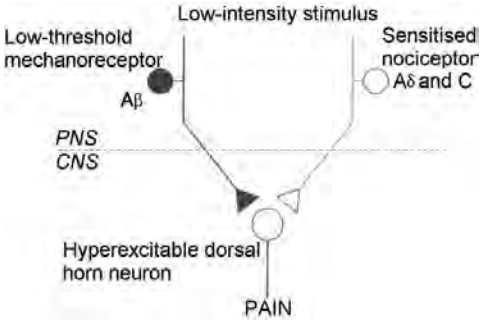


Figure 2-1 – Low-threshold mechanoreceptors (Ab) accessing the pain system via sensitised dorsal horn neurons.

(From [222])

The processes that produce wind-up are believed to be sufficient to produce central sensitisation [64]. C-fibre afferents can produce slow synaptic potentials that summate temporally on low repetition rates leading to non-linear increasing discharge (wind-up)

and, act as a trigger for prolonged alterations in membrane excitability that at a system level is central sensitisation [64]. However, while wind-up is believed important to the initiation of central sensitisation, it is possible for central sensitisation to occur in the absence of wind-up. Wind-up can initiate central sensitisation because it contributes to the neurochemical imbalances believed necessary for central sensitisation, not because of the manifestation of wind-up of progressive increase in action potential discharge. Central sensitisation will still occur if the required neurochemical imbalance exists (elevated intracellular calcium), and not necessarily with an associated change in action potential firing [64].

Central sensitisation is more general than wind-up and can be produced by the asynchronous activations of skin, joint, muscle or visceral afferent nociceptors, which may not produce a detectable pattern of progressively increasing action potential discharge or wind-up. Magerl et al. [216] established that wind-up and central sensitisation are in fact independent phenomena, with no appreciable interaction between them. The mechanisms of wind-up and central sensitisation are different, but may act in series [216].

Central sensitisation manifests clinically as spatial field extension. Woolf [69] explained that signals from the A β *low-threshold mechanoreceptors* may be *misinterpreted as if they were from nociceptors*. Under normal circumstances, input from low-threshold mechanoreceptors to the nociceptor pain sensory pathway, either directly or via interneurons, is subliminal or ineffective; hence, a failure of low intensity stimuli to produce pain. However, an alteration to the excitability of neurons in the nociceptor-pain pathway from central sensitisation could result in previously subliminal input from the low-threshold afferents generating action potentials, activating the pathway and generating pain. In this model, the dorsal horn neurons have certain inputs that, under normal circumstances, have a high probability of generating a response and others that have a low probability. Under changed conditions, the low probability inputs could acquire a high probability of activating a cell. These changes would indicate that the CNS is not hard-wired and instead can provide dynamic alterations in different situations by altering its function. This is known as functional neuronal plasticity.

Woolf [69,70] proposed a model of a dorsal horn neurone with a convergence of afferents with different peripheral receptive fields. Spatial extent of a dorsal horn cell's

receptive field was determined not only by anatomical constraints but also by the synaptic efficacy and membrane excitability that could allow changes in the size of the receptive field as well as their thresholds. The main *firing zone* represented an area of skin where stimulus produced a discharge of action potentials. The *low-probability firing zone* constituted a fringe area of skin where stimulus evoked a post-synaptic potential but no significant action potential discharge. In the firing zone there were considerable subthreshold inputs representing a *reservoir* of potential responsiveness. The subthreshold inputs to a dorsal neuron in the firing and low-probability zones represented a reservoir of potential responsiveness that could contribute to dynamic receptive field alterations if the dorsal horn membrane excitability or the synaptic efficacy changed. Modification of the dorsal horn neurons receptive field properties can be triggered by C-fibre activity from stimulus of joints, muscle, and thermal and mechanical skin stimulation. The changes were a consequence of the conversion of subthreshold input into suprathreshold. These alterations increased the receptive field size of dorsal horn neurons together with an amplification of their responsiveness, and a fall in their threshold. These changes persisted long after the noxious stimulus that triggered these changes was removed.

As a result of central sensitisation, activity in the low-threshold mechanoreceptor afferents can cause a response in *wide-dynamic range* dorsal horn neurons *and* the *nociceptive specific* dorsal horn projection neurons, whereby they are ‘converted’ into multireceptive cells that respond to innocuous as well as noxious stimulus [215,223]. The enhanced responsiveness of synapses from Aβ fibres that are not part of the original C-fibre conditioning pathway indicate that central sensitisation is explained as *heterosynaptic* facilitation, unlike wind-up which has been described as homosynaptic facilitation [215,216].

Important questions remain regarding the maintenance of central sensitisation, once it has developed. *Little continuous peripheral input is required to maintain central sensitisation* [224]. It is not known whether the abnormal changes in the excitability of dorsal horn neurons due to central changes simply drift back to their normal setting or whether there are central processes that force the setting back toward normal [225]. Also, does it become independent of its precipitating cause or is it maintained by steady input from nociceptors [215]? Long-term central sensitisation is unlikely to occur in the

absence of a steady pathological nociceptive peripheral source [48,215,226]. Reduction of nociceptor input from injured skin by cooling or anaesthesia leads to rapid suppression or even complete abolition of secondary hyperalgesia to light touch [215]. However, Kramis et al. [58] suggest that central sensitisation induced by prior nociception, can persist to some degree, even in the absence of ongoing nociceptive afferent activity. Another proposed hypothesis suggests that long term alterations to the central processor may become autonomous and independent of peripheral input [55]. Potentially irreversible changes in the central nervous system or spinal cord plasticity may persist after resolution of tissue damage [52]. These have important implications for patients with chronic musculoskeletal pain.

2.3.3.3.1 Long-term potentiation (LTP) in pain pathways

Long-term potentiation (LPT) is a cellular model of synaptic plasticity, and is defined as a long-lasting (but not necessarily irreversible) increase in synaptic strength between neurons. At least two stages can be described for LTP: early phase which lasts for up to three hours, and late phase LTP which can last for a life span, and may involve structural change at synapses. LTP in the brain (at synapses in the hippocampus) are the main areas of investigation (involving models of learning and memory), but studies have shown that LTP can be induced in pain pathways and may contribute to hyperalgesia. Is particular, LTP at synapses of nociceptive C-fibres in the superficial section of the dorsal horn layer could be a cellular mechanism underlying some forms of hyperalgesia [217]. Both pre- and post-synaptic mechanisms may be involved [227].

LTP in pain pathways can be induced from high and low frequency electrical nerve stimulation. Low level afferent input can also induce LTP in pain pathways if the descending pathways are also weak or interrupted [217]. This strengthening of the efficacy of synaptic transmission that occurs following nociceptive activity across a synapse shares many features that are associated with the development of chronic pain [222]. Hence, the descending pain modulation system can raise the threshold for nociception, but also the induction of LTP in the dorsal horns cells of the CNS [217,227]. The descending pain modulation system and hyperalgesia is discussed below.

2.3.3.3.2 Hyperalgesia, secondary hyperalgesia and allodynia

The International Association for the Study of Pain (IASP) defined hyperalgesia as "an increased response to a stimulus which is normally painful". This phenomena reflects increased pain on suprathreshold stimulation. Allodynia was defined as "pain due to a stimulus which does not normally provoke pain". The IASP further described that allodynia involves a change in the quality of a sensation, whether tactile, thermal or of any other sort. Thus, the sensory modality was not specified.

The phenomenon of central sensitisation is expressed clinically as hyperalgesia (both primary and secondary) and allodynia. Hyperalgesia and allodynia are important pain manifestations involved in chronic musculoskeletal pain syndromes. As noted above, when an acute tissue injury occurs, there is an increase in the sensitivity at the site of the injury (primary hyperalgesia), a spread or increase in the spatial extent of the hypersensitivity (secondary hyperalgesia) and non-noxious mild mechanical stimulus begins to cause pain (allodynia) [64]. Coincident with the spreading of the hyperalgesia is sensitisation of the dorsal horn neurons [67].

There is typically an inflammation response at a site of injury [67]. Peripheral sensitisation has been shown to occur at the injury site, manifesting as a lowering of the threshold of nociceptors and increased responsiveness. However, peripheral sensitisation does not account completely for the mechanical sensitivity seen at the injury site, because soft or mild mechanical sensitivity is mediated by non-nociceptive $A\beta$ low-threshold mechanoreceptive afferents. Instead, when the excitability of the spinal cord is increased, as part of central sensitisation, afferent input from $A\beta$ low threshold mechanoreceptors somehow gains access to the central nociceptive pathways and produces pain – something the mechanoreceptors never normally do [64]. Peripheral sensitisation also cannot account for secondary hyperalgesia, where no change in the transduction sensitivity of nociceptors has been found in the zone outside the area of injury [53,216]. Instead, central sensitisation provides an explanation of how $A\beta$ low-threshold mechanoreceptors, which normally generate only innocuous sensations, begin to produce pain after acute C-fibre stimulus, by the recruitment of previously subthreshold inputs (latent) to nociceptive dorsal horn neurons [67,215,228,229] (see Figure 2-2). As noted above, this effect is a result of an increase

in the synaptic efficacy or membrane excitability in dorsal horn neurons, converting previously subthreshold input to a suprathreshold response [53,194].

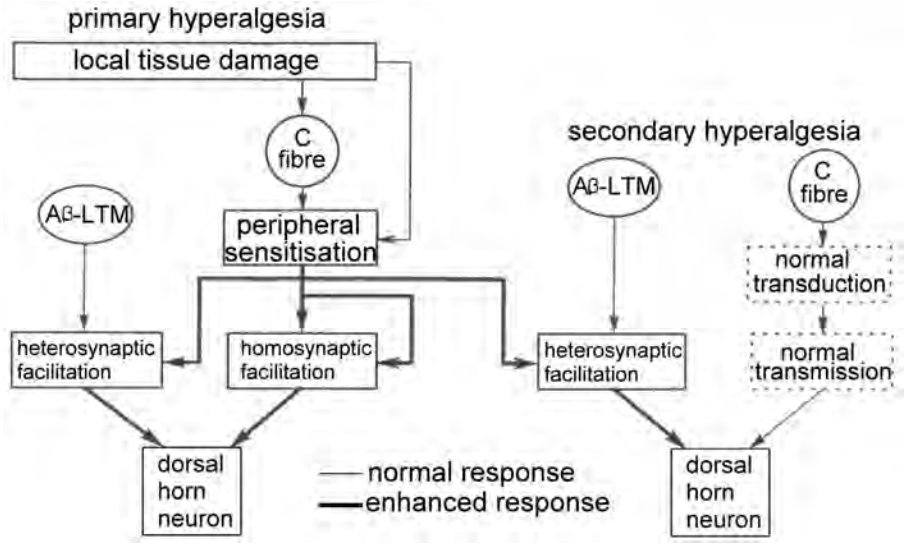


Figure 2-2 – Mechanisms operating in primary and secondary hyperalgesia.

(From [215]).

Interestingly, the changes in a dorsal horn neurone *mechanical* response properties are readily reflected throughout the receptive field (primary and secondary hyperalgesia zones), but hyperalgesia to *heat* is not observed in the secondary hyperalgesia zone [215,216]. A change in heat responsiveness is only altered in the directly injured skin areas, the primary hyperalgesia zone. This phenomenon provides further evidence that secondary hyperalgesia is mediated not by peripherally sensitised nociceptors, but instead by low-threshold mechanoreceptors that normally signal non-painful touch sensation. Furthermore, these changes suggest that there is not a generalised increase in the excitability of dorsal horn neurons, because this would predict that the responses to heat stimuli would also be enhanced when delivered anywhere within the receptive field, which is not the case. Instead it has been hypothesised that the increased excitability of dorsal horn neurons to mechanical stimuli is presynaptic and mediated by a subgroup of sensitised interneurons, which may respond only to noxious mechanical and not to noxious thermal stimuli [215,216,230,231].

Neuroplastic changes associated with central sensitisation have also been shown in studies into deep *muscle* tissue in animals. Mense and Hoheisel [232] demonstrated that that the input region of a muscle nerve can expand; i.e. the population of dorsal horn neurons responding to an electrical stimulus applied to a muscle nerve can grow larger.

Mense [211] also showed that injection of a pain producing substance in one part of a muscle caused expansion of the injected receptive field, a lowering of threshold in non-injected receptive fields, formation of new receptive fields and effects that far outlasted the influence of the pain-producing substance introduced by injection (due to central sensitisation of the dorsal horn neurons). Normally the new receptive fields were formed *distally to the original one* [198]. Noxious stimulation of deep tissues referred pain predominantly to other deep tissue areas, not to cutaneous areas [198,211]. These outcomes are probably of clinical significance as they may explain the hyperalgesia, spread and referral of pain, all of which is typical for prolonged muscle pain [232].

Kramis et al. [58] proposed that *deep somatic pain* may also be caused by *activity in non-nociceptive afferents* that somehow gain access to the central pain pathways (similar to the pain system at a cutaneous level). Musculoskeletal non-nociceptive afferents that normally serve proprioceptive functions and respond to innocuous joint positions, postures and innocuous movements may cause pathologically persistent pain via activation of dorsal horn neurons sensitised by the mechanisms of central sensitisation [58]. Unfortunately, the particular types of non-nociceptive deep tissue afferents that may excite sensitised dorsal horn neurons and thus produce non-nociceptive musculoskeletal pain remains largely undetermined. The potential role of proprioceptive afferents in deep pain has received little attention from physiologists [58].

2.3.3.4 DESCENDING PAIN MODULATION SYSTEM

Dysfunction of the descending pain modulation system has been shown to cause significant and widespread changes in the control of pain transmission in the dorsal horn neurons. This supraspinal level globally projecting system may contribute to the ‘whole of body’ pain seen in generalised musculoskeletal pain syndromes, such as FM. This is discussed below and is introduced here in detail.

Supraspinal sites can selectively modulate the transmission of pain at the dorsal horn level, which is accomplished via the descending pain modulatory control pathways. These pathways are a bi-directional network of neurons that *exert control over the dorsal horn nociceptive transmission neurons*. These pathways are presumed to exist to facilitate escape in a threatening situation by suppressing reflexes or pain behaviours

[71]. This system has also been called the antinociceptive system [198] or the anti- and pro-nociceptive systems.

Electrical stimulation of the midbrain periaqueductal grey (PAG) can produce a highly specific and robust suppression of behavioural responses to noxious stimulation. The PAG is part of a CNS circuit that controls nociceptive transmission at the level of the spinal cord, by selectively inhibiting neurons at the dorsal horn. The PAG receives a significant projection from dorsal horn lamina I nociceptive neurons [233,234].

The PAG is reciprocally connected to the rostral ventromedial medulla (RVM) that receives sparse spinal projections, but may receive spinal input from the PAG and other supraspinal regions. The RVM includes the midline nucleus raphe magnus (NRM). The PAG-RVM connection is believed critical to supraspinal pain modulation as the PAG only minimally projects to the spinal cord; pain modulation actions of the PAG is relayed largely, if not all, through the RVM. Electrical stimulation of the RVM has been shown to selectively inhibit nociceptive dorsal horn neurons. Axons in the RVM project to the spinal cord dorsal horn and are most dense in laminae I, II and V. As described above in Sec. 2.3.3.1, these laminae are targets of the primary nociceptive afferents and their neurons respond maximally to noxious stimuli. The dorsolateral pontomesencephalic tegentum (DLPT) is adjacent to the PAG and shares many anatomical features including input from lamina I dorsal horn neurons and projection to the RVM. The DLPT also projects to the spinal cord (Figure 2-3) [233,234].

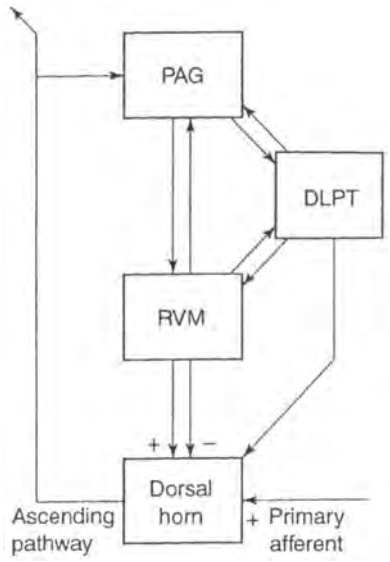


Figure 2-3 – Descending pain modulation pathways.

(From [233])

The pain-modulatory networks can inhibit pain and also facilitate nociceptive transmission; it is likely that inhibitory and facilitatory controls are produced by different pain-modulatory neurons. Three classes of cells have been identified in the RVM: those that discharge (*on cells*), shut-off (*off-cells*) and show no consistent change in activity (*neutral-cells*) in response to withdrawal from noxious stimulation. On-cells are consistently excited by noxious stimuli over much of the body surface and off-cells are inhibited by the same stimuli. Neutral-cells show variable response or are unresponsive to noxious stimuli. Off-cells are most consistently related to suppression of nociceptive transmission, and on-cell activity is likely related to facilitation of nociceptive transmission, at the level of the dorsal horn (see Figure 2-4). On and off-cells project from the RVM to the laminae I, II and V of the dorsal horn.

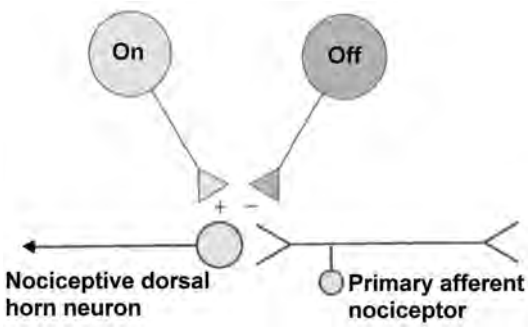


Figure 2-4 – Descending pain modulation at the dorsal horn neuron.

(From [233])

RVM and DLPT modulatory neurons are believed to inhibit nociceptive transmission at the dorsal horn by several mechanisms: direct inhibition of projection neurons; inhibition of transmitter release from primary afferents; excitation of inhibitory interneurons; and, inhibition of excitatory interneurons [61,233]. The RVM also contains a high percentage of spinally projecting serotonergic neurons [71], the vast majority of which are neutral-cells [233]. Serotonin is likely involved in pain modulation [71,233], and the RVM is the major, if not sole, source of serotonin in the dorsal horn [61,71]. Electrical stimulation of the RVM evokes release of serotonin in the spinal cord cerebrospinal fluid. The conditions under which these RVM serotonin cells come into play is uncertain, though they are believed to have a slow tonic discharge that may tonically modulate the effect of the RVM on- and off-cells at the dorsal horn.

Importantly, the receptive fields of the pain-modulating neurons in the RVM, PAG and DLPT are *very large and virtually 'total-body'*. Individual RVM neurons project diffusely to the dorsal horn at multiple spinal levels. Furthermore, many RVM neurons have highly collateralised axons within the RVM itself and cells of the same class tend to fire at the same time [233]. Fields and Basbaum [233] believe that this organisational arrangement suggests that the neurons of each physiological class function as a unit that exerts *global*, rather than topographically discrete, control over pain transmission.

Cooling the spinal cord (cold blocks) blocks the pathways in the dorsal portion of the spinal cord and eliminates most of the descending influences from the supraspinal inhibitory centres, the PAG and NRM [198]. Cold block of the spinal cord produces a completely reversible increase in activity of A-fibre and C-fibre responses [227], an increase in the number of receptive fields [198], an increase in ongoing activity, a lowering of stimulation threshold, and an increase in response magnitude in nociceptive dorsal horn neurons [75]. Cold block has also been used to show that descending inhibition has a significantly stronger action on the deep tissue HTM neurons compared with the LTM neurons in the dorsal horn [197,211].

In addition, some dorsal horn neurons receive nociceptive input from deep and cutaneous tissues. Analysis of the relative increase in response magnitude before and after cold block of such neurons demonstrated that stimulation of the deep tissue receptive field was much larger than from stimulation of the cutaneous receptive field. Together, these results demonstrate that descending inhibition not only *has a stronger action on HTM versus LTM dorsal horn neurons, but also inhibits the input from deep somatic nociceptors more strongly than that from cutaneous nociceptors* in one and the same cell [197,211]. These outcomes have also demonstrated that nociceptive inhibition of the input from deep nociceptors is tonically active; otherwise it could not be cold blocked. The tonic nature of inhibition implies that cells at the supraspinal level are continuously releasing transmitter substances that maintain the inhibition [211].

Psychological factors appear to play an important role in the descending pain modulation systems where increased attention and stress levels may facilitate nociceptive transmission [234]. In animal studies, stress, fear or hopelessness, and pain intensity and duration have been shown to be important factors for activation of the antinociceptive system [234]. Studies have shown that analgesia induced by the

antinociceptive system can be physiologically activated by prolonged noxious stimulation and by exposing animals to a variety of stressful stimuli [234]. For example, by placing animals in threatening situations such as proximity to a predator, many animals freeze and become unresponsive to noxious stimulation [233]. These responses can also be learned in animals, and analgesia can be conditioned to activate to an external stimulus such as light or tone [233]. Animals can also be conditioned to increased responsiveness or an anti-analgesia effect from external stimuli such as a light [233].

In human and in animal studies, expectational and attentional factors can alter perceived pain intensity [233]. It is likely that there is a central component to the response of dorsal horn neurons and that this centrally generated component incrementally adds to the perceived intensity of the pain [233]. Studies of monkey dorsal horn neuron responses after conditioning and learning showed that they underwent abrupt increases or decreases in activity due to an external cue. The task-related changes in activity occurred prior to any onset of noxious stimulation, demonstrating that the activity of dorsal horn neurons can be increased or decreased by a context-specific modulatory signal that originates in the CNS [233]. From these animal studies, Fields and Basbaum [233] suggested that, given the presence of facilitatory modulation of dorsal horn neurons, it is possible that pain could be produced by a centrally originating drive of dorsal horn neurons without activation of primary afferent nociceptors. Fields [235] further speculated that the sensation of pain could be generated by purely central mechanisms under physiological circumstances. A patient focusing on a minor pain may increase its intensity.

Transposing these outcomes to humans may account for the widespread pain observed in patients with fibromyalgia [75]. This is discussed below.

2.4 PATHOGENSIS OF PAIN IN FM AND RPS

Despite extensive research the definitive aetiology of FM [47,78,79,236] and RPS [5-10,17,36,39,44,45] is unknown.

Bennett [237] in a review of fibromyalgia described this complex syndrome as a “pain hyperalgesic syndrome, in which abnormalities of central sensory processing interact

with peripheral pain generators, and psychoneuroendocrine dysfunction to generate a wide spectrum of symptoms and distress". Rather than being regarded as a distinct entity based on a specific pathology [237], this pain syndrome and RPS are generally believed to be the result of a convergence of many causes [24].

Several theories have been proposed for the central feature of this pain syndrome [184]. These include FM interpreted as a psychological disorder, sleep disorder, muscle disorder, pain modulation disorder [184], neuroendocrine disorder [34,238] and a biopsychosocial disorder [26,184]. Some of these are discussed below. It is unlikely that one specific cause would create these pain syndromes. Researchers have proposed an integrated biopsychosocial model to help explain the pain interaction with a multitude of physical, behavioural, societal, biologic, psychological, familial, genetic, neurohormonal and disease-related abnormalities and problems [26,184]. The biological element of this model concerns mainly the pain and tenderness seen in FM and RPS, as well as changes related to continuous physical and emotional stress [188]. Indeed, researchers now believe that CNS dysfunction and/or neuroendocrine dysfunction are the two main pathogenetic mechanisms of FM [34]. A full discussion of this model is beyond this thesis, but the biological element of the model, and in particular the pain aspects, are discussed below.

Pain modulation disorders are central to many theories regarding FM and RPS. Many studies have emphasised the role of central nervous system pain processing abnormalities in FM [28,31,33,105,106,111,239] and RPS [17,33,59,60,79,92] and at different central levels, including spinal (wind-up, central sensitization, LTP) and at the supraspinal level (descending modulation, stress regulating system). However, several studies examining the muscles in chronic musculoskeletal pain syndromes also point towards peripheral mechanisms as contributing to the pain hypersensitivity [51], particularly from the trapezius muscle [36,37,39,42,43]. It has been hypothesised that strong peripheral nociception from the deep musculoskeletal system could either initiate or maintain central sensitization, or both and at different levels of the CNS [239]. Hence, peripheral mechanisms may also be a significant factor in the pain symptoms seen in RPS and FM.

In this section of the thesis, some of the factors of FM and RPS are discussed. Particular attention is given to pain modulation factors, including peripheral and central

mechanisms. It is discussed also that in FM and RPS, patient sub-groups exist with different and multiple pain mechanisms involved, possibly at the same time. FM and PRS are not homogenous pain syndromes. Finally, a hypothetical model has been proposed by researchers encompassing some dysfunctional pain mechanisms. The model explains some aspects of the pain sensitivity observed in RPS and FM, however it does not explain all aspects. This is reviewed below.

2.4.1 PSYCHOLOGICAL ISSUES

The psychological status of FM patients has been extensively studied in innumerable investigations [183]. FM patients have more abnormalities in virtually every psychological test administered [183,240]; the majority of studies have demonstrated a consistent pattern of emotional and psychological abnormalities [241]. In many individuals, psychological abnormalities are part of lifetime patterns [241]. In a study of FM and RPS patients, both groups expressed a proneness to somatise psychological pain [242]. Somatisation is a concept whereby patients overreact to normal bodily sensations [243].

However, potential psychological disturbances seen in FM patients must be interpreted with caution. Patients with chronic pain, regardless of aetiology, will score abnormally on a number of psychological tests when compared with healthy controls [244]; it remains unclear if psychological disturbances are causes of FM or a product thereof [245]. Some psychological studies of FM patients, have not shown significant differences in psychological tests when compared with other chronic pain disorders [244,246] [246] [242] [247,248], suggesting that psychological aspects of fibromyalgia can be considered as psychological aspects of chronic pain [247]. Furthermore, the pain features of FM are not influenced by the psychological status of the patients [31,249-251] indicating an independence of the psychological status [252].

From these results, FM is not believed to be purely a psychiatric disease, such as depression [28,253]. The central pain features of FM are independent of psychological status, and the psychological abnormalities found in some FM patients are more likely to result from the chronic pain [28,243,254,255]. However, regardless of whether psychological disturbances precede the onset of symptoms of FM or whether they are a

result, they contribute to the disability, and may increase the intensity of the pain [185,244,254].

2.4.2 SLEEP DISTURBANCE

Sleep disturbance is a common symptom of FM, with sufferers regularly reporting waking feeling unrested from nonrestorative sleep [174,175]. An anomaly of the stage 4 "alpha EEG NREM sleep" has been reported in FM patients. However, this irregularity was not specific to FM and can occur in other conditions, and also in as many as 15% of healthy individuals [256]. Furthermore, since as many as 60% of FM patients do not express this sleep anomaly, the sensitivity of the alpha-delta sleep anomaly for FM has been questioned [256]. For these reasons, sleep disturbance is viewed more as a non-specific symptom acted upon by the sufferers pain [256]. The neurotransmitter serotonin is believed to mediate NREM sleep and has been shown to be dysfunctional in some FM patients. Thus, sleep disorders may play a contributory role in the dysfunction of central mechanisms [184].

2.4.3 NEUROTRANSMITTERS

Substance P (SP) has been found at three-fold elevated levels in the cerebrospinal fluid of FM patients compared with healthy persons [257,258]. SP is believed to act as a modulator or transmitter in forwarding afferent noxious input at the spinal cord [258], involved in central sensitisation. SP is released by afferent Aδ and C-fibre spinal terminals into the dorsal horn laminae I, II and V [191]. These central dysfunctions may result in pain modulation problems and an amplification of nociceptive input [105,106].

Serotonin is also believed to play an important role in FM. This neurotransmitter participates in the regulation of deep restorative sleep, pain perception in supraspinal and peripheral levels and is known to modulate the function of substance P in regard sensory stimuli [259]. Serotonin plays an important role in the descending pain modulation systems [61,71,71,233], and inhibits the release of SP by afferent neurons in response to peripheral stimuli.

FM patients have been shown to have lower levels of cerebrospinal fluid serotonin than controls [191,260]. Wolfe et al. (1997) [259] demonstrated a significant difference in serotonin levels between FM patients and healthy controls. However, there was great

variability in results and the difference was not significant when adjusted for age and sex. Hence, the relationship between FM symptoms and serotonin levels remains unclear. It has been suggested that dysfunction of the descending pain modulation system could contribute to the pain hypersensitivity seen in FM, and a serotonin deficiency supports this. This is discussed further in Sec. 2.4.6.2.

Dysfunction of the neurotransmitters, both inhibitory and excitatory, or other neurohormonal modulators of pain may cause an aberrant central pain system which could to be responsible for the pain in FM [28,105,261]. However, Yunus [28] commented that to consider FM as simply a serotonin deficiency syndrome may be naïve. Instead FM most likely involves a complex, interacting network of multiple neurotransmitters and other neurochemicals, including hormones [28]. The low correlation of cerebrospinal fluid SP with clinical painful symptoms suggest that it is not acting alone and that other neurochemicals are involved [262].

2.4.4 NEUROENDOCRINE DYSFUCTION (THE STRESS SYSTEM)

The hypothalamo–pituitary–adrenal (HPA) axis plays a major role in the regulation of responses to stress [238]. This system is the physiologic mechanism for coping with adversity [263]. Circadian inputs, sleep, food intake and physiological stresses including hypoglycaemia, infection and hypo-tension are involved in the regulation of the HPA axis [238]. The HPA axis is activated when the body adapts to different stresses (e.g. emotional, psychological events) and interacts with other central nervous system centres [263]. The HPA axis is activated by corticotropin-releasing hormone (CRH) which in turn releases adrenocorticotropic hormone (ACTH) and arginine-vasopressin (AVP). These hormones act to regulate the HPA axis in response to situations of chronic stress [263]. Serotonin is also involved in the stress-induced activation of the HPA axis [263], which as noted above has been found at elevated levels in the cerebrospinal fluid of FM patients. Possible outcomes of a disturbance of this system may include chronic stress and/or pain [264].

Perturbed function of the hypothalamic-pituitary-adrenal (HPA) axis is believed to contribute the pathophysiology of FM [263], although what role dysfunction in this system plays in FM remains unclear [238,265]. Several studies have shown an abnormal function of the HPA axis in FM. In several tests, FM patients demonstrated a

hyperactive pituitary ACTH release [266]. Hyper-reactive ACTH and CRH releases have also been measured in FM patients after insulin induced hypoglycemia [264]. This has also been observed in low back pain patients [264]. Other studies suggest that a subset of FM patients have significant neuroendocrine dysfunction [265]. Some FM patients exhibit functional abnormalities in HPA control of the adrenal cortex, thyroid and growth hormone, as well as in the sympathoadrenal system [34].

However, it is unknown if the changes in the HPA axis are causal or consequential [238]; it is unknown if the pain or stress comes first in FM [188]. As well, it is not known if permanent changes in the central nociceptive system are primarily caused by changes in the stress-regulating systems [188]. More research is required in this area regarding the subset of FM patients with HPA dysfunction.

2.4.5 PAIN MECHANISMS

2.4.5.1 PERIPHERAL MECHANISMS

It is not clear how the purported central hyperexcitability in FM patients is maintained, but it probably includes an ongoing nociceptive afferent input from peripheral nociceptors of the deep musculoskeletal system [48,267,268]. As will be discussed below, pain analysis of FM and RPS patients support the notion that the pain is nociceptive, which means that at least part of the pathogenesis includes involvement of nociceptors in muscles or other deep tissues [50,100,185,269].

In FM, pain studies have revealed that both unmyelinated C fibres and A-delta fibres (with polymodal nociceptors) are sensitised. These nociceptors have increased activity in response to multimodal stimulation. This has been shown with chemical, heat and mechanically induced vasodilation, or flare on the skin [100,270-272].

Further evidence of the involvement of peripheral mechanisms derives from results of epidural opioid blockades given to FM patients. Bengtsson et al. [46] showed that an opioid blockade produced pain relief and reduced the number of sensitive TePs in FM patients by acting on the spinal cord and possibly reducing the hypersensitivity of the dorsal horn cells. The blocks acted in the absence of sympathetic, sensory or motor blockade, and indicated that the pain in FM was of peripheral nociceptive and/or spinal

origin. The authors concluded that it was probable that there was a peripheral component to FM [51].

In a subsequent investigation, Sorensen et al. [47] showed that with the administration of analgesic drugs to FM patients peripheral and central spinal and/or supraspinal mechanisms were involved in the pathogenesis of FM. Their results pointed to spinal and/or supraspinal nociception, but also supported the notion that the pain and hyperalgesia may have been provoked and/or maintained by excitation and sensitisation of peripheral nociceptors. It was surmised that increased sensibility in muscle with spontaneous pain may rely on a combination of peripheral and/or central mechanisms, such as peripheral nociceptor sensitisation and central sensitisation [273]. However, as discussed below in Sec. 2.4.5.3 the main outcome of this study was that there were differences in the pain processing mechanisms of patients with FM, so while peripheral mechanisms may be important in some patients, it may not be the case in all.

Staud and colleagues [48,49] investigated temporal summation in FM patients with mechanical pressure and electrical stimulation. FM patients showed greatly exaggerated temporal summation for mechanical stimulation of the deep tissues, and moderately decreased thresholds and temporal summation for cutaneous thermal pain. The authors interpreted these results as evidence of both abnormal peripheral and central sensitisation [48].

Because the main symptoms of FM and RPS are reported by patients to occur mainly in the muscles, it was logical for researchers to also investigate the muscles in addition to the pain studies described above. Investigations have included muscle biopsies, microdialysis and electromyography, with mixed results. These are discussed below. In RPS, research has focused on the trapezius muscle is patients with the disorder ‘trapezius myalgia’. This disorder is a work-related musculoskeletal disorder characterised by pain from the trapezius region, pain upon palpation of the trapezius muscle and a sense of stiffness in the neck during movements [36]. It is likely that this work-related musculoskeletal disorder could also be described as RPS although, as discussed above, the issues around disorder classification make this unclear.

De Stefano et al. [50] showed that in the trapezius muscle of FM and regional myofascial pain patients there was greater amount of Substance P compared with

normal controls. The results pointed to a peripheral hyperactivity of the peptidergic nervous system in symptomatic participants, supporting involvement of the afferent nervous system. These findings highlight the importance of afferent input for maintaining FM symptoms [274].

Larsson et al. [36] investigated muscle biopsies in cleaners with trapezius myalgia compared to those without and healthy teachers. Age, occupation as a cleaner and a tender point in the trapezius was significantly associated with an increased prevalence of ragged-red muscle fibres. Ragged-red fibres were believed to indicate insufficient blood supply. There was no significant difference between the cleaner groups, leading Larsson et al. [36] to suggest that the prevalence of ragged-red fibres was more related to static work, rather than myalgia. Ragged-red fibres have also been found in muscle tissue in FM patients [275].

Kadi et al. [37] also conducted muscle biopsies in the neck and shoulder areas of forest workers with and without myalgia, and controls, and found an association between the work conditions and muscle structural changes. The changes were believed to be related to injury-regeneration cycles. In a subsequent study, Kadi et al. [38] used muscle biopsies of women with neck and shoulder myalgia to investigate morphologic and metabolic characteristics of muscle fibres. Results indicated an energy crisis within the muscle cells and a low capillary to fibre area ratio. This supported the concept of a reduced capillary supply in the muscle.

Larsson et al. [39] in a subsequent study of cleaners with and without trapezius myalgia and controls, used muscle biopsies to investigate the prevalence of moth-eater fibres, and disturbed capillary supply of different fibres. In the cleaner group with myalgia, there was a significantly lower number of capillaries per fibre area. It was postulated that this was due to insufficient peripheral microcirculation. There were also significantly more moth-eater fibres in the cleaners both with and without myalgia, suggesting this outcome was more to do with the physical demands of work, rather than myalgia.

Larssson et al. [40] used muscle biopsies to also investigate the cross-sectional area of type II muscle fibres. There was reduced cross-sectional area in workers with frequent static and repetitive work, compared to other workers, possibly due to different

activation patterns. However, the cross-sectional area was not associated with trapezius myalgia in type I and II muscle fibres. The authors also investigated myosin heavy chain isoforms, and found no significant differences between cleaners with and without trapezius myalgia, and controls [276].

In FM patients, Lund et al. [277] used magnetic resonance spectroscopy to show that metabolite concentrations and muscle pH in the forearm muscles was reduced at different levels of contraction. FM patients also demonstrated a 50% decreased dynamic work output compared to controls [277].

Surface electromyogram has shown that FM patients compared to controls have increased levels of unnecessary muscle tension at rest and at high endurance levels in the shoulder flexors [278]. FM patients have insufficient relaxation between contractions, which may lead to hypoxia during dynamic muscle work. These outcomes suggested that impaired muscle metabolism and/or disturbed regulation of microcirculation that might lead to persistent excitation and sensitisation of intramuscular nociceptors [35,188,277]. However, the surface electromyogram results showed that not all patients with chronic pain have increased muscle tension, suggesting subgroups of patients within this syndrome.

Electromyography studies in cleaners with myalgia of the trapezius, compared to healthy cleaners and teachers, demonstrated lower levels of endurance and a higher degree of perceived fatigue during forward flexions of the shoulder muscles [41]. In the cleaner group (both with and without myalgia) there was an inability to relax the trapezius compared to the teachers.

Microdialysis has been used to investigate local muscle metabolic responses to repetitive low-force contractions in the trapezius muscle in patients with trapezius myalgia. In two studies, Rosendal et al. [42,43] showed that in healthy patients metabolic events in the trapezius muscle conditions were not found systematically. It was found that in some areas of the muscle, there were signs of anaerobic metabolism. It was speculated that inhomogeneous activation of muscle fibres resulted in local metabolic changes that could sensitise nociceptors. The parts of the muscle working the most under the low-force conditions may have had impeded blood flow, forcing them to

work in part anaerobic conditions. The heterogeneous activation of the trapezius muscle might activate nociceptors under these low-threshold work conditions.

Rosendal et al. [44,45] then examined patients with and without trapezius myalgia with microdialysis and examined local metabolic changes in the trapezius under different work conditions. The trapezius myalgia group had increased levels of muscle serotonin, lactate, pyruvate, potassium and glutamate and anaerobic metabolism. It was hypothesised that continuous activity of a subset of muscle fibres in the patients with trapezius myalgia were prevalent, thus impending blood flow to the parts of the muscle that need oxygen, forcing an anaerobic state (this was also evidenced by the increased lactate level during work). Resting levels of nociceptive substances in the muscle was also found. The outcomes supported the biopsy findings described above of changes in the muscle fibres, and indicated that peripheral nociceptive processes were active.

Similar findings have also been reported in patients with whiplash associated disorders with microdialysis [279], and analgesic drug delivery [280,281]. This pain syndrome is not RPS, but highlights the importance of peripheral factors in the maintenance of chronic pain conditions. Like FM and RPS, the whiplash associated disorders research also indicated that there existed sub-groups of patients with several and different pain mechanisms.

However, in FM and to some extent RPS, it is now thought unlikely that pathology in the muscles is *the sole* cause of pain [237,268]. In separate review articles, Simms [282-284] concluded that studies of muscle in FM patients do not solely support the hypothesis of a muscle energy-crisis. In addition, Bengtsson [51] in a review of muscle studies in FM, concluded that muscle biopsy studies do no conclusively show that there are specific changes in muscles in FM. Further, the muscle pain at rest cannot solely be explained by muscle biopsy studies, unless a state of central sensitisation does not exist in FM patients. Interpreting the FM muscle metabolism and dynamic work studies, Bengtsson [51] concluded that there is a defect in the muscle, but that it is not seen at rest or submaximal load, but is seen at maximal load and static contraction.

Instead, the pain hypersensitivity of RPS and FM is thought to include peripheral factors, including the muscles and particularly the trapezius, *in combination* with central factors [55,59,185,237]. A peripheral afferent nociceptive barrage may act as initiator

and then subside to maintain central changes in the dorsal horn neurons, because little ongoing nociceptive stimulation is required for the maintenance of central sensitisation once it has been established [224]. The contribution of muscle pain to the initiation and perpetuation of symptomatology is believed to be central to understanding FM and RPS [268].

The investigations described above support the hypothesis that in some patient groups, peripheral nociception in the muscles is present, and that there is a muscle defect in the pain groups [51]. Anaerobic muscle activity and increased levels of nociceptive substances in the muscle, whether due to an inability to relax the muscle (from electromyography studies), poor microcirculation, poor capillary supply or another mechanism, seems to be present as evidenced by ragged-red fibres, moth-eater fibres and microdialysis results. Contraction under anaerobic conditions quickly causes ischemic pain [190], and long term deep pain can contribute to the initiation and perpetuation of a state of central hyperexcitability, even with minimal input [74]. A state of central hyperexcitability in FM patients can be maintained by an ongoing nociceptive afferent input from peripheral nociceptors of the deep musculoskeletal system [48,267,268]. As will be discussed below, a hypersensitivity of the central nociceptive system could explain exaggerated pain in the presence of minimal and undetectable tissue damage, as the nociceptive signal could be amplified by hyperexcitable central neurons [52].

2.4.5.2 CENTRAL MECHANISMS

Change in pain modulation at the central nervous system is believed to play a role in the pain hypersensitivity seen in FM and RPS patients. In FM, the generalised decreased pain threshold, hyperalgesia and allodynia seen in these patients suggests this [52,53,285]. FM patients demonstrate a generalised non-modality and multiple tissue pain hyperresponsiveness to stimuli including mechanical pressure (at not only the tender points but also at other body sites, including control sites and non-muscular locations of skin, bones, muscles and other areas) [33,177,286,287] heat [270,272,288] electrical stimulation [54,273,287,289] and cold [34,290,291].

Heat pain thresholds are determined by activity in skin nociceptors rather than muscle nociceptors. Consequently, the dissimilarity of heat pain thresholds between FM

patients and controls supports the notion of CNS involvement, and not solely pathology of deep peripheral tissues [287]. As well, electrical stimulation of the skin, subcutaneous tissue and muscle has distinguished FM patients from myofascial pain patients [292]. Hyperalgesia from electrical stimulation was found in the skin, subcutaneous tissue, muscle and regions outside the painful areas [292], suggesting that the widespread painful regions of FM patients could be defined as regions of secondary hyperalgesia [54]. The skin sensibility was unchanged, pointing towards central hyperexcitability mainly related to muscular tissue [273]. Secondary hyperalgesia, as noted above, is believed to be a phenomenon related to central sensitisation.

Cohen and colleagues [54-56] demonstrated abnormal responses to electrical stimulation in FM and RPS patients when compared with controls. They [54-56] believed that the responses to electrical stimulation tests in the upper limbs of FM and RPS patients indicated that the tested musculoskeletal regions resembled areas of secondary hyperalgesia, which in turn implied perturbation of central mechanisms.

These multi-modal studies suggest that FM is not solely a condition with enhanced sensitivity to noxious mechanical stimulation. Rather, a generalised non-modality and multiple tissue pain hyperresponsiveness due to central nervous system hyperexcitability has been proposed [52].

FM patients have reduced regional blood flow in areas of the brain. Using photon-emission computed tomography, Mountz [293] showed that in FM patients there was reduced blood flow in particular structures of the brain that are involved in processing nociceptive input. This indicated functional abnormality within the central nervous system in the FM patients, probably at the dorsal horn level or the supraspinal level [293].

Repeated mechanical stimulus applications in FM patients has demonstrated altered responses. Repeated pressure pain thresholds (PPT) measurements during, and following, isometric contractions (before and after skin hypoesthesia), were varied in FM patients compared to controls. Input from cutaneous and deep tissues was inhibited during isometric contractions, indicating sensitisation of mechano-nociceptors from muscle ischemia and/or an absence of pain modulation during contraction [294].

Descending pain inhibitory control may be have been lacking in the FM patients. The descending pain modulation was reviewed above in Sec. 2.4.6.2.

The pain mechanism of wind-up also appears to be altered in FM. Repeated mechanical and electrical stimulation of FM patients demonstrated increased temporal nociceptive summation (wind-up) compared with healthy controls [48,273,289]. For mechanical pressure tests, FM patients demonstrated greater levels of temporal summation compared to controls, and at lower forces and lower frequency of stimulation [48]. Temporal summation of pain (wind-up) from thermal stimulation demonstrated several clear differences in perceived magnitude at the start of and during stimulation, and greater after-sensations (second pain), compared with controls. The levels of wind-up consistently exceeded those of control subjects over a range of stimulation frequencies. These studies [49,273,289] suggested that the enhanced wind-up occurred due to sensitised central neurons and a state of central hyperexcitability of the nociceptive system.

Banic et al. [52] applied the minimum electrical current required to evoke a spinal reflex and found it was significantly lower in the FM than healthy controls. This study was the first to clearly demonstrate that spinal cord neurons are indeed sensitised in FM patients [52]. However, the mechanism(s) that supported the central state of hypersensitivity remained unknown. Banic et al. [52] concluded that the underlying mechanism responsible for the neuronal hypersensitivity may be either a sustained central facilitation by nociceptive input from a peripheral source, spinal cord plasticity changes that persist after resolution of tissue damage or imbalance of descending modulatory pathways due to psychological factors. These hypotheses for central hyperexcitability in FM and RPS are discussed below.

2.4.5.3 DIFFERENT PAIN MECHANISMS

It is also likely that pain mechanisms vary between and within patients [185]. Studies have shown that the tenderness in chronic musculoskeletal pain patients may be from different pain processing mechanisms [46,47]. Bengtsson et al. [46] found that opioid blockade produced pain relief and reduced the number of sensitive TePs in FM patients by acting on the spinal cord and possibly reducing the hypersensitivity of the dorsal horn cells. The blocks acted in the absence of sympathetic, sensory or motor blockade,

and indicated that the pain in FM was of peripheral nociceptive and/or spinal origin [51].

In a similar study, Sorensen et al [47] showed with the administration of analgesic drugs to FM patients, peripheral and central spinal and/or supraspinal mechanisms were involved in the pathogenesis of FM. Their results pointed to spinal and/or supraspinal nociception, but also supported the notion that the pain and hyperalgesia may have been provoked and/or maintained by excitation and sensitisation of peripheral nociceptors [273]. However, the major findings of this research was that there were differences in the pain processing mechanisms of FM patients; the cause or causes of the pain in FM patients may not necessarily have been the same [289]. Based on this study, and others by the same group [295,296], the pain mechanisms in the FM patients, and possibly RPS patients, was not homogenous and there existed sub-groups. As well, because of the different response to different analgesic drugs, some patients had several and different active pain mechanisms at the same time. Patient sub-groups with different and possibly several active pain mechanisms have also been reported in chronic low back pain [296] and whiplash associated disorders [280].

Is another series of studies, Kosek et al [274,291,294,297] tested whether sensory abnormalities in FM patients were generalized or confined to areas with spontaneous pain. Repeated mechanical stimulus applications were applied to FM patients compared and controls. Repeated pressure pain thresholds (PPT) measurements during, and following, isometric contractions (before and after skin hypoesthesia), were altered in FM patients compared to controls. Input from cutaneous and deep tissues was inhibited during isometric contractions, indicating sensitisation of mechano-nociceptors from muscle ischemia and/or an absence of pain modulation during contraction. Kosek et al interpreted the spontaneous results as probably related to disinhibition/facilitation of nociceptive afferent input from normal (or ischemic) muscles. Descending pain inhibitory control may be have been lacking in the FM patients. This implied that supraspinal structures were involved, since the descending pain system is modulated at this level. The descending pain modulation was reviewed above in Sec. 2.3.3.4.

As noted above, temporal nociceptive summation (wind-up) in FM patients was increased compared to controls [48,273,289]. The enhanced wind-up occurred due to

sensitised central neurons and a state of central hyperexcitability of the nociceptive system.

2.4.5.4 SUMMARY

The studies outlined above indicate that in FM, and to some extent RPS, the hyperexcitability of the pain pathways most likely includes changes in the central nervous system [188,220]. The two mechanisms for pain hypersensitivity in muscle pain syndromes has been described by Henriksson [72] as the bottom to top mechanism. The bottom mechanism relates to changes in the deep tissues of the periphery and supports ongoing nociceptive input, whereas the top mechanism relates to pain hypersensitivity origins from the stress-regulatory systems and pain-regulating systems in the brain. Two top down systems are believed to be relevant in FM, that being CNS dysfunction, and neuroendocrine dysfunction [34]. However, as noted above, in any one patient, several mechanisms can be present at the same time and are not always the same between patients. As well, peripheral factors were reviewed above, and are also likely involved in both FM and RPS. However, there is still no agreement over whether the respective pathological steps are initiated by primary central or peripheral mechanisms [298] or both.

2.4.6 HYPOTHESIS OF PAIN MECHANISMS IN RPS AND FM

A hypothesis for the central pain mechanisms operating in RPS and FM has been proposed, incorporating different mechanisms at different levels of the nociceptive system [75-77]. However, while this hypothesis may assist in the understanding of possible mechanisms for the pain and tenderness in RPS and FM it is speculative and does not explain all the symptoms of these pain syndromes [75,76]. As discussed above, several other factors may be involved in these pain syndromes.

Furthermore, as noted above, it has been shown that pain mechanisms vary between and within FM and RPS patients and different mechanisms can be operating at the same time [185]. Spinal and/or supraspinal nociception mechanisms may be involved, but it is also possible that pain and hyperalgesia may be provoked and/or maintained by excitation and sensitisation of peripheral nociceptors [46,273,289]. Hence, for some FM

and RPS patients, the pain mechanisms discussed below may be relevant, but this will not always be the case.

This hypothesis is proposed because it partly presents a pathway for the development of increased pain sensitivity as a result of strong peripheral nociceptive pain. In an occupational environment, nociceptive pain (e.g. from mechanical load on the muscles, tendons, or joints) could be consequent upon ergonomic risk factors (such as poor working postures, static postures, and/or repetitive actions) [97,299]. In this way, ergonomic risk factors could contribute to the development of and maintenance of persistent musculoskeletal pain, and in turn drive changes in the function of the central pain system.

2.4.6.1 CENTRAL SENSITISATION AND RPS

The mechanisms underlying secondary hyperalgesia have been proposed as a possible pathophysiological basis for the pain and tenderness seen in FM and RPS patients [54,56,58,292,294]. As reviewed above (Sec. 2.3.3.3.2), central sensitisation of the dorsal horn cells provides an explanation of how secondary hyperalgesia can occur, by the recruitment of subthreshold inputs (latent) to nociceptive dorsal horn neurons [67,215,228,229].

Central sensitisation at the spinal level is believed to occur from neurochemical changes in the dorsal horn cells. Strong and prolonged C-fibre activity is an important trigger of these changes because action potentials from these afferents can evoke slow synaptic potentials that may last up to 20 seconds, much longer than from Aδ nociceptor afferent fibres. The slow action potentials of the C-fibre afferents are due to the actions of particular neurotransmitters, including substance P (SP). SP is believed to act as a modulator or transmitter in forwarding afferent noxious input at the spinal cord [258,300]. The long duration of these action potentials can lead to a summation of subsequent action potentials from repeated stimuli, generating a progressively increasing and longer-lasting depolarisation of the dorsal horn neurons (or wind-up) [66].

The short-lived changes cannot by themselves explain persistent dorsal horn neuron receptive field changes. Instead, it is possible that neurotransmitters (including SP due to its slow synaptic potentials [66,198]) trigger longer lasting changes of other

messenger systems in the dorsal horn neuron, which may produce a sustained change in the membrane properties of the cell. A sustained change in membrane properties may lead to changes of intracellular chemicals and, in turn, persistent changes in the excitability of the cell [69]. The central sensitisation most likely includes activation of N-methyl-D-aspartic acid (NMDA) receptors, probably on wide-dynamic range (WDR) neurons [73] (see Sec. 2.3.3.1 for WDR neuron review).

Research on SP has shown that when administered to animals there was an increased and prolonged excitability of dorsal horn neurons [294]. In addition, there was an unmasking of latent synaptic connections to these neurons. In response to unilateral C-fibre electrical stimulation, SP was released in the dorsal horn cells on the side of stimulation and, to a lessor extent, in the contralateral dorsal horn cells [301]. In addition, SP is a volume transmitter because it demonstrates the ability to diffuse over long distances in the spinal cord after being released from the spinal terminals of primary afferent neurons. This gives SP the capability to influence large populations of dorsal horn neurons in the vicinity of the release site [198,224].

Other animal studies have mapped dorsal horn neurons responding to stimulation of nociceptors in an inflamed muscle. After inflammation, more neurons could be activated by afferents in the muscle [198]. The effect was most marked in both the spinal segments that, before inflammation of the muscle, responded to stimulation of the muscle, and in the rostrally adjacent segment where there was no apparent input before inflammation of the muscle (see Figure 2-5). The expansion demonstrated that the changes in the dorsal horn connectivity were not restricted to the spinal segment of the lesion, and that the increase in excitability (i.e., the central sensitisation) spread within the dorsal horn [198].

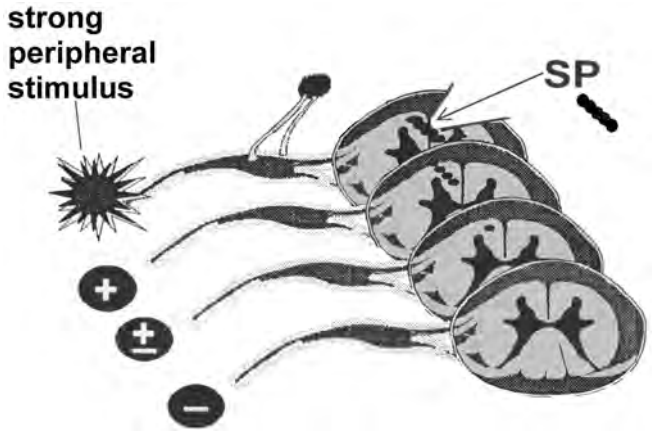


Figure 2-5 – Spread of pain and tenderness to normal tissues by spill over of Substance P.

(From Bennett [268])

Psychophysically, the spread of central sensitisation to adjacent neuron populations in the dorsal horn may correlate to the subjective experience of 'spreading' or 'radiating' pain, including to regions outside the segment of the original lesion (i.e. the pain could be referred) [198]. The spread of pain has been observed in animal studies [198] and in human studies [302]. In RPS, the release of SP could be one mechanism that explains the spreading of muscle pain from a localised injury to encompass larger body areas, e.g., chronic neck pain that may spread distally to include pain in an entire arm [75]. The unmasking of ineffective or latent synaptic connections via central sensitisation changes in the dorsal horn (over a few spinal segments) would explain the increase in painful regions. This is one mechanism (of several) that may explain in part the pain and tenderness seen in RPS (characterised by secondary hyperalgesia) [54].

These animal and human pain studies point to one hypothetical spinal level mechanism for the pain hypersensitivity in RPS. For FM, Mense and Henriksson [75-77] proposed that central sensitisation at the spinal cord level caused by the release of SP at the dorsal horn cells is not a sufficient explanation for the development of pain on both sides of the body or the 'pain all over'. The main reason is that the spread of excitation in the spinal cord, from a strong peripheral stimulus, is limited to a few segments only [75,198] and only moderately on the contralateral side of the spinal cord [301]. Thus it is unlikely that central sensitisation could accommodate the 'whole of body' generalised pain seen in FM. Nonetheless, central sensitisation of dorsal horn nociceptive neurons due to activation of NMDA receptors, probably involving wide-dynamic neurons, may in part contribute to the pain manifestations observed in FM [75,76].

2.4.6.2 DYSFUNCTION OF THE DESCENDING PAIN MODULATORY SYSTEM

Another hypothesis suggests that the global pain and tenderness of FM patients is caused by dysfunction of another mechanism of central sensitisation, but acting at the supraspinal level in the descending pain-modulation system [75,76,79,274]. The descending pain modulatory system (reviewed in Sec. 2.3.3.4), modulates pain either by inhibiting or facilitating the discharges of the dorsal horn nociceptive neurons [75]. Mense [75,76] postulated that dysfunction of the globally projecting anti-nociceptive system may be one mechanism that could contribute to pain and tenderness seen in FM. Also, it equally possible that increased facilitation or decreased inhibition may be a mechanism that contributes to the pain and tenderness of FM [100].

In animal studies, dorsal horn neurons responses to nociceptive stimuli from deep somatic tissues under conditions of with and without spinal cord cold blocks (see Sec. 2.3.3.4 for review) showed that cold blocking restricted the pathways in the dorsal portion of the spinal cord and eliminated most of the descending influences from the supraspinal inhibitory centres. After the cold block, the dorsal horn neurons that normally responded to stimuli from deep somatic tissue increased in background activity, developed responses to innocuous stimuli and increased the magnitude of responses to noxious muscular stimuli [75,76,303,304]. It was concluded that the descending system strongly and tonically inhibited the dorsal horn neurons that presumably mediated deep pain. It was presumed to be a tonic system as, otherwise, it could not have been abolished by cold blocking [75]. Furthermore, it appeared that the descending system acted specifically on input from deep nociceptors [75]. The descending spinal pathways controlled not only the mechanical excitability, but also the degree of convergence in the dorsal horn cells with deep input [304].

Mense [75] transposed these outcomes to patients and, assuming similar operational mechanisms, hypothesised that dysfunction of the descending modulation system would likely lead to: an increased background activity of dorsal horn neurons that may correlate to spontaneous deep pain in the individual; increased responsiveness in the dorsal horn neurons to noxious stimulus that could induce hyperalgesia; and a lowering of the mechanical threshold so that formerly high-threshold dorsal horn neurons begin to respond to weak mechanical stimuli and cause allodynia.

Serotonin is believed to be an important modulator in the descending pain modulation system [61,71,71,233]. The serotonin metabolism disturbance seen in FM patients suggests that the function of the descending inhibitory modulation system could be impaired. As noted above, because this system operates predominantly on the nociceptive input from the deep tissues, impairment of this system will increase the ongoing activity and excitability in the dorsal horn neurons that process deep nociceptive afferent input [75]. Mense [75] believes that dysfunction of this system could result in spontaneous pain and tenderness, characterised by hyperalgesia and allodynia in the deep tissues.

Impairment of this system would result in global pain transmission changes. Putative pain-modulating supraspinal neurons project diffusely to the dorsal horn cells at multiple spinal levels. This provides them with receptive fields that are very large and virtually total body. Furthermore, due to the arrangement of the neuron axons in the supraspinal regions, cells of the same class tend to fire at the same time [233]. This organisational arrangement suggests that the neurons of the descending modulation system function as a unit that exerts global, rather than topographically discrete, control over pain transmission [233]. Therefore, dysfunction of the descending pain modulation system could hypothetically cause widespread pain [75].

Mense [75,76] suggested that the widespread pain and disturbance of the serotonin metabolism (which as noted above is one of the main spinal transmitters of the descending antinociceptive system) supports the hypothesis of dysfunction of the descending pain modulation system in FM.

2.4.6.2.1 Psychosocial factors and FM

Fields and Basbaum [234] believe that psychological factors may influence the descending pain modulation systems where increased attention and stress levels may facilitate nociceptive transmission. Animal and human studies have shown that learned responses, expectational and attentional factors, and levels of stress and fear can inhibit or facilitate dorsal horn neuron activity both with and without noxious stimulation of primary afferents. Presumably, this is due to activation of either the descending inhibitory or facilitatory modulatory pain systems at supraspinal levels [233]. Animal attentional studies have increased dorsal horn neuron activity [235]. Fields [235]

speculated that in patients with ‘minor’ pain, attentional problems may in fact increase its intensity due to activation at the supraspinal level of the descending pain modulatory system, and that the psychological factors may be a major contributing factor to chronic pain.

These outcomes raise the possibility that mental or psychological processes can increase pain sensations in FM patients [32,75]. Psychological and emotional disturbances such as current depression, lifetime depressive states, anxiety, mental stress and emotional stress have been reported in FM patients [95,105,241]. Psychosocial factors may also play a role as psychosocial abnormalities occur frequently in FM patients [170,241]. Psychosocial factors (including education levels, increased rates of divorce, obesity, smoking, physical and sexual abuse, being an immigrant, living in a compromised housing area, lower social supports, a family history of pain) have been noted in clinical and epidemiological studies [170,241]. It has been hypothesis that these factors could influence the dorsal horn neurons pain settings through the descending modulatory pathways [17,18].

However, as noted above (Sec. 2.4.1) the role of psychological factors is controversial among FM patients [249]; in RPS little research has been done regarding personality factors [122]. Patients with chronic pain, regardless of aetiology, will score abnormally on a number of psychological tests when compared with healthy controls [244]. Furthermore, studies have shown that the central features of FM are independent of psychological status. As well, the psychological abnormalities found in some FM patients are more likely to result from the chronic pain, rather than the other way round [28,243,254,255].

Regardless of whether psychological disturbances precede the onset of symptoms of FM (or whether they are a result) they contribute to the disability, and may increase the intensity of the pain [185,244,254]. Therefore, although this hypothesis suggests a possible influence of psychological factors on spinal nociceptive processes in FM (via the descending pain modulatory system as discussed above), these mechanisms are complex and poorly understood [52].

2.5 SUMMARY

The ergonomic literature has identified that postural risk factors are an important risk factor in the development of work-related musculoskeletal disorders. A positive relationship has been shown to exist between exposure to postural work risk factors and disorder development. However, it is now recognised that the nature of work-related musculoskeletal disorders is complex and multifactorial. The pathophysiological mechanisms behind these disorders remains unclear. In particular, for regional pain syndrome (which is a non-specific work-related musculoskeletal disorder) altered pain processing mechanisms have been suggested as a possible pathophysiological factor for the hyperalgesia and allodynia seen in some of patients.

The ergonomics community has not accepted the potential neurobiological basis for RPS, and this has limited investigation of the relationship between ergonomic exposures, such as posture and repetitive actions, and pain manifestations such as hyperalgesia, referred hyperalgesia, referred pain and allodynia. There exist very few investigations exploring the association of ergonomic risk factors and changes in pain sensitivity.

As well, the rheumatology and pain fields have also not extensively investigated the putative association between ergonomic risk factors (such as poor posture and repetitive actions) and features of RPS and FM. Workplace ergonomic exposures that may act as aetiological factors in chronic musculoskeletal pain syndromes are unclear. Specific guidelines regarding ergonomic workplace factors and hypersensitivity of the peripheral and/or central pain system, which may manifest as tenderness, allodynia and referred tenderness and pain, are presently at their very early stages.

In this chapter, the literature regarding mechanisms of pain hypersensitivity was reviewed, and possible factors associated with the pathogenesis of FM and RPS explored. Later in the thesis, external aetiological factors relevant to RPS and FM are investigated including ergonomic factors of posture and work actions (Ch. 4), and dysfunction of spinal structures (Ch. 6). These factors could contribute to changes in the excitability of the nociceptive system that, in turn, may associate with features of RPS and FM.

Several theories have been proposed for the central feature of these pain syndromes including psychological disorder, sleep disorder, muscle disorder, pain modulation disorder, neuroendocrine disorder and a biopsychosocial disorder. Some of these were discussed above. It is unlikely that one specific cause would create these pain syndromes. However, pain modulation disorders are central to many theories regarding FM and RPS. Many studies have emphasised the role of central nervous system pain processing abnormalities in FM and RPS and at different central levels, including spinal (wind-up, central sensitization, LTP) and at the supraspinal level (descending modulation, stress regulating system).

However, several studies examining the muscles in chronic musculoskeletal pain syndromes also point towards peripheral mechanisms as contributing to the pain hypersensitivity, particularly from the trapezius muscle. It has been hypothesised that strong peripheral nociception from the deep musculoskeletal system could either initiate or maintain central sensitization, or both and at different levels of the CNS. Hence, peripheral mechanisms may also be a significant factor in the pain symptoms seen in RPS and FM.

Adding to the complexity of these pain syndromes, patient sub-groups have been found to exist within RPS and FM with different and multiple pain mechanisms involved. It seems that FM and PRS are not homogenous pain syndromes, and that patients can have different and several pain mechanisms operating at once.

Finally, a hypothetical model has been proposed by researchers encompassing some dysfunctional pain mechanisms. The model explains some characteristics of the pain sensitivity observed in RPS and FM, however it does not explain all aspects. This hypothesis was explored because it partly presents a pathway for the development of increased pain sensitivity as a result of strong peripheral nociceptive pain. Simplistically, in an occupational environment, nociceptive pain (e.g. from mechanical load on the muscles, tendons, or joints) could be consequent upon ergonomic risk factors (such as poor working postures, static postures, and/or repetitive actions). Strong and ongoing nociceptive pain has been shown to change the pain sensitivity in the CNS. In this way, ergonomic risk factors could contribute to the development and maintenance of persistent musculoskeletal pain, and in turn drive changes in the

function of the central pain system. However, this will not be the case in all FM and RPS patients.

CHAPTER 3

FWAP-Link: POSTURE AND ACTION MEASUREMENT SYSTEM

- **CHAPTER SUMMARY**

The development of an instrument-based posture action measurement and analysis system was the first goal of this thesis. This goal is the focus of this chapter.

Comprehensive posture analysis with video or the unaided eye (visual) is a time consuming process [305], suffers from inherent flaws of inaccuracy, questionable reliability for dynamic movement analysis [306] and assessment of some posture angles [307]. Minor posture alterations are difficult to detect. There exist several technologies for accurate, fast and reliable kinematic measurement and recording. However, these technologies have not been applied to the assessment and classification of work actions and postures based on the manual Fine-detailed Work Action and Posture (FWAP) code.

This chapter describes a new instrument-based posture and action measurement system, called the FWAP-Link system. This new system was based on the manual FWAP posture code. It was developed in this thesis for a specific posture research application that is described in the next chapter (Ch. 4). The FWAP-Link system was developed for this specific research application and presently application outside the research setting is limited. However, there is potential for further development and possible application in the workplace.

The technical specifications of the FWAP-Link system, including electromagnetic tracking technology, three-dimensional (3D) computer animation, storage of motion capture data, kinematic geometry, anatomical landmark descriptions, and local reference system definitions are discussed in App. A.

3.1 POSTURE MEASUREMENT METHODS

Posture can be defined functionally as the body position adopted that is appropriate for the task being performed [128,308]; a particular posture occurs as a response to the demands of a given task [128]. Posture definition can be described in various ways [82] and definition is closely related to the set of measurements used to record the posture parameters [128]. Therefore, for a sophisticated posture measurement system (such as FWAP-Link described later) a three-dimensional geometrically detailed definition is needed: *posture* is described geometrically by the orientation *angles* of a body segment relative to the axes of the segment immediately proximal [309] or to a vertical plane.

A posture and action measurement system is an essential ergonomic tool in the assessment of postural and repetitive work action risks, and when estimating risk of development of musculoskeletal disorders [82]. These ergonomic tools can be broadly classified as observational or instrument-based [80,310]. There are numerous observational methods including posture measurement by the eye unassisted [84,311-313] and videotape and computer assisted methods [85,314-317].

There are evident limitations associated with observational posture measurement methods. Criteria for classification of body postures and movements with respect to body angles seems poorly defined for some observation methods [318]. As well, some commonly used body posture definitions have few literature references supporting their use. There is also a lack of standardised body angles, which limits comparison between different methods [80,318]. In addition, observation posture measurements methods are limited in their ability to fully characterise physical stress exposure [319]. Yen and Radwin [319] believe that they lack resolution, take a great deal of time, require highly trained observers and are subject to analyst biases and experience. In addition, some [82] have questioned the internal and external validity of these observational methods[318].

Instrument-based techniques are varied and provide different aspects of posture and movement measurement depending upon the technology on which they are based. Instrument-based techniques include hand-held devices such as goniometers or inclinometers [320,321], two-dimensional photographic methods [322], strain gauges [323], lumbar spine motion measurement [324,325], opto-electronic transducers

including camera based systems [326-329], electro-goniometers [330-334], ultrasonic transducers [83,335] and electromagnetic tracking systems [336-339]. These devices are more precise and reliable than observational methods and are advantageous as they provide detailed and accurate results [82]. However, the measurement devices are more costly, complex, time consuming to use and may influence performance of a task [82]. In addition, these methods produce copious amounts of posture data, and managing and analysing the data can be difficult [319]. Reviews of posture measurement methods have been reported [80,82,318,340,341].

Importantly, with all posture measurement techniques there is a trade-off between the time required to perform the observation and analysis, the level of detail provided by the results, and the cost [342,343].

3.2 THE MANUAL FINE-DETAILED WORK ACTION AND POSTURE CODE (FWAP)

3.2.1 MODULAR ARRANGEMENT OF PREDETERMINED TIME STANDARDS (MODAPTS)

Predetermined Motion Time Standard (PMTS) systems resulted from experimental studies into the evaluation of manual work elements. The first system was developed in 1924 [344] and PMTS systems became more widely known and used after the introduction of Methods Time Measurement (MTM) in 1948 [345].

These systems were developed to measured the time required for people to perform generic, fundamental work motions under a variety of conditions. They identify fundamentally the motions by which all work can be described [346]. By describing a job as a sequence of fundamental motions (each with a known time requirement), the normal time required to complete the job can be predicted by summing the time values for each of the fundamental motions [347]. They describe step-by-step the work actions undertaken in the completion of a task. Because they predict the *normal time* required to perform a job, the subjective exercise of performance rating is not required [347]. This is key advantage of PMTS systems [348].

In 1966, Heyde [349,350] introduced the MODular Arrangement of Predetermined Time Standards (MODAPTS) as a new PMTS code for the description of actions

undertaken during the completion of a work task. MODAPTS was different from other PMTS codes, because it applied the same code for similar actions, thereby significantly reducing the complexity of this code. It also differed from other PMTS codes in that it focused on the body part being moved during an action, rather than the distance covered by the body part or object being handled [345]. These differences contributed to its speed and efficient use when completing analysis of a work task, compared with other PMTS systems.

MODAPTS provides a code by which any work action can be described, and it provides the average time taken to perform it. MODAPTS is a form of shorthand for describing how long a work task takes, by listing the sequence of body actions involved in carrying it out. MODAPTS provides a script for how work is done, *action-by-action*. The times for all MODAPTS codes are based on modules of 0.129 seconds (one MOD time unit), which is the time taken for the simplest of MODAPTS actions, a finger move. There are approximately 90 MODAPTS elements that describe particular work actions, and they are all based on multiples of MOD time units. The addition of the MOD time units required to complete a task provides a reasonable estimate of the time taken for an *average* person to complete that task [345]. Because MODAPTS is a PMTS system, it maintains the key advantage associated with these systems, that being it is not necessary to use the stop-watch method to assess the time taken for each action of a task.

3.2.2 FINE-DETAILED WORK ACTION AND POSTURE CODE (FWAP)

In 1992, Farrell [346] extended the value of the MODAPTS concept by adding details of postures and actions at each MODAPTS step. Farrell [346] developed the Fine-detailed Work Action and Posture code (FWAP) as a manual work analysis system that enabled consistent recording of action and postural characteristics at the workplace, and the presentation of how action and postural patterns occurred *over time*. FWAP documents concurrent actions and postures and builds a record of the frequency, speed and duration of these characteristics [346].

A FWAP analysis is preceded by a MODAPTS analysis of a work task. FWAP builds onto this PMTS system to document the step-by-step actions that comprise a work task and the time taken to complete them. It adds posture and action descriptors to each MODAPTS work step [346]. The action codes describe hand actions and forces that the

hands accommodate, and the posture codes indicate the posture at the completion of the MODAPTS work step. The addition of the FWAP action and posture codes beside the MODAPTS codes builds a comprehensive record of the pattern over time of the action and postural characteristics of the task.

3.2.3 FWAP FOR WINDOWS

'FWAP for Windows©[1]' is commercially available software version of the FWAP code. This software is based on Microsoft Excel and appends the FWAP codes to a MODAPTS analysis of a task. The MODAPTS time units quantify the postural and action content of that task. As well, this software provides investigation tools for the analysis of the postural and repetitive characteristics of a measured task (see Figure 3-1). The MODAPTS codes for the left and right hands are manually entered or downloaded to columns on the left side of the spreadsheet, and the FWAP action and/or posture codes of interest are added in the columns beside them. The MOD time units establish the duration of the FWAP actions and postures, undertaken during each step of the task [351].

The FWAP for Windows© program provides seven analysis tools to the user. These seven tools summarise or specifically analyse given postural characteristics. The tools provided are shown in Table 3-1

[1] Pioneer Development & Research Pty Ltd, PO Box 1470, Box Hill, VIC 3128, Australia

No	Analysis tool Title	Description
1	All classes in One given characteristic	Identifies the occurrence of all classes from one action or posture code
2	Occurrence of Simultaneous characteristics	Presents the continuous simultaneous occurrence of selected classes from 2 or more given action or posture codes
3	Occurrence of Alternation classes	Presents the occurrence of continuous unbroken alternation between 2 or 3 classes within one action or posture code
4	Occurrence of Holding	Presents the occurrence of continuous holding of any item grasped. The time from the end of the Get to the end of the FWAP release
5	All classes with Simultaneous characteristics	Identifies all classes which occurred in one selected action or posture code when given classes in other codes were occurring simultaneously
6	All classes with Alternation classes	Identifies all the classes which occurred in one selected action or posture code when sets of unbroken alternation between 2 or 3 classes in another action or posture code were occurring simultaneously.
7	All classes with Holding	Identifies all the classes which occurred over time in one selected action or posture code while an item was being held

Table 3-1 – Description of the seven analysis tools available from the FWAP for Windows © software.

(From [351]).

Each tool presents a summary report to the user that contains the frequency and duration per cycle and per hour of the FWAP code(s) entered for analysis [351] (see Figure 3-2 and Figure 3-3). The analysis tools help the user to investigate the postural and repetitive action characteristics of the work task.

			Left Modapts				Right Modapts				FWAP POSTURE TRUNK		TRUNK		SHOULDER		HEAD			FWAP POSTURE ARM		ARM		FOREARM		
Left hand Description	Right hand Description	No	L M v	L T U	L T l	L Ot hr	R M v	R T U	R T l	R Ot hr	SF H	SS H	TR	C	LS EV	RS EV	HF	HR	HTT	LE FS	RE FS	LE LS	RE RS	L FX	R FX	L PR
	collects thread	1					M2	2			F20						F50			E15	25	0	20	100	45	P25
	from body of fabric	2						3	G3		F20						F50			E20	25	0	20	100	45	P45
collects thread	places thread into	3	M2				M1	2			F20						F50			E20	25	0	25	100	45	P25
from right hand	left hand	4			G1			1	P0		F20						F50			E20	30	0	25	100	60	P25
pulls thread across	collects thread	5	M3				M3	3			F20						F50			E20	30	0	30	120	90	P25
fabric to right hand	from left hand	6			P0			1	G1		F20						F50			E20	35	0	35	100	120	P25
reaches for and		7	M3					3			F20						F50			E20	45	0	40	120	135	P25
moves reade		8			G1			1			F20						F50			E20	45	0	40	135	135	P25
		9	M3					3			F20						F50			E20	45	0	40	120	135	P25
		10			P0			0			F20						F50			E20	45	0	40	90	135	P25
moves reade back to		11	M3					3			F20						F50			E20	45	0	40	150	135	P0
original position		12			P0			0			F20						F50			E20	45	10	40	180	135	P0
	right hand drops	13					M1	1			F20						F50			E0	45	10	40	180	135	P0
	thread	14						0	P0		F20						F50			E0	50	10	45	180	120	P0
	presses pedal to	15						3		F3	F20						F50			E0	50	10	45	120	120	P0
	collects thread	16					M3	3			F20						F50			E0	50	20	45	120	60	P0
	from body of fabric	17						3	G3		F20						F50			E0	55	30	45	120	45	P0
collects thread	places thread into	18	M2				M1	2			F20						F50			E0	55	20	50	100	60	P0
from right hand	left hand	19			G1			1	P0		F20						F50			E0	50	10	45	100	90	P0
pulls thread across	collects thread	20	M3				M3	3			F20						F50			E0	45	0	40	100	100	P0
fabric to right hand	from left hand	21			P0			1	G1		F20						F50			E0	35	0	35	100	120	P0
reaches for and		22	M3					3			F20						F50			E0	45	0	40	120	135	P0
moves reade		23			G1			1			F20						F50			E0	45	0	40	135	135	P25
		24	M3					3			F20						F50			E0	45	10	40	120	135	P25
		25			P0			0			F20						F50			E0	45	0	40	90	135	P25
moves read back to		26	M3					3			F20						F50			E0	45	20	40	120	135	P25
original position		27			P0			0			F20						F50			E0	45	10	40	180	135	P25
	presses pedal to	28						3		F3	F20						F50			E0	45	20	40	180	135	P25
collects thread	right hand passes	29	M3				M2	3			F20						F50			E0	35	30	45	150	130	P25
from right	thread around edging	30			G1			1	P0		F20						F50			E0	30	30	45	130	120	P25

Figure 3-1 – Example of the computer program FWAP for Windows© spreadsheet.

(see Table 3-2 for explanation of the posture codes shown above)

FWAP Analysis Report

All Classes in one given Characteristic : ' LFX '

Job	Cycle time (secs)	Cycles per hour	Simultaneous FWAP characters and classes within the set		Sets and seconds / CYCLE			Seconds / set				Time per HOUR		
			Character /Class	Character /Class	Set Length	Number	Total secs	Mean	SD	Min	Max	Secs	Mins	%
JoiningMachineFWAP	19.866	181.21	LFX / 100		1.032	2								
			LFX / 100		0.129	1								
			LFX / 100		0.903	1								
			LFX / 100		0.645	1	3.741	0.748	0.380	0.129	1.032	677.92	11.30	18.83
			LFX / 120		0.387	6								
			LFX / 120		1.161	1								
			LFX / 120		1.548	1	5.031	0.629	0.351	0.387	1.548	911.69	15.19	25.32
			LFX / 135		0.129	2								
			LFX / 135		0.516	3								
			LFX / 135		0.903	1								
			LFX / 135		0.387	1	3.096	0.442	0.150	0.129	0.903	561.04	9.35	15.58
			LFX / 90		0	3								
			LFX / 90		0.387	4	1.548	0.221	0.099	0	0.387	280.52	4.68	7.79
			LFX / 150		0.387	2	0.774	0.387	0	0.387	0.387	140.26	2.34	3.90
			LFX / 180		0.129	2								
			LFX / 180		0.387	1								
			LFX / 180		1.419	1								
			LFX / 180		1.548	1								
			LFX / 180		1.935	1	5.547	0.925	0.307	0.129	1.935	1005.19	16.75	27.92
			LFX / 130		0.129	1	0.129	0.129	0	0.129	0.129	23.38	0.39	0.65
			LFX / 135		0.129	2								
			LFX / 135		0.516	3								
			LFX / 135		0.903	1								
			LFX / 135		0.387	1	3.096	0.442	0.101	0.129	0.903	561.04	9.35	15.58

Figure 3-2 – Example of the data output from the computer program FWAP for Windows© for the analysis of "Identifies classes in one characteristic". LFX refers to left elbow flexion

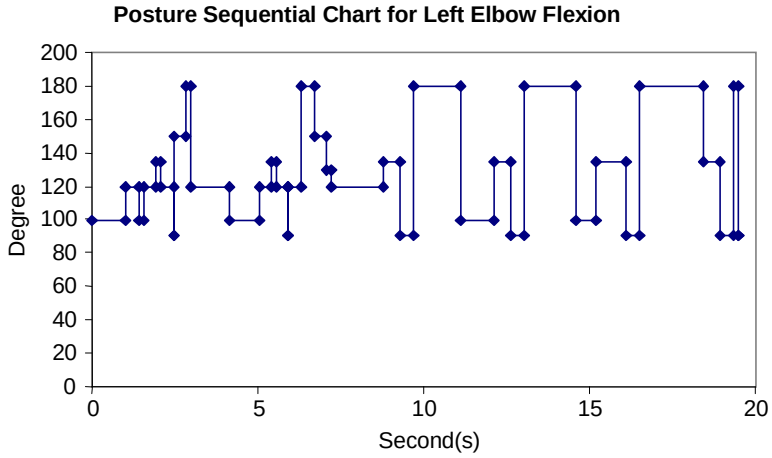


Figure 3-3 – Example of a FWAP for Windows© analysis level one "Identifies classes in one characteristic" graphical output.

3.2.4 USE OF FWAP

The FWAP code is a manual observational method that can be videotape and computer assisted. FWAP analysis normally involves videotaping a work-task and identifying the MODAPTS actions and estimating the postural angles from the video playback. Alternatively, this process can be carried out at the workplace directly, for occasions when videoing a work-task is not feasible. The MODAPTS codes and posture angles

are then entered manually to the FWAP for Windows© spreadsheet. FWAP provides a high level of detail about a work task, but as a trade-off is a labour intensive process.

Numerous observational work analysis systems have been developed (see Sec. 3.1). Unlike the FWAP code, these systems generally do not capture a number of action characteristics that influence control of hand or arm position and therefore do not capture all aspects of static muscle work [352]. Further, much of the detail which some work analysis systems collect is lost by being grouped before the output is provided [352].

In addition, the FWAP code is one of few work analysis systems that takes advantage of building onto a PMTS code. Using PMTS codes (including MODAPTS) is beneficial to the user because they: name all actions that comprise a task, provide the time in which an average trained worker would be expected to perform a task, present a written pattern from which a job can be reproduced and they are written and used internationally by industrial engineers [346]. In many jobs, MODAPTS analysis is completed by industrial engineers for production estimates and costs. These analyses provide opportunities to assist with FWAP workplace analysis. Also, the use of MODAPTS with the FWAP code precludes the requirement for the stopwatch method to establish a time base for the work task actions.

Postural-work activity classification methods that evaluate the combined effects of body postures and work activities, and also supplement a PMTS code should be further expanded [310], as they would be of great benefit for ergonomic analysis of work tasks. The FWAP work analysis code is such a classification system and the FWAP code was chosen in this thesis for further development and application in the applied research field.

3.3 THE FWAP-LINK SYSTEM: LINKING POSTURE MEASUREMENT AND MODAPTS WITH FWAP FOR WINDOWS©

3.3.1 GENERAL DESCRIPTION

It is inappropriate to include entries for every FWAP code in any study, and the user must decide which action and posture characteristics are relevant to their needs

[346,351]. In this context, a new instrument-based posture measurement system (based on the manual FWAP code) was developed in this thesis for a specific research based task to measure the posture and actions of the *upper torso and right arm*. An accurate posture measurement system was required so that the relationship between specific ergonomic risk factors and pain variables could be investigated. This research is reported in the next chapter (Ch. 4).

The *FWAP-Link system* was developed in this thesis to be an instrument based posture measurement system that *linked* motion capture technology, three-dimensional computer animation, kinematic geometry, MODAPTS analysis and FWAP for Windows©. An electromagnetic tracking system[2] (ETS) was used to measure the posture and actions of participants as they undertook specific computer-based work tasks (the task is described in Ch. 4). In basic terms, FWAP-Link used the data from the ETS and with custom software developed in this thesis (described immediately below), converted this to a format that could be used in FWAP for Windows©. A step-by-step description of the FWAP-Link system is described in Sec. 3.4 and the operational specifics of the system are discussed in App. A.

Some aspects of the FWAP-Link system are not novel as there are several posture and posture-analysis systems for measuring and recording posture with various measurement technologies, including with ETSs. Some are available commercially (see App. A, Table A-1). However, no instrument-based posture measurement system has been developed that analyses posture and work actions based on the MODAPTS code. In this respect, *FWAP-Link is a new development*.

[2] Fastrak system, Polhemus Incorporated, 40 Hercules Drive, Colchester, VT, USA

3.3.2 FWAP-LINK POSTURE ANGLE DEFINITIONS

The following posture angles were measured with FWAP-Link:

Segment	No	Code	Description	Positive	Negative
Trunk	1	SFH	Angle from vertical by which shoulders (C7) are forward or behind the hips	Ventral	Dorsal
	2	SSH	Angle from vertical by which shoulders (C7) are to the side of the hips	Right	Left
	3	TR	Angle of trunk rotation. Use line between the shoulders (neck local reference system) compared with line between the hips	Right	Left
	4	C*	Trunk curvature. Angle between hips (HP), upper thoracic spine centre (SC) and neck centre (NC)	Flexion	Extension
Head	5	HF	Head flexion relative to vertical	Flexion	Extension
	6	HR	Head rotation	Right	Left
	7	HT	Lateral flexion relative to vertical	Right	Left
	8	HNF*	Head flexion relative to the base of the neck	Flexion	Extension
	9	HNT*	Head lateral flexion relative to the base of the neck	Right	Left
	10	HNR*	Head rotation relative to the base of the neck	Right	Left
Shoulder	11	RSEV	Angle from base of neck (NC) that right shoulder is elevated	Superior	Inferior
	12	RSF*	Angle that right shoulder is ventral or dorsal	Protraction	Retraction
Arm	13	REFS	Angle from vertical that the right arm is flexed/extended	Flexion	Extension
	14	RERS	Angle from vertical that the right arm is abducted	Abduction	Adduction
	15	RDS	Angle of right arm rotation	Right	Left
Forearm	16	RFX	Right elbow flexion		
	17	RPR	Pronation/supination of the right forearm	Pronation	Supination
Wrist	18	REX	Right hand flexion/extension	Flexion	Extension
	19	RDV	Right hand ulna or radial deviation	Ulna	Radial

Table 3-2 – The FWAP-Link posture codes

(From [346,351])

* Indicates new angles measured by the FWAP-Link system not included in the original FWAP code. The mathematical derivation of the FWAP posture codes and the anatomical location codes in brackets are described in App. A.

3.3.3 FWAP-LINK COMPUTER PROGRAM

A key component of the FWAP-Link system was the development of a new custom software application (by the author) that allowed a MODAPTS analysis of a measured task.

This new custom software application was called the FWAP-Link computer program and is shown in Figure 3-4. This program displayed computer generated human animation videos so that the user could visually observe the actions undertaken during completion of the measured task. Two computer videos were created and displayed: a

general video of the worker and a close up their right arm and hand. This step is discussed later in Sec. 3.4.

The FWAP-Link computer program was designed so that the user was required to observe the animation videos and when *the user decided* a MODAPTS action had occurred, pause the videos and entered the appropriate MODAPTS code into the FWAP-Link program. FWAP-Link automatically suggested to the user, when paused, which Moves action (M1 to M7) had occurred based on the travel distance of the hand (e.g., if the hand travelled greater than 300mm and less than 450mm, then FWAP-Link would suggest an M4 [345]).

The user also added comments at each MODAPTS action to describe the work action the worker was undertaking. The MODAPTS entry was then saved and the playback of the videos continued until the *user deemed* the next MODAPTS action had occurred. The playback was again paused and the appropriate MODAPTS action code and description of the purpose of the work action again entered to the program. These steps were repeated until the end of the animation videos, or if the user decided that the work cycle had ended. The FWAP-Link data file was then saved and closed, with all MODAPTS entries, work action comments and posture codes.

The posture of participant at each MODAPTS entry was automatically stored with the FWAP-Link data file. The user *was not required* to make posture estimates, as the posture was derived from measurements with the ETS data. This aspect of the software was a *great advantage* of the system, because it removed, arguably, the most time consuming aspect of manual posture analysis, that being, estimating the posture of the participant at each work action However, this method of analysis did not obviate the user from a solid understanding of the MODAPTS code.

The FWAP-Link program was developed with Microsoft Visual Basic v6.0. The FWAP-Link program was approximately 1200 lines of code and the author completed all programming. The FWAP-Link computer program is shown in Figure 3-4.

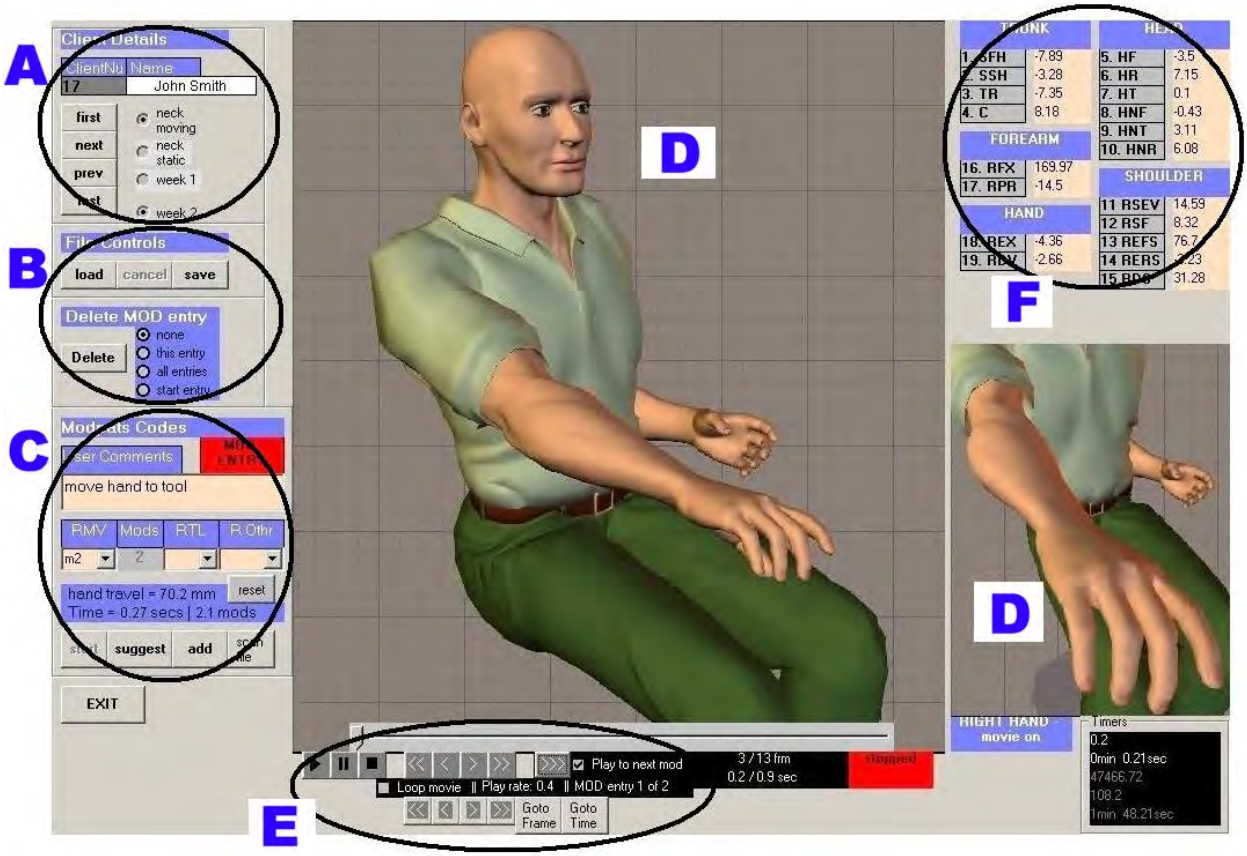


Figure 3-4 – Example of the FWAP-Link posture and MODAPTS action analysis program

A. **CLIENT DETAILS**: database controls that permit the user to specify which worker data file to load.

B. **FILE CONTROLS**: loads data files and saves or cancels MODAPTS entries. 'Delete MOD Entry' permits deletion of some or all MODAPTS entries.

C. **MODAPTS CODES:** permits the user to make right hand MODAPTS entries to the FWAP-Link data file. 'RMV' refers to moves and cranks MODAPTS codes [345]. 'MODs' show the number of MOD time units for the entered code and is automatically generated. 'RTL' and 'R Othr' refer to terminal actions and other actions MODAPTS codes, respectively [345]. The user enters the appropriate MODAPTS code into the RMV or RTL or R Othr fields. 'User Comments' describe what the worker was doing at the time of the work action. 'Hand Travel' distance estimates the distance the hand travelled between each MODAPTS entry. This value is updated each time the videos are paused.

D. **COMPUTER ANIMATION VIDEOS:** The 'General' and 'Right Hand' animation videos are located centre and lower right respectively.

E. **VIDEO CONTROLS**: These are located below the general video and permit playback at slow, normal and fast speeds, looping of playback and playback between MODAPTS entries only.

F. **FWAP-Link POSTURE ANGLES**: are shown above the right hand video. These posture angles are automatically updated every time the videos are paused, when the user moves between MODAPTS entries, or when a MODAPTS entry is made.

3.4 USING THE FWAP-LINK SYSTEM

The FWAP-Link system is outlined in Figure 3-5.

Each step is discussed in detail below (the specifics of the FWAP-Link system are described in App. A):

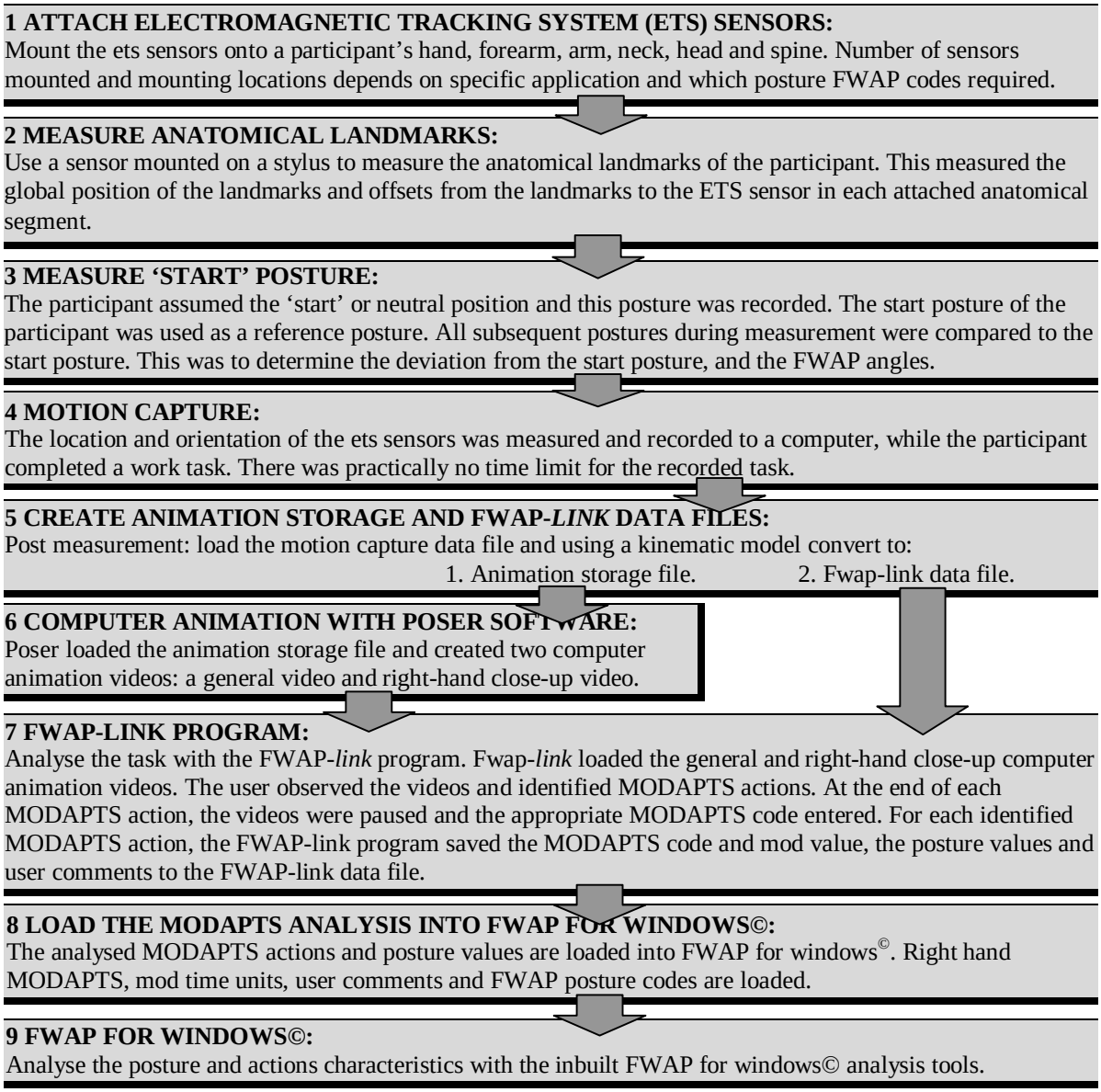


Figure 3-5 – Flow chart of the FWAP-Link posture measurement and analysis system.

3.4.1 STEP 1. ATTACH ELECTROMAGNETIC TRACKING SYSTEM (ETS) SENSORS

The ETS sensors were attached to the participant to be measured. In Ch. 4, an upper torso and right arm posture analysis was undertaken. For this application, a six-sensor configuration was employed and sensors were attached to the: head, neck, spine, arm, forearm, and hand. Other ETS sensor configurations could easily be used (e.g., more or less sensors, and measuring other body segments) depending on the requirements of the task being assessed.

The small sensor dimensions (28x23x15mm) permitted easy mounting onto the person to be measured. Electromagnetic tracking is further discussed in App. A.

3.4.2 STEP 2. MEASURE ANATOMICAL LOCATIONS

The global coordinates of specific *anatomical landmarks* were measured at the body segments that in Step 1 were identified for investigation. The landmarks used with FWAP-Link are described in App. A at Sec. A.4. The landmarks global coordinates were determined with an ETS sensor mounted to a small stylus (see Figure 3-6). When a landmark was measured, the location and orientation of the ETS sensor attached to the anatomical segment with which the landmark was associated was also measured.

The coordinates of landmarks were used to convert the data from the ETS sensor (the technical reference system) to the local segment reference system. This is further discussed in the 'kinematic geometry' section in App. A, Sec. A.3.

Variance of the measured location of the bony landmarks was partially random (e.g. palpation error and stylus endpoint inaccuracies), and partially fixed (e.g., magnetic field distortions) [353]. This random factor was diminished by performing repeated measurements [353]; each anatomical landmark was measured five times, almost instantly. The average of the five measurements was used to define each anatomical landmark in the Global Reference System (the global reference system is discussed in App. C, Sec A.3)

Figure 3-6 – Stylus used to measure superficial musculoskeletal anatomical landmarks

3.4.3 STEP 3. MEASURE START POSTURE

The start or neutral posture of each participant was measured before the participant undertook any actions. The start posture recorded the participants posture when they were in the neutral position. This neutral position was used as a reference posture to which all subsequent postures that were assumed, when the participant was undertaking

the required tasks, were compared. *Each posture was compared with the start posture and the difference between the later posture and the start posture was used to determine the FWAP-Link angles*.

For the start posture, the participant was requested to assume an upright posture, with the trunk in a vertical orientation and look straight ahead. The right arm was placed next to the upper torso, in a vertical orientation pointing inferiorly. The forearm was flexed at 90 ^{deg}, such that it was placed in a horizontal orientation, pointing anteriorly. The forearm was also pronated so that the palm was facing down. The wrist, hand and fingers were aligned with the longitudinal axis of the forearm. The start posture was measured five times almost instantly, and averaged.

3.4.4 STEP 4. MOTION CAPTURE – RECORD MOVEMENTS WITH ETS

The ETS measured continuously the movements of the person as they completed the task under investigation. The ETS sent the position and orientation data of each sensor to the computer. Approximately 12 measurements were made each second (0.08 secs per measurement). The computer recorded this information with the time (in milliseconds) of the measurement.

3.4.5 STEP 5. CREATE ANIMATION STORAGE AND *FWAP-LINK* DATA FILES

Once the work task had been measured, the motion capture data files were converted to a Biovision[3] file and a FWAP-Link data file. The Biovision animation file storage system is described in App. A, Sec. A.2. This process loaded the recorded position and orientation data for each ETS sensor and, using the global coordinates of the anatomical landmarks, converted the ETS data to a local segment reference system for each anatomical segment.

The local reference system is a mathematical description of the position and orientation of an anatomical segment in space [354]. The local reference system, for each segment, was compared with adjacent segments to derive a joint rotation matrix [355]. The joint

[3] BioVision Motion Capture Studios, 9311 Blind Pass Rd, St. Pete Beach, Fl, 33706, USA

rotation matrix mathematically described the orientation of a distal segment relative to a proximal segment. The joint rotation matrix does not easily convey an immediate interpretation of the relative movement between two anatomical segments [355]. Therefore, a *'Joint Coordinate System'* (JCS) was used to describe the orientation of each joint in a clinically meaningful manner. The JCS used three axes, two body fixed axes and a floating axis, to describe three rotations of a distal segment relative to a proximal segment [356]. Body fixed axes were located in the proximal and distal segments, and the floating axis was perpendicular to the two body fixed axes [357]. Rotations about the fixed and floating axes matched the clinical definitions for relative movement between two anatomical segments [355] and numerically described the posture of a joint between distal and proximal segments. The local segment system for each segment, rotation matrices and the JCS are described in App. A, Sec. A.4.

The joint coordinate system angles, or the posture, were written to the Biovision animation storage and FWAP-Link data files. The animation program used the Biovision file format to complete 3D animation of the recorded data. This is described in step 6.

3.4.6 STEP 6. ANIMATION SOFTWARE

Poser[4] v4.0 is a computer program that creates three-dimensional computer animation videos of human figures. Three-dimensional computer animation is discussed in App. A, Sec. A.2.

The Biovision animation storage file provided the link between the raw ETS data and the animation program. Poser loaded the Biovision animation storage file and created two computer human animation video files. The Poser animated human figure simulated exactly the actions recorded previously from the participant as they completed the work task. Two computer animation files of equal length were created: a general video that observed the animated figure slightly above head height from the figures front and right. This video gave an overall view of the animated figure. The second animation video

[4] Curious Labs Inc, 655 Capitola Rd, Suite 200, Santa Cruz, CA 95062

was a close-up of the animated figures right arm, forearm and wrist movements (see Figure 3-4).

The viewpoints of the general and right arm close-up animation videos were chosen for the specific research application described in the next chapter (Ch. 4). The upper torso and the right arm were the areas of interest. These body segments may not always be the regions of interest for FWAP analysis. However, *Poser can easily depict the animated figure from different perspectives. It can animate the figure from any angle and focus close-up on any body segment*. Computer animation offered great flexibility in the visual depiction of the movements completed by the measured person and was a great advantage to this system.

3.4.7 STEP 7. MODAPTS ANALYSIS WITH THE FWAP-LINK PROGRAM

A MODAPTS analysis of the work task was completed with the FWAP-Link program as described above in Sec. 3.3.3.

3.4.8 STEP 8 AND 9. LOAD INTO FWAP FOR WINDOWS©

In Step 8 the completed MODAPTS analysis of the work task was loaded into FWAP for Windows© (FWAP for Windows© was described above in Sec 3.2). The right hand MODAPTS codes, MOD time units and FWAP posture angles for each MODAPTS step were loaded (see Figure 3-1). Task analysis with the seven inbuilt FWAP for Windows© tools (see Sec. 3.2.3) was then possible.

In Step 9 the user could investigate the postural and action characteristics of the measured task with the analysis tools of the FWAP for Windows©.

3.5 FWAP-LINK ACCURACY

To test the accuracy of the FWAP-Link system, posture angles measured by the FWAP-Link system were compared with postural angles measured from video camera posture analysis. Three participant's postures were measured with the FWAP-Link system while they completed specific actions. Most actions involved moving a segment to the extreme of its range of motion. The participant's actions were also recorded with a

handheld video recorder. The videos were later copied to a computer and converted to a Microsoft Windows Media Player format.

A custom designed program was used to analyse the handheld video camera Windows Media Player video files. The custom program was used to estimate the angles of specific body segments from the video files. The user paused the video playback and drew lines along the participant's anatomical segments with the computer mouse. The angles of the mouse drawn lines indicated the posture of the participant from the video. The author completed all programming and this program was approximately 2000 lines of code. The video posture analysis program is shown in Figure 3-7.

Figure 3-7 – Video posture analysis program; angles were determined from the lines drawn onto the computer video as shown

The angles measured from the video files were compared with the posture angles measured by the FWAP-Link system. Table 3-3 indicates the average absolute difference between the handheld video and FWAP-Link posture measurements for individual body segments.

Body Segment	Action	Angle Difference between video and FWAP-Link values	SD	COUNT
Arm	abduction/adduction (<70)	1.9	1.6	3
Arm	flexion	2.1	1.9	9
Arm	rotation	18.2	12.3	4
Forearm	flexion	6.4	3.6	15
Forearm	rotation	57.6	14.6	9
Wrist	flexion/extension	14.3	6.6	12
Wrist	ulna/radial deviation	5.5	4.6	9
Head	flexion/extension	3.8	2.9	12
Head	lateral flexion	4.9	4.5	12
Head	rotation	1.1	0.7	5
Trunk	flexion/extension	3.2	1.2	3
Trunk	lateral flexion	2.3	1.1	6
All Data		**10.8**	**16.6**	**99**
All Data without arm and forearm rotation		**5.5**	**5.4**	**86**

Table 3-3 – Average absolute difference between video and FWAP-Link angles for specific body segment motions. Count refers to the number of times that an action was assessed.

In Table 3-3, arm and forearm rotation posture data varied greatly between angular measurements recorded from the video analysis and the FWAP-Link system. This was likely due to skin movement of the ETS sensor on the arm and forearm during rotation motions. Skin displacement and muscle contractions can cause sensors to move relative to the segments, which can introduce error to the angular measurement [339,358]. Without these two posture codes, there was an average of 5.5 deg difference between the FWAP-Link posture estimates compared with the video analysis.

A three-dimensional instrument based posture measurement system would have been a preferred method of accuracy testing the FWAP-Link posture measurements. Posture measurement systems based on technologies of ultra-sonic technology[5], passive infra-red camera system[6] or active light-emitting-diode (LED) camera system[7] would have served as a better benchmark against which to compare FWAP-Link. Unfortunately, due to budget and time constraints, it was not possible to compare the FWAP-Link system against a more accurate gold standard instrument based three-dimensional posture measurement system.

[5] Zebris, WilhelmstraBe 134, D-72074 Tubingen

[6] Vicon, Oxford Metrics, Unit 14, 7 West Way, Botley, Oxford OX2 0JB, UK

[7] Optotrak, Northern Digital, 403 Albert stiffness, Waterloo, Ontaria, Canada, N2L 3V2

Video posture measurement has several disadvantages. Firstly, with only one video camera it can only measure posture in two dimensions and cannot measure segment motion in all planes. This necessitates that actions be completed in a plane perpendicular to the measurement plane of the video. It may be necessary for the camera operator to follow the participant to maintain optimum camera/subject distance and orientation [359]. Video posture measurement systems lack resolution, require trained operators and are subject to analyst biases and experience [319]. Because of the limitations of video posture analysis, the accuracy testing reported above provided support for the accuracy of the FWAP-Link system, but the evidence was not definitive.

3.6 ADVANTAGES AND DISADVANTAGES OF FWAP-LINK

3.6.1 ADVANTAGES

The ETS provided an accurate, reliable and extremely fast method of continuous posture measurement and recording.

FWAP-Link removed the need for the user to estimate the posture of the body segments measured with the ETS. This was a considerable improvement in achieving posture measurement, compared with video or the eye unassisted. Arguably, the most time consuming aspect of completing a manual FWAP analysis is estimating the posture of the participant at each MODAPTS action. The FWAP-Link system removes this time-consuming task.

Using kinematic geometry, FWAP-Link converted the ETS motion capture data to anatomically meaningful information. The 3D animation software (Poser) used this information to create 3D computer animation of the recorded movements. 3D computer animation permitted the user to view the actions completed by the animated figure from any angle and distance and could focus on particular body segments. This gave the user great flexibility in viewing the recorded movements.

The high measurement resolution and accuracy of the ETS permitted the user to measure and record minor posture alterations. As well, five FWAP-Link posture codes were added to the standard FWAP posture code list, because they could be measured with the high ETS resolution and accuracy. These were (from Table 3-2):

- C – Trunk curvature. Angle between hips, upper thoracic spine and the neck
- HNF – Head flexion relative to the base of the neck
- HNT – Head lateral flexion relative to the base of the neck
- HNR – Head rotation relative to the base of the neck
- RSF – Angle that right shoulder is ventral or dorsal

3.6.2 DISADVANTAGES

The ETS has operational limitations that must be considered. These include:

- The range of the transmitter is approximately 1m and a transmitter-to-sensor distance of greater than this value may introduce error.
- Metal objects placed between the transmitter and sensors may potentially introduce error to measurements. This could be a problem if conducting measurements at a workplace where work tools and/or equipment are metallic.
- The ETS sensors are attached to a measured person with long wired connections. These wires could potentially restrict freedom of movement and alter normal work actions and posture.
- The sensors were too large for mounting onto small body parts such as the fingers and therefore could not capture finger movements.
- The ETS is also a considerable financial investment compared with a simple video camera recorder.

The FWAP-Link process also has limitations. Importantly, it did not link the work actions completed by the measured person with the movements depicted by the human animation figure. If FWAP-Link were applied in a normal workplace as an ergonomic analysis tool, the user may be required to record a detailed description of work actions.

The analysis only includes FWAP posture angles for the body segments measured by the ETS. The user was limited by the number of ETS sensors available and may be required to visually estimate the posture of body segments not measured by the ETS and manually enter results into FWAP for Windows©. Similarly, FWAP-Link did not accommodate most FWAP 'actions' codes and the user may be required to add these to FWAP for Windows© manually, if they are required.

The FWAP-Link system was developed for research into the upper torso and the right arm body segments posture; the left arm and lower limbs were not accommodated for analysis. However, FWAP-Link could easily be further developed to include all body segments.

The ETS sensors are attached via long wired connections, which could potentially restrict freedom of movement and alter normal work actions and posture. Jasiewicz et al. [360] tested wireless inertial sensors that incorporated a rate gyroscope, accelerometer and magnetometer, and compared these sensors against a criterion system, the 3-Space Fastrak. The wireless inertial sensors were valid, accurate and suitable for assessing cervical joint motions. Hence, these wireless sensors could be applied to other areas of the musculoskeletal system, to measure posture and overcome the hard wiring disadvantage.

3.7 FUTURE DIRECTIONS

Considerable development work would be required to take the FWAP-Link system from a research-based tool, to a robust and efficient field measurement tool. Limitations of the ETS system would have to be considered for any field based application. The ETS may be affected by the presence of metal in the immediate environment, particularly when metal is between the sensor and the transmitter. However, with careful placement of the transmitter and sensors this limitation could be managed. As well, a DC ETS is less affected by metal than an AC ETS. Therefore, a DC ETS could be used if metal interference is anticipated. For ergonomic analysis of work environments and interaction between the person and work equipment, mock set-ups with non-metallic material may also help overcome this problem.

The FWAP-Link system utilised computer animation for representational purposes in the MODAPTS analysis. As discussed above, this potentially removed the link between what actions were completed and the task the person was completing at the time. A normal video could be used instead of, or complement, the computer animation. The video could be downloaded to a computer and could replace, or complement, the animated figure to provide the user with a clear visual record of all actions and tasks undertaken by the person. The video could be used with the MODAPTS analysis (step

7) of the FWAP-Link system. It would also be possible to have both a video of the work task, and an animation video that would permit a flexible visual representation (e.g., close-ups, different viewing angles).

The FWAP-Link program could be developed to directly provide animation of the motion capture data, removing the necessity of using Poser to provide animation of the participant's actions. This would remove step 6 of the analysis process. When completing the MODAPTS analysis (step 7) with the FWAP-Link program the user was locked into the animation videos created by Poser – it was not possible to modify the viewpoint without repeating step 6. If computer animation were incorporated directly with the FWAP-Link program this would give the user more control of the figure while completing the MODAPTS analysis. The user would be able to view the animated figure from any angle and distance while completing the MODAPTS analysis in step 7.

The FWAP-Link program still required a user to manually analyse the movements completed by the participant during the MODAPTS analysis (step 7). This took some time to complete and in this respect was not a significant improvement on current methods of video camera and the eye unassisted. The user must also have a solid understanding of the MODAPTS code. There is potential to take the MODAPTS analysis to an automated stage, whereby a computer program would analyse the motion capture data file and seek movement patterns in the data. Computer algorithms could be developed to provide a MODAPTS analysis automatically, reducing the need for human input. This would require considerable development work and research, but would represent a significant improvement in completing MODAPTS and FWAP analysis and reduce the analysis time.

3.8 CONCLUSION

The FWAP-Link system provided a new method of analysing motion capture data from an ETS with computer animation, and converting this to a FWAP for Windows© format. The FWAP-Link system was developed to assist with MODAPTS and FWAP analysis of a specific task in a custom research environment. The FWAP-Link system has not been developed for application outside this specialised research area and therefore is

currently not applicable outside the research field. There is considerable scope for improvement and progressing FWAP-Link to a field measurement tool.

The FWAP-Link system represents a significant step forward in using modern technology for contribution to ergonomic evaluation, and particularly posture analysis based on a predetermined motion time standard. It removes, arguably, the most time-consuming aspect of completing a manual posture analysis, by removing the need to manually assess posture.

Comparison of the FWAP-Link system with a simple video posture analysis supported the accuracy of this system for posture measurement, but the evidence was not definitive.

CHAPTER 4

THE ASSOCIATION OF POSTURE AND PAIN

- **CHAPTER SUMMARY**

This chapter investigates the association of posture and pain, and describes in detail the posture research and findings, which is a key component of this thesis (goal two). The relationship between different ergonomic risk factors and pain sensitivity was investigated.

Work-related musculoskeletal disorders are a significant challenge to industrialised nations. They include a wide range of *specific* inflammatory and degenerative clinical disorders and also *non-specific* musculoskeletal pain disorders, which are less well-standardised conditions that are not classified as a specific disorder. Within the working population, work-related musculoskeletal disorders that are non-specific most likely occur more commonly than discrete clinical disorders. Chronic forms of this type of disorder that are diffuse, non-specific and are regionalised have been termed regional pain syndrome (RPS). This pain syndrome was discussed in Ch.2 Sec. 2.1.3.

Knowledge is lacking regarding the relative importance that individual ergonomic risk factors play in the pathogenesis of musculoskeletal disorders. This is especially so for non-specific pain syndromes. *Postural factors* are commonly cited as an important ergonomic risk factor associated with the development of these disorders, because non-neutral and static postures are the most frequent form of static muscular effort in the workplace. However, specific ergonomic guidelines for working postures and risk of injury do not exist.

A better understanding of the pathogenesis of musculoskeletal disorders is required, particularly for the more challenging and common non-specific disorders, and for their effective treatment and indeed, prevention. Multidisciplinary approaches have already enhanced knowledge about these disorders, and it is important that work in this area continues. This will contribute to understanding the risk factors associated with musculoskeletal disorders.

The exact aetiology of RPS is unknown, but it is believed that aberrant peripheral and possibly central pain mechanisms are involved (see Ch. 2, Sec. 2.4). Aberrant central pain mechanisms can manifest as hyperalgesia, referred hyperalgesia, referred pain and allodynia, all of which are characteristic of RPS in the painful region. Importantly, it has been shown that persistent pain from the musculoskeletal system is a significant factor in inducing long-standing changes in the excitability of the dorsal horn neurons in the spinal cord. Persistent pain stemming from the spinal zygapophysial joints or related structures, or muscles (particularly the trapezius), tendons and joint capsules in the upper limb and/or peripheral nerves could be consequent upon ergonomic risk factors such as working postures. In this way, *ergonomic factors* could contribute to the development and maintenance of persistent musculoskeletal pain and, in turn, drive changes in the sensitivity of the central pain system. However, the putative association between ergonomic risk factors and pain sensitivity has not been extensively investigated. The research in this thesis helps to shed some light on this relationship, however more work is needed to fully understand the nature of the relationship.

As will be discussed in Ch. 6, the *cervical spine* is more susceptible than other regions of the musculoskeletal system to the initiation of aetiologic factors in RPS. The postural load and actions undertaken in the completion of work by the cervical spine and related structures (such as the head and shoulder girdle) may be important factors in the development of dysfunction in neck structures. Pain stemming from cervical structures is effective at initiating centrally mediated pain phenomena, the manifestations of which could be representative of RPS. A key goal of this thesis was to better understand the susceptibility of the cervical spine and related structures to pain dysmodulation and therefore RPS. If the results proved that the posture and actions of the neck and related structures are indeed important factors associated with pain dysmodulation, then this would indicate that these structures should be considered as risk factors of RPS, and should also be assessed during ergonomic analysis of work tasks.

Posture Experiment:

The posture experiment was undertaken to examine the association between the specific ergonomic risk factors of non-neutral and static working posture, combined with repetitive work actions, and the clinical variables that are characteristic of RPS and FM. The following hypotheses were tested:

1. Short-term exposure to specific ergonomic risk factors would be associated with a change in the function of the pain system.

2. The more dynamic the work actions of the cervical spine, the fewer the musculoskeletal pain symptoms.

Healthy females participated in two simulated work sessions, where they were required to undertake computer-based tasks in body positions of poor posture. The sessions were of four hour duration and were conducted one week apart. The two sessions did not differ except that in one session the posture of the head and neck were static throughout (neck-static), and in the other session the head and neck were required to move substantially once every minute (neck-mobile).

The following factors were measured during the simulated work sessions:

1. Changes in the function of the cervical spine and musculoskeletal system. These were measured using:

    a. pain sensitivity measurements in the cervical spine and at specific anatomic locations in the musculoskeletal system (at tender points and control points),

    b. self-reporting instruments, and

    c. passive cervical range of motion.

2. The posture of participants. This was measured using an electromagnetic tracking system with six sensors (as described in Ch. 3).

The key results from the experiments were as follows:

Pain sensitivity was significantly higher for the task that involved a static neck posture, compared with the neck-mobile session. This outcome indicated that the cervical region of the musculoskeletal system may have influence over pain sensitivity both within, and at locations distal to, the neck.

There was a significant change in pain sensitivity between the start and end of the measurement sessions at most measured locations in the cervical spine and

musculoskeletal system. This indicated that the ergonomic risk factors significantly influenced pain sensitivity. Whether this was from peripheral nociception, or also from central mechanisms was unknown. Self-reports of pain were significantly increased when the neck posture was relatively static, compared with the neck-mobile action characteristics. There was also a significant change in some of the ROM results.

The results of this investigation supported the hypothesis that ergonomic risk factors, in particular working postures and actions, *can influence pain sensitivity*. Static and constrained postures, when combined with repetitive actions of the arm and hand, were associated with an increase in the excitability of the pain system (possibly from a combination of peripheral and central pain processing changes). Any change in pain sensitivity can increase the risk of RPS and FM [186]. Therefore, long-term exposure to ergonomic risk variables (such as spending long hours sitting at a computer with poor and static posture and few breaks) that that increase pain sensitivity, possibly as a consequence of central pain changes, could be a risk factor associated with the onset of RPS.

4.1 INTRODUCTION

4.1.1 POSTURE, WORKPLACE ACTIVITIES, RPS AND FM

There are gaps in knowledge regarding the relationship between ergonomic risk factors and musculoskeletal pain syndromes. Ergonomic factors, such as static postures and repetitive actions, are frequently cited as potentially contributing to musculoskeletal discomfort and pain, but many conclusions are based on associations and suggestions [90]. As well, the association between specific ergonomic factors and abnormal pain-processing function has not been extensively investigated.

Investigations of the occupational environment and its impact on workers have traditionally been conducted in the fields of ergonomics and occupational health and safety (OHS). However, FM and RPS, and the putative neurogenic basis of these syndromes (outlined in Ch. 2 Sec. 2.4), are rarely mentioned in these literature fields. It appears that the strong evidence supporting a neurobiological basis for chronic musculoskeletal pain (from rheumatology and pain research fields) has not been effectively communicated to the ergonomics and OHS fields [79]. A consequence of

these omissions is limited acknowledgement of recent advances in pain knowledge regarding possible contributory factors to musculoskeletal pain. The omission of altered pain processing mechanisms is also evident in the near absence of ergonomic research that incorporates objective measurement of the pain system, such as pressure algometry (discussed below in Sec. 4.3.5.1).

Similarly, the rheumatology and pain fields have not extensively investigated the putative association between ergonomic risk factors (such as poor posture and repetitive actions) and features of RPS and FM. The effect of the occupational environment on patients with chronic musculoskeletal pain is not clearly understood [91,92], although recent work has been undertaken in this area [29,92,361]. Workplace ergonomic exposures that may act as aetiological factors in chronic musculoskeletal pain syndromes are undefined. In addition, the association between specific ergonomic factors and hypersensitivity of the peripheral and/or central pain systems (which may manifest as tenderness, allodynia and referred tenderness and pain) are presently at their very early stages. There exists a requirement to explore these associations.

Previous rheumatology investigations have identified that occupational tasks which involve prolonged repetitive actions and static postures are least tolerated by FM patients [29,91,92,361-363] and may be a triggering factor for FM [237]. Specific tasks, including computer and typing work, prolonged sitting and standing, and walking have been reported as activities that most aggravate conditions [91,362]. Waylonis et al. [91] found that working at one task for a long period of time, especially with arms and shoulders held in an isometric position, aggravated symptoms in FM patients. They [91] suggested that ‘too much of anything’ tended to aggravate the symptoms of FM, especially when there are superimposed environmental stressors [91]. Light sedentary occupations that allow *varied* tasks and changing postures appeared to be tolerated best [29,91].

Occupational tasks that require precise manipulation are a likely risk factor for RPS. Henriksson et al. [2] investigated women who had reported RPS in the neck and/or shoulder. Participants were working in sedentary positions in a sitting position that involved precision manipulation for assembly testing and inspection work. Pain was experienced most commonly in the neck, shoulder and upper limb regions. Henriksson et al. [2] also reported unpublished evidence that 80% of workers involved in similar

production facilities experienced pain in the neck and shoulder region and/or upper extremities. The most important factors associated with pain were *repetitive movements* demanding *precision* and repetitive light lifting.

Liedburg, Henriksson and colleagues investigated the factors that women with FM perceived as influencing their capacity to remain in a work role [29,92,361,362,364]. While their research did not investigate specific ergonomic risk factors, the outcomes indicated the aspects of work that were perceived as important in maintaining the musculoskeletal pain in FM. They categorised the factors that impacted on the ability of FM patients to remain at work as societal and individual. Under the individual category, physical and psychosocial factors were important. Physical work characteristics identified as impossible included *static and repetitive movements*, heavy tasks and practical tasks that required muscle strength and endurance. Jobs such as computer work, telephone work, administration, service and care, processing, and work without the required formal vocational training were identified as difficult. These jobs were characterised by work tasks that included cleaning, serving tables, handwriting, and working with elevated arms. Even *light* work tasks demanding *static muscle work*, or bending, dexterity and coordination increased the pain, and for some FM sufferers were impossible to manage. These jobs represented areas where the risk of musculoskeletal disorders was high.

Liedburg [92] concluded that the work actions associated with these jobs were not suitable for women with FM and *may have contributed to the development of FM*. Liedburg [92] argued that tasks that involve static and repetitive work should be avoided by people with FM. Further, the ability to *vary work postures* and opportunity for *short breaks* was important for remaining in employment.

Postural load placed on the cervical spine also appears to be a significant factor associated with the onset of chronic musculoskeletal pain. As noted above, mechanical stresses in the cervical spine have been reported as a significant aetiologic factor for RPS and FM [20,78,93,162]. Poor workplace posture, particularly constrained and static postures with little action variation, may place high mechanical stresses on various structures of the deep paraspinal region, which, in turn, may contribute to the onset of spinal dysfunction [20,81,365,366]. In the cervical spine, mechanical stresses applied to

adjacent regions, such as the shoulder girdle, may also play a crucial role in initiating spinal dysfunction in this region [20,365,366].

In addition, ergonomic variables such as mechanical load, posture and repetitive actions may act as external aetiology factors for widespread pain, FM and RPS [20,97,367,368]. However, most investigations of RPS and FM in the workplace have been retrospective studies and only provide broad indicators of occupational risk factors for RPS and FM. There is limited information for FM that permits direct assessment of whether mechanical factors are either associated with widespread pain or whether exposure predicts future onset [367]; specific work guidelines for preventing FM do not exist.

However, this in not the case with regionalised musculoskeletal disorders where there is significant ergonomic information regarding mechanical risk factors for this syndrome [367]. However, as noted above, the ergonomic field has not entertained the putative neurogenic basis for this syndrome [107]. Hence, most ergonomic risk factors of RPS are based on mechanical loads of the musculoskeletal system and discrete pathological conditions and do not encompass putative changes to the nociceptive system. Further elucidation of occupational risk factors associated with RPS and FM is required.

Prospective investigations are now required to study specific risk factors associated with the causative sequence of RPS and FM [24]. Farrell and Littlejohn [352,363,368,369] conducted prospective studies of occupational task performance in FM and healthy controls. Under controlled conditions, healthy participants completed four occupational tasks of different work action patterns with different ergonomic risk characteristics of frequent repetition and muscle work [368]. The different work action patterns were used to examine the association of changes in pain sensitivity and task performance. They [368] hypothesised that pain sensitivity changes in healthy participants would be valuable predictors of patterns that may cause pain in those with pre-existing low pain thresholds as seen in RPS and FM. Results indicated that *repetition frequency, static muscle work and force can influence pain sensitivity* scores on both the side used in the tasks and on the contralateral side and, in some cases, the size of the change [368]. The change in pain sensitivity on the side not used during the tasks may have occurred due to central mechanisms, possibly spinal carryover [368].

Farrell and Littlejohn [363] conducted another similar prospective investigation, where FM patients and age-matched controls were assessed in controlled work circumstances. Participants undertook four one-handed tasks with different repetitive actions. Tasks included different ergonomic risk characteristics of resistance worked against, little action variation and static muscle work. A detailed posture and action analysis was completed to determine the postural and repetitive action characteristics of each undertaken task.

Results indicated that in FM patients, there was a clear increase in pain that was associated with performance of *repetitive tasks* and that the increase varied with the nature of the actions required by the task. The location of the pain was associated with the body part used. It was hypothesised that alternating actions and/or postures may vary the sensory stimuli at the dorsal horn cells. This may increase time intervals between stimuli at dorsal horn cells, and an increase in sensitivity of those cells may be less. This would mean that pain levels would not increase during the period of muscle and joint activity [363]. Interestingly, the *change* in pain sensitivity did not differ between the FM patients and controls. Instead *the actions* required by each task influenced the amount of pain sensitivity change. Farrell and Littlejohn's [363,368,369] research demonstrated how specific risk factors can be investigated under controlled circumstances.

These first steps by Farrell and Littlejohn highlighted the strong need for further elucidation of the relationship between ergonomic specific risk factors and clinical variables characteristic of RPS and FM. The specific ergonomic risk factors of *static posture* and task actions (particularly *repetitive actions*) have been identified previously as important for these pain syndromes by Liedburg, Henriksson and others [2,91,92,361] and important risk factors for musculoskeletal disorders in the ergonomic literature (see Ch. 2 Sec. 2.1.1). The association between these ergonomic risk factors and clinical characteristics of RPS and FM (particularly pain sensitivity) is investigated in this chapter.

4.2 OBJECTIVE AND HYPOTHESES

An experiment was undertaken to examine the association between specific work risk factors (identified from the ergonomic literature) and pain variables. The objective of

the experiment was to assess prospectively the contribution of poor static and non-static cervical postures, combined with repetitive arm actions, to the development of abnormal function of the neck, changes in the sensitivity of the pain system, and other clinical features characteristic of RPS.

The experiment aimed to test two main hypothesises:

1. that persistent nociceptive afferent stimulus from cervical spinal structures, and muscles, tendons and joints in the upper limbs (as a consequence of the postural load placed on these structures) could influence the function of the nociceptive system, and

2. that dysfunction of the nociceptor rich deep somatic spinal region would be an effective driver of central pain modulation changes.

To test these over-arching hypotheses, the following specific hypotheses were tested:

Time: start vs end of performance of computer-based tasks	
$H0_1$-A	There would be no change in the pressure pain threshold (*PPT*), or pain sensitivity, at the tender points, control points or at the cervical spine after undertaking two four-hour computer-based work sessions with poor ergonomic characteristics.
$H0_1$-B	There would be no change in the *self-reported body-part discomfort* after the two four-hour computer-based sessions.
$H0_1$-C	There would be no change in the *cervical range of motion (ROM)* after the two four-hour computer-based sessions.

Neck-status: neck-static vs neck-mobile	
$H0_2$-A	The *PPT* at the *tender points* and *control points* would not significantly decrease after performance of the task that had a static cervical spine posture (the *neck-static* measurement session), as *compared with* the task that had more dynamic work actions in the cervical spine (the *neck-mobile*

	measurement session).
$H0_2$-B	The *PPT* in the *cervical spine* would not significantly decrease after the neck-static measurement session, as compared with the neck-mobile measurement session.
$H0_2$-C	The *self-reported body-part discomfort* would not significantly increase after the neck-static measurement session, as compared with the neck-mobile measurement session.
$H0_2$-D	The *cervical ROM* would not significantly decrease after the neck-static measurement session, as compared with the neck-mobile measurement session.

4.3 MATERIALS AND METHODS

4.3.1 EXPERIMENTAL DESIGN

This intervention experiment had a single-factor design with repeated measures. 'Neck Status' was an independent factor with two levels: *'neck-mobile'* and *'neck-static'*. All participants were tested under both levels of Neck Status. At each Neck Status measurement session, participants were tested at intervals of one-hour for most of the dependant variables. Participants were randomly assigned to a neck-mobile or a neck-static session.

Ethics approval was given for this research prior to commencement from the Swinburne University of Technology, Human Research Ethics Committee. App. H shows the ethics approval provided from this committee.

4.3.2 EXPERIMENTAL PROCEDURE

Participants undertook two simulated work sessions, where they were required to undertake computer-based tasks in body positions of poor posture. The sessions were of four hour duration. The measurement sessions were conducted one week apart to avoid possible experimental carryover effects. At each measurement session participants played several computer games at a customised workstation, on a personal computer.

Electromagnetic tracking system (ETS) sensors were attached to participants to monitor their movement throughout the sessions. The computer games were operated by a standard computer mouse with the right hand; there was no keyboard operation. The computer games are described in detail in Sec. 4.3.5.5.

The workstation was adjusted for each participant, based on their own body dimensions, to ensure that the angles of the anatomical segments (i.e. the posture) was similar for each participant at the start of each measurement session. The workstation layout is shown in Figure 4-1 and Figure 4-2. Figure 4-3 shows a participant at the computer work station, with the Fastrak sensors attached. The workstation dimensions are described below in Sec 4.3.7 and the ergonomic risks associated with this layout are discussed in Sec 4.4.

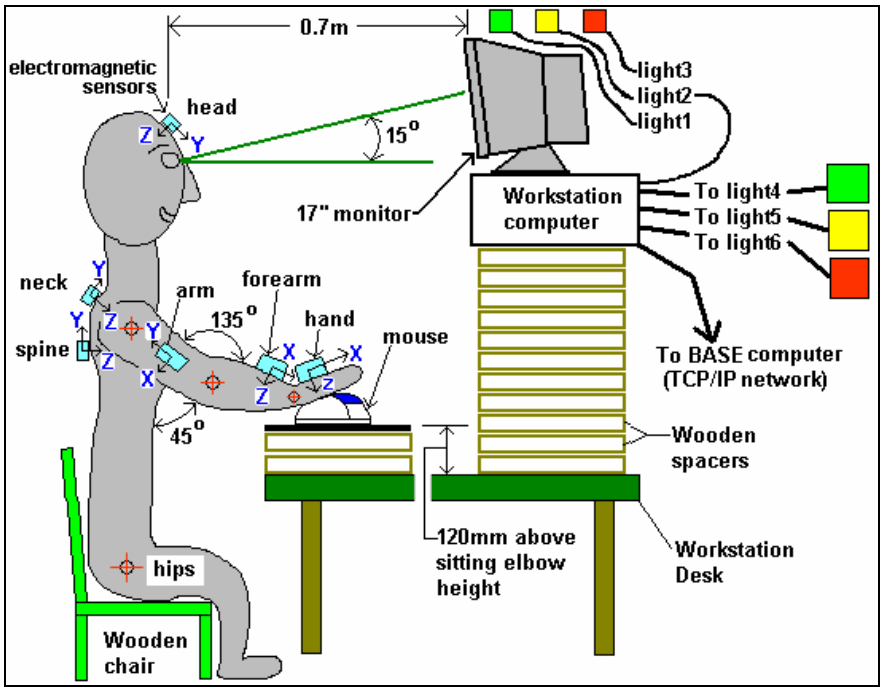


Figure 4-1 – Computer workstation layout at the start posture with the coordinate axes of the electromagnetic sensors.

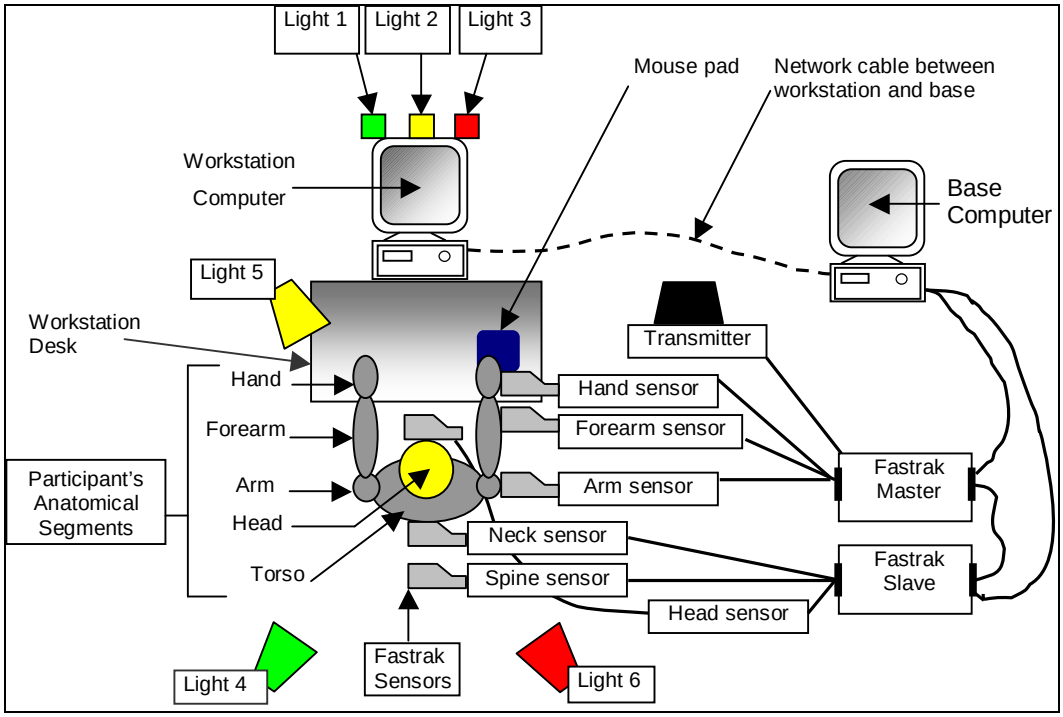


Figure 4-2 – The computer workstation and base computer layout.

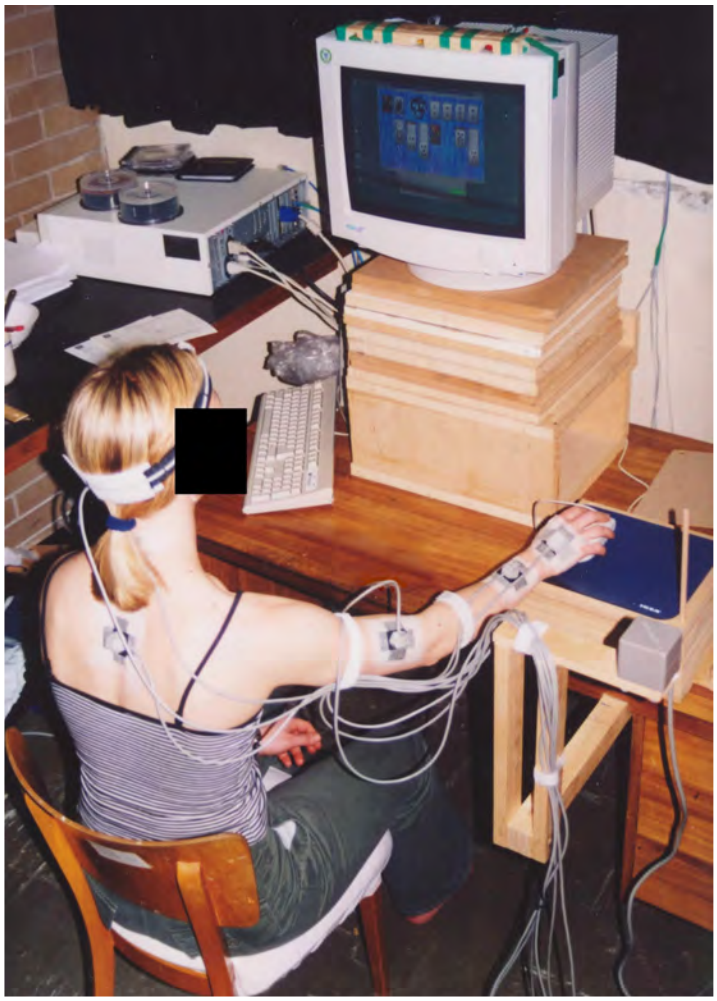


Figure 4-3 – Photo of participant playing computer games with the six Fastrak sensors attached.

The workstation layout was modified to dimensions that were contrary to recommendations from the ergonomic scientific literature. The objective of the workstation arrangement was to place the participant in a 'poor' or 'unnatural posture', which was *slightly* greater than recommended workstation layouts. It was *not* the objective of this experiment to place participants in an 'extreme' posture that deviated greatly from recommended ergonomic postures. Workstation dimensions were usually adopted from the maximum, or just greater than the maximum, recommended ranges for workstation dimensions. The selected workstation sought to achieve a balance between the experimental objective of achieving change in the dependant variables due to the postural load, and the wellbeing and safety of participants. The workstation dimensions are discussed in Sec. 4.3.7. As a safety precaution, participants were advised at the beginning to take a break from the given tasks or cease testing altogether if the discomfort became too great. However, no participants requested a break during testing.

Six coloured lights were placed strategically around the seated participant. Lights one, two and three (green, yellow and red respectively) were placed on top of the workstation monitor, directly above the participant's line-of-sight. Lights four, five and six (again, green, yellow and red respectively) were placed out of the participant's line-of-sight. Light four was placed above head height and behind the participant, on the left side. Light five was placed under the workstation desk, also out of line-of-sight. Light six was similarly located to light four, but behind the participant's right side. About every 70 seconds the workstation computer randomly turned on a light, paused the computer games and asked the participant to identify and record which light had been turned on. The operation of the lights and the recording of which light was on is discussed in Sec. 4.3.5.5.

The placing of the lights was crucial in differentiating the neck-static from the neck-mobile session. In the *'neck-static'* session, only lights one to three were operated. Because lights one to three were directly in the line-of-sight, participants did not need to move their head to identify which light had been randomly turned on. In contrast, during the *'neck-mobile'* session, only lights four to six were operated. Lights four to six were strategically placed in difficult-to-see locations. To observe lights four and six, participants were required to significantly rotate the head and neck. To observe light five, participants were required to significantly flex the head and neck. *The static and*

non-static nature of the head and neck during the once a minute light identification task constituted the only difference between the two measurement sessions.

The dependant variables were assessed before, during and after testing. Before commencing, measurements were taken of the participant's pressure pain threshold (PPT) in the neck and at specific musculoskeletal sites, their passive cervical ROM, and other self-reporting instruments (including a body-part discomfort questionnaire). These measurement variables are described in Sec 4.3.5. During the four-hour measurement sessions, small breaks were taken every hour so that participants could complete a body-part discomfort questionnaire. The PPTs at specific musculoskeletal sites were also measured at the half-way break (2 hours). At the conclusion of each four-hour measurement session, all dependant variables were assessed again.

4.3.3 PARTICIPANTS

To reduce effects of other variables on the results only young, healthy females were invited to participate in the experiment. Fifteen asymptomatic young female participants were measured, with the following general characteristics:

- The average age of participants was 24.5yrs (with a standard deviation of 2.1yrs).
- Most participants were engaged in full-time employment in an office environment, spending a majority of their work time engaged at a computer desk. Three participants were tertiary students.

Participants were required to have no major neck and headache pain (and no previous history of neck or headache pain) and no internal metallic objects or pacemakers.

4.3.4 EXAMINER

The author undertook measurements of all instrument based dependant variables.

4.3.5 EQUIPMENT AND MEASUREMENT VARIABLES

4.3.5.1 PRESSURE ALGOMETRY

The *pain threshold* is defined as the minimum amount of stimulation that reliably evokes a report of pain [370]. *Pressure algometry* is a method for the *quantification of tenderness* [371,372]. Pressure algometry involves application of a mechanical pressure

for the assessment of *tenderness* or *pain sensitivity to pressure*, which is expressed quantitatively by the *pressure pain threshold* (PPT) [371]. The PPT is defined as the minimum pressure that induces pain or discomfort [371,373,374]. The PPT value is attained by increasing the applied pressure until, at a certain critical level, the quality of the sensation produced changes to one where pain is first felt [69]. This assessment method has been used previously as an assessment tool in ergonomic investigations [2,375-377] [141,363,368,375,377,378]. Pressure algometry has been shown to have good intra-examiner [379,380] and inter-examiner [377,381-384] in different regions of the musculoskeletal system.

Pressure algometry may provide important information about both the underlying tissue at the measured site and the nociceptive system; increased tenderness may reflect primary or secondary mechanisms depending on whether it originates in tissue that has been damaged (primary) and/or in normal tissue that may be neuroanatomically related to the area of damage (secondary) [385]. However, it is difficult to establish whether tenderness is a result of primary (peripheral) or secondary (central) mechanisms or a combination of both [55,385-387]. For this reason, control determinations from nonaffected, extra-segmental areas are important [387].

There is considerable variance in PPT values between healthy individuals [375,377,380,388-390] and absolute values are impossible to give as normal values [388]. Because of the variability between persons, pressure algometry has been described as a good device for measurement of tenderness when a participant acts as their own control [377,391]

Tender points (TePs) are regions of mechanical sensitivity at specific anatomical regions of the human body. Compared with surrounding tissue, they are a region of localised tenderness to mechanical pressure [101] and represent areas of mechanical hyperalgesia [185]. TePs are defined as hypersensitive if an applied force of approximately four kilograms elicits pain [101]. Many of the TePs sites involve musculotendinous sites that are normally endowed with a rich supply of nociceptors, perhaps explaining tenderness at these sites among healthy individuals [105,392]. TePs do not display polymodal increased sensitivity; they are only more sensitive to mechanical pressure [287].

Tender points may simply reflect areas of the musculoskeletal system that are most densely supplied with receptors for noxious and non-noxious stimuli [185]. A possible pathogenetic mechanism for hypersensitive TePs is that they represent areas of primary and secondary hyperalgesia [185] due to peripheral and central pain mechanisms.

Pressure algometry was applied in this investigation at tender points and control points in all subjects, at multiple locations using the electronic PPT meter described in App. F.

4.3.5.1.1 Tender point (TeP) and control points (CP) pressure pain thresholds

The pressure pain threshold (PPT) was measured at six bilateral locations (twelve in total) on each participant. For each measurement, pressure was applied at the specific location until the person indicated that the pressure was beginning to become painful. The highest amount of applied force was recorded as the PPT, in Newtons. The maximum applied force at the TeP and CP locations was 120N (this was the limit of the accurate range of the force algometer). If a participant's PPT was not reached before this value, then that location was recorded as 120N. Eight tender points (TeP) [101] and four control point (CP) [33] locations were assessed. These are described in Table 4-1 and Figure 4-4. These locations were selected for measurement because they were easily accessible.

All TeP and CP PPT measurements were only measured once per session at each site. Current research practice is to test three times consecutively and take the average of the three results an the value. This was not applied due to the large number of sites tested within each participant and the inconvenience to the participant. However, in the cervical spine locations, sites were measure three times consecutively and averaged. This is explained below.

Quadrants were defined for the TeP and CP locations. PPT measurement sites were either in the upper left, upper right or lower body quadrants.

Change in pain sensitivity at locations that are not tender points may be indicative of more generalised pain sensitivity changes, suggesting involvement of the central pain system. For this reason the control points were included for PPT measurement.

Measurements were conducted with the participant in the seated position. Measurements were conducted three times during a measurement session:

- time 1 at the start of the measurement (zero hours),
- time 2 half way through the session (two hours), and
- time 3, the end of the measurement session (four hours).

Measurement location	TeP or CP	Quadrant	Description
RThb	CP	Upper right	Right hand thumbnail
REpi	TeP	Upper right	Lateral epicondyle: 2cm distal to the right lateral epicondyle
RDel	CP	Upper right	Mid right deltoid
RTra	TeP	Upper right	Trapezius: at the midpoint of the right upper border
RSup	TeP	Upper right	Supraspinatus: at origins, above the scapula spine near the right medial border
LSup	TeP	Upper left	Supraspinatus: at origins, above the scapula spine near the left medial border
LTra	TeP	Upper left	Trapezius: at the midpoint of the left upper border
LDel	CP	Upper left	Mid left deltoid
LEpi	TeP	Upper left	Lateral epicondyle: 2cm distal to the left lateral epicondyle
LThb	CP	Upper left	Right hand thumbnail
RKne	TeP	Lower	Knees: at the right medial fat pad proximal to the joint line
LKne	TeP	Lower	Knees: at the left medial fat pad proximal to the joint line

Table 4-1 – Description of tender point and control point locations.

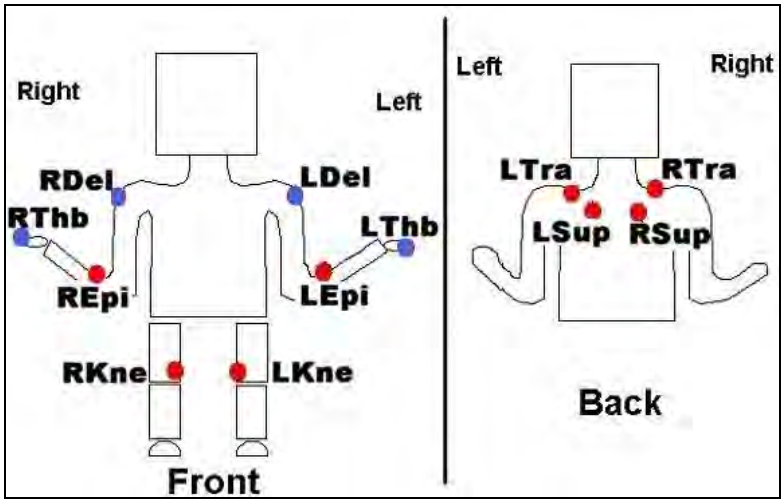


Figure 4-4 – Tender point (red dots) and control point (blue dots) pressure algometry measurement locations

4.3.5.1.2 Cervical spine pressure pain thresholds

The PPT was also assessed at twelve measurement locations at the postero-lateral aspect of the cervical spine. Ten measurement locations, five on the left (beginning cephalically, locations L1 [upper] to L5 [lower]) and five on the right (locations R1 [upper] to R5 [lower]). These are described in the next section.

The lowest two measurement locations were at the upper trapezius on the left (TL) and right (TR) sides. The TL and TR measurement locations were positioned midway between the acromion process of the scapula and the lateral neck at C6 level, and 3 cm posterior from the superior edge of the upper trapezius belly [393]. The trapezius measurement locations were included in this investigation, because it was likely that this muscle was active during actions completed with the right arm. This muscle is involved with shoulder actions and head and neck motions [394].

Each measurement location was assessed consecutively three times and the average of the three assessments was derived and used in statistical calculations.

Pressure algometry measurement of the cervical locations required that the participant be in a prone position. This precluded measurement of these locations during the posture experiment because the participant was bound to the workstation desk with the ETS sensors. Therefore, the cervical and trapezius locations were assessed only before (time zero) and after (time four hours) each measurement session, not during the session.

For each measurement, the highest amount of applied force was recorded as the PPT, in Newtons. The maximum applied force at the cervical locations was 50N. If a participant's PPT was not reached before this value, then that location was recorded as 50N. When a participant's PPT was reached, the measurement was ceased immediately.

4.3.5.1.2.1 Locating the cervical measurement sites

Manual therapists have difficulty in locating specific spinal levels and misidentification of exact vertebral level can be a major source of error [395-397]. Studies investigating the accuracy of site location in the cervical region are not available [398], highlighting the need for easily identifiable landmarks. The lack of studies investigating the accuracy of site location in the cervical region [398] necessitated a standardised methodology to assist with measurement site location. The standardised measurement location protocol did not verify which structures of the cervical spine were measured with PPT. Instead, it was hoped that the standardised protocol would reduce site location variability by assisting in locating similar measurement locations between participants. Only large and easily identifiable landmarks with palpation were used. Easily identifiable landmarks included the mastoid processes, the lateral tips of the transverse processes of the atlas

(C1), the external occipital protuberance (on the skull), the spinous process of the axis (C2) (which is the first one that is palpable inferior to the external occipital protuberance and is also the largest in the upper cervical spine) and the spinous process of the vertebral prominens (normally C7) which is the largest spinous process in the lower cervical spine [399]. Site locations that are not as easily identifiable include the remaining cervical spinous processes and the zygapophysial joints. Location of the zygapophysial joints involves moving the hand approximately 20mm [400] to 25mm [399] lateral from the spinous process of the axis (C2) and palpating to find the joints. The lateral border of the upper cervical part of the trapezius muscle and semispinalis capitus lying deep to it provide an anatomical reference for the location of the cervical zygapophysial joints which lie deep to these muscles [401]. The splenius capitus lies superficial to semispinalis capitus (which overlays the joint [402]) and deep to the upper trapezius [401].

All measurement locations were identified and marked with a non-permanent texta with the participant in a seated position. They were located in the posterolateral aspect of the cervical spine. More specifically one measurement site in the suboccipital region and four measurements between C2 and the C7 in equal increments, on each side (ten measurement locations in total) (see Figure 4-5). Measurement sites were marked with non-permanent marker and lay approximately over the lateral atlanto-axial joints and the zygapophysial joints on the left and right sides of the posterior neck. PPT was assessed in the marked 5 points on each side in a set sequence beginning cephalically. Measurements on the left side were completed before measurements on the right commenced.

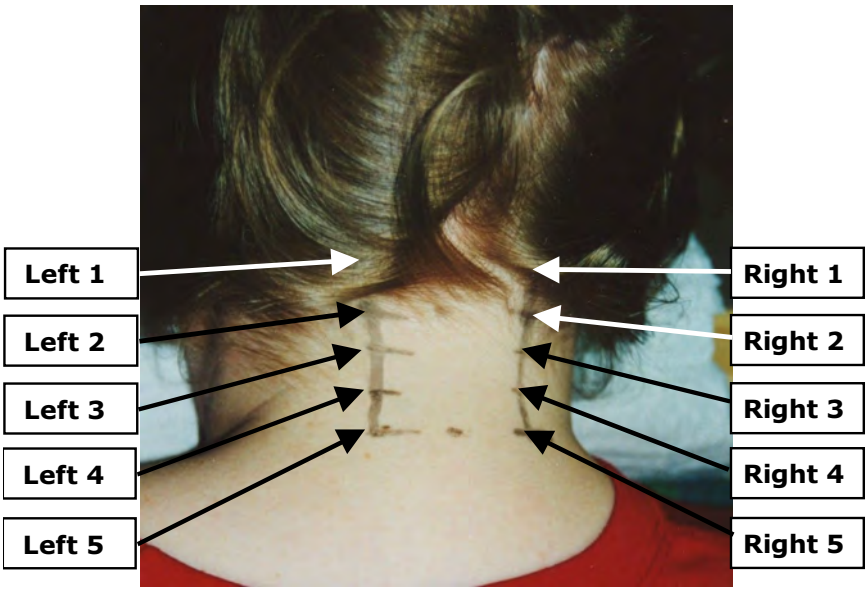


Figure 4-5 – Cervical spine marked for PPT measurement. The participant was lying prone.

The second measurement location was located initially and marked with non-permanent texta (location L2 on the left and R2 on the right). The easily palpable spinous process of the axis (C2) was located and lateral to this by approximately 25mm [399] the lateral border of the upper cervical part of the trapezius muscle and semispinalis capitus lying deep were located. This position was marked on the left and right sides and was approximately over the zygapophysial joints of C2-C3. The distance from the spinous process of the axis to the marked measurement locations was recorded. The most inferior measurement locations were positioned at the vertebral prominens (C7) on the left (location L5) and right (location R5) sides at same lateral distance as used at C2. This measurement location was approximately over C7-T1 zygapophysial joints.

A vertical line was drawn from the marked measurement locations (left and right) at the level of the axis to the level of C7. This line was split into 3 equal segments and marked accordingly with the middle marks representing the third and fourth measurement locations at approximately C3-C4 and C6-C7 zygapophysial joints, respectively (locations L3 and L4 on the left side and R3 and R4 on the right). It is acknowledged that during measurement at these locations, other tissues other than the zygapophysial joints would have been be stimulated during assessment.

To locate the first and most superior measurement locations (location L1 on the left and R1 on the right) in the sub-occipital region, a flexible ruler was placed across the posterior aspect of the head from the external occipital protuberance to the tip of the mastoid process. Inferior to the ruler, the PPT device was placed. The device was placed

along the ruler at the intersection of the ruler and the marked line that purportedly represented the position of zygapophysial joints lying inferior to the ruler. This placed the PPT measurement device tip at approximately the left and right lateral atlanto-axial joints.

4.3.5.2 BODY-PART DISCOMFORT SCORES

Participants indicated areas of discomfort on a body-map discomfort diagram (see Figure 4-6 and Table 4-2) with predefined divisions [403]. A posterior view of the whole body was also given. The level of discomfort experienced for each area marked on the body-map diagram was measured on a 100mm visual analogue scale (VAS) – described below. The VAS's were anchored with 'No Discomfort' at 0mm and 'Very High Discomfort' at 100mm. A thin vertical line at 50mm was placed on the mid-point of the scales. Participants drew a cross or line along the horizontal scale to indicate the level of discomfort (this VAS arrangement has been used previously by others in ergonomic investigations [151]). Participants completed the body-part discomfort questionnaire five times during a testing session at intervals of 1 hr: time 0 (start of testing session), time 1 (1 hour), time 2 (2 hour), time 3 (3 hour), time 4 (4 hour and end).

Drury and colleagues [404-406] used their body-part (BP) discomfort results to derive 'whole of body region' scores, including body-part discomfort frequency (BP Frequency) and body-part discomfort severity (BP Severity). The BP Frequency was calculated as the number of body-parts *rated greater than zero* and BP Severity the average of *all non-zero ratings*. Liao and Drury [404] also calculated the BP Frequency Severity, which was derived by multiplying the BP Frequency by BP Severity. These measures were used in the current investigation.

Body-part Code	Description
EY	Eyes
RN	Right neck
LN	Left neck
RS	Right shoulder
LS	Left shoulder
RUA	Right upper arm
LUA	Left upper arm
RE	Right elbow
LE	Left elbow
RUF	Right upper forearm
RLF	Right lower forearm
LUF	Left upper forearm
LLF	Left lower forearm
RW	Right wrist
LW	Left wrist
RT	Right thumb
LT	Left thumb
RH	Right hand
LH	Left hand
UB	Upper back
MB	Middle back
LB	Lower back
UL	Upper legs
LL	Lower legs

Table 4-2 – Description of body-map parts.

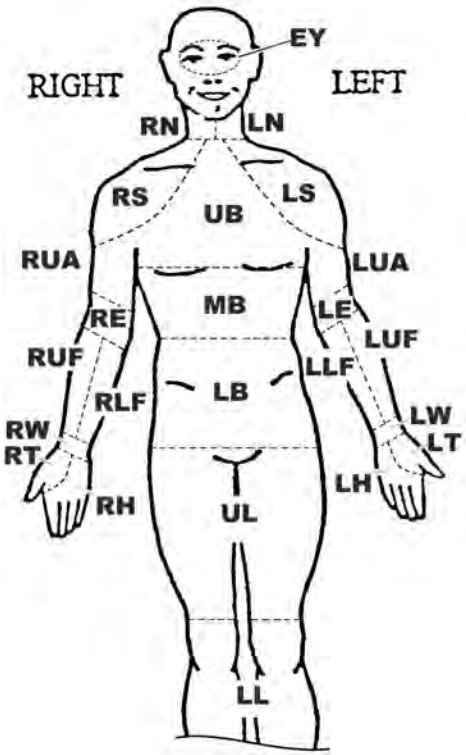


Figure 4-6 – Body-part discomfort map.

The Visual Analogue Scale (VAS) consists a horizontal line with two endpoints labelled ‘no pain’ and ‘worst ever pain’ (or similar verbal descriptors) [407]. The VAS is a reliable and valid method for rating the intensity of pain [408] and changes in rating are likely to be real changes of opinion [409]. Ten, 15 and 20cm VAS’s are less variable than a 5cm VAS and a choice of which length to use is a matter of convenience [409]. The 10cm VAS is the most commonly used length [407]. The VAS is a suitable method

of recording a participants experience of pain, including severe pain [409], and should be used to measure present pain [410]. The VAS is a ratio scale measurement that is preferable to interval scale data as a ratio scale allows meaningful statements about the magnitude of pain sensation [408]. The VAS has demonstrated good correlation with Borg's Category Ratio Scale [410]. The VAS reliably measures and provides meaningful information about experimentally induced pain or chronic (clinical) pain [408] and is the most commonly used numerical scale, with widespread use both clinically and experimentally [411].

VAS scores have high correlations with other measures of pain and with self-efficacy for pain, physical functioning, fatigue, and stiffness in FM patients. The correlations between the VAS and fatigue and stiffness were better than those of other pain measures, and may be the most useful measure of pain with patients with FMS [412]. In addition, an advantage of the VAS compared with ordinal scales is that this measure has ratio scale properties. If two different stimuli intensities are presented, when one of them is double the amount of the other, the higher VAS score should be double that of the low score [413].

Because of the good reliability and pain measuring ability of the VAS, and for other reasons given above, the VAS was chosen for use as a measurement instrument in this experiment.

4.3.5.3 PASSIVE CERVICAL RANGE OF MOTION (ROM)

Cervical ROM measurements were conducted before and after the four-hour computer based tasks. Electromagnetic tracking sensors were attached to the head and neck and were used to measure passive cervical ROM. The head and neck sensor mounting locations are described in Table 4-3. Several anatomical locations were measured about the anatomical segments of the head and neck to develop local coordinate reference systems for the head and neck. A joint coordinate system (JCS), similar to that reported for the knee by Grood and Suntay [356], was used to describe the motion between the head and neck coordinate systems. The JCS described the clinical rotations of the head *relative* to the neck (see App. A, Sec. A.3).

The use of two sensors to measure motion of the neck and the head differs from the methodology described later in Chs. 6 and 7. One sensor was used in the later chapters,

and hence, movement of the upper thoracic spine was included in the ROM results obtained in these later investigations. In this chapter, the use of two sensors to measure cervical ROM excludes potential contribution from the upper thoracic segments. This mounting arrangement was similar to previous spinal ROM investigations [414-417].

The author conducted all measurements. The author has demonstrated acceptable inter- and intra-reliability for cervical ROM measurements with an ETS (see Ch. 5, Sec. 5.5). In addition, the FWAP-Link system has demonstrated acceptable accuracy in measuring movements of the head (see Ch. 3, Sec. 3.5).

Participants were measured in the seated position on an upright wooden chair with feet flat on the floor and the lower back touching the back of the chair. Hands and forearms were placed in a relaxed position resting on the participant's thighs. All head and neck jewellery were removed to eliminate any potential interference with the ETS.

Participants were seated in front of a mark on the wall, at approximately eye level, upon which they were requested to focus to attain a neutral starting posture. There was no real-time output from the ETS to assist with this. It was assumed between measurements that participants could attain a similar neutral position by focusing on the same mark on the wall. Whenever a neutral position was required the examiner asked the participant to focus on the mark on the wall.

For recording a ROM position, the examiner used a small button on a long lead and pushed the button to record a ROM position. The examiner standing behind the seated participant started with a neutral posture and a recording of the participant's head orientation was made. The examiner then guided the head to full right rotation on the basis of end-feel [418]. This position was determined by the examiner taking the head to the limit of normal passive motion where a firm resistance was felt [418-420]. A recording of this head position was made by pushing the small button. The head was then moved from full right rotation to full left rotation and again the position was recorded. The head was returned to the neutral posture and the same measurements were made again but in reverse order, i.e. neutral, left rotation and right rotation. The same procedure was used for lateral flexion and for flexion and extension; a total of eighteen ROM measurements. This measurement methodology produced two measurements of

each measurement plane per assessment. The two values in each plane were averaged for analysis purposes. Warm-ups did not occur.

4.3.5.4 SELF-REPORTING INSTRUMENTS

Participants completed a general questionnaire before commencing the first testing session. Participants indicated their age, areas of the body where they had suffered frequent pain over the past three months, and the number of hours per week that they undertook significant manual activities, maintained static postures and exercised. On the questionnaire there was also a picture of the body broken down into a total of eighteen segments where participants could indicate where they had experienced frequent pain over the past three months. Six main areas were available for selection (neck, front chest, upper-back, lower-back, arm/shoulder, and leg/buttock), which were further split into left, middle and right sides of the body. A 'total region count' was derived by adding the number of regions indicated as painful.

In addition, participants completed the following questionnaires: Neck Disability Index (NDI) [421], Profile of Mood States (POMS) [422] and Spielberg State Anxiety [423]. These are described below.

Before commencing the second measurement session, participants completed a smaller questionnaire that only included the NDI, POMS and the Spielberg. The pain section was not repeated because it was assumed that in only a week there would not have been a significant change in the areas of the body which were painful.

4.3.5.4.1 Neck Disability Index (NDI)

The Neck Disability Index (NDI) is a 10-item scaled questionnaire that assesses disability and other musculoskeletal pain conditions, and the effect of the condition on activities of daily living [421]. This instrument was designed specifically for patients with neck pain and it assesses the effect of this disability upon work and lifestyle activities [424]. The NDI was based on other questionnaires, including the Oswestry Low Back Pain Index. At the time of development, no instrument existed that assessed the effect of neck pain on activities of daily living. The NDI was tested on a small sample of neck pain sufferers with good reliability, good comparison with pain

measures, internal consistency and sensitivity to the levels of severity of complaint [421].

Further investigations with the NDI on larger participant populations revealed high internal consistency (Cronbach alpha 0.92), no demonstrable response set bias, unidimensional results and equal weight contribution from each item [424]. The NDI was related positively to the level of pain intensity measured by a VAS [424]. The NDI possessed stable psychometric properties and provided an objective means of assessing the disability of patients suffering from neck pain [424].

The NDI is one of few self-reporting instruments that specifically assess neck disability. This fact and other factors given above influenced the selection of the NDI as a measurement variable in this experiment.

4.3.5.4.2 Psychological assessment tools

Littlejohn [425] reviewed instruments available for psychological assessment of particular characteristics believed to be relevant to FM. Two characteristics reviewed included depression and anxiety: *depression* is an expression of distress or unhappiness including feelings of worthlessness, self-depreciation, listlessness, apathy and guilt. *Anxiety* represents extreme uneasiness of mind or unfocused fear characterised by restlessness, nervousness and tension. The Profile of Mood States (POMS) questionnaire may measure depression and anxiety characteristics and the Spielburger State-Trait Anxiety Inventory (STAI) may measure anxiety characteristics. The Spielburger STAI has been used to investigate psychosomatic aspects in FM and rheumatoid arthritis patients [426].

These two instruments were selected for use in investigations conducted in Chs. 5 and 7 because, as discussed in Ch. 2, psychological factors may be of importance to FM and RPS.

4.3.5.4.2.1 Profile of mood states

The *Profile of Mood States* (POMS) was developed as a rapid and economical method of assessing transient fluctuating affective states. POMS measures six identifiable mood or affective states: *Tension-Anxiety*, *Depression-Dejection*, *Anger-Hostility*, *Vigour-*

Activity, *Fatigue-Inertia* and *Confusion-Bewilderment*. POMS consists of sixty-five different adjectives describing mood status. For each adjective the participant marks a response on a five-point scale that ranges from ‘not at all’ to ‘extremely’. Participants are asked to include the ‘past week including today’ in the ratings to emphasize a period both sufficiently long to depict the participants typical and persistent mood reactions to current life situations and sufficiently short to assess acute events. Summing the adjectives defining the factor derives a score for each mood factor. A *Total Mood Disturbance Score* is derived by summing the six primary mood factor scores [422].

Tension-Anxiety is defined by adjective scales descriptive of heightened musculoskeletal tension. The defining scales include reports of somatic tension and observable psychomotor manifestations. *Depression-Dejection* appears to represent a mood of depression accompanied by a sense of personal inadequacy. *Anger-Hostility* appears to represent a mood of anger and antipathy towards others. *Vigour-Activity* is defined by adjectives suggesting a mood vigorousness, ebullience and high energy. *Fatigue-Inertia* represents a mood of weariness, inertia and low energy level. *Confusion-Bewilderment* appears to be characterised by bewilderment and muddle-headedness. The *Total Mood Disturbance Score* (TMD) describes a single global estimate of the affective state of the participant. It can be assumed that the TMD will be highly reliable because of the intercorrelations of the six primary POMS factors [422].

POMS has high internal consistency and acceptable test-retest reliability. Research of different participant groups has demonstrated evidence of the predictive and construct validity. Data pertaining to different participant populations is available. POMS has proved to be a very sensitive measure of the effects of various experimental manipulations on normal and other nonpsychiatric populations [422].

For these reasons, the POMS psychological assessment tool was relevant in examining potential mood state differences between different participant groups, based on pain status, as reported in Ch. 6. In addition, the POMS tool helped to identify potential mood state differences in participants that were engaged in work tasks with poor ergonomic performance, as reported in Ch. 4.

4.3.5.4.2.2 Spielberger: State-Trait Anxiety Inventory (STAI) for adults

Personality states may be regarded as temporal cross sections in the stream of life of a person and emotional reactions as expressions of personality states. An emotional state exists at a given moment in time and at a particular level of intensity [423]. Anxiety states are characterized by subjective feelings of tension, apprehension, nervousness, and worry, and by activation or arousal of the autonomic nervous system [423].

The STAI has high and low test-retest reliability for trait and state-anxiety respectively and high internal consistency for both scales [423]. The state-anxiety scale has high criterion validity and excellent internal consistency [425]. The STAI comprises 40 separate self-report questions for measuring state and trait anxiety. Each item is given a weighted score of 1 (‘not at all’) to 4 (‘very much so’) where a rating of 4 indicates the presence of a high level of anxiety. The first 20 questions refer to state-anxiety that evaluate how participants fell ‘right-now’ and the remaining 20 questions refer to trait-anxiety that assess how participants ‘generally’ feel. Trait-anxiety refers to relatively stable individual differences in anxiety proneness or differences between people in the tendency to perceive stressful situations as dangerous, and to respond to such situations with elevations in the intensity of their state-anxiety reactions. The stronger the anxiety trait, the more probable that the individual will experience more intense elevations in state-anxiety in a psychologically dangerous or threatening situation. The essential qualities evaluated by the state-anxiety scale are feelings of apprehension, tension, nervousness and worry. Scores of the STAI state-anxiety (STAI-S) scale increase in response to physical danger and psychological stress and decrease as result of relaxation training. The STAI trait-anxiety (STAI-T) has been proven useful for identify persons with high levels of neurotic anxiety and has been used widely in assessing clinical anxiety in research participants. Psychoneurotic and depressed patients generally have high scores on this scale. The STAI questionnaire has been used extensively in research and clinical practice [423].

The combination of the POMS and the STAI assessment instruments, enabled specific analysis of anxiety in participants in patients with chronic musculoskeletal pain, and in those without.

4.3.5.5 WORKSTATION AND BASE COMPUTERS

4.3.5.5.1 Workstation computer

4.3.5.5.1.1 Monitor

The workstation computer monitor was placed in front of the participant on the workstation desk. Participants played computer tennis, a tanks game, an air-fighter game and solitaire on the workstation computer. Each game was played twice during the measurement sessions, but the order of playing was randomised. The interactive games required constant visual observation and fast, repetitive finger actions over the mouse button to keep up with game requirements. Each time the mouse was clicked the workstation sent a message to the base computer via the network. The base computer recorded this in the data file at the time of the mouse click. These games are shown in Figure 4-7.

Figure 4-7 – Example computer games played by the participants

4.3.5.5.1.2 Lights

The workstation computer also controlled lights one to six; approximately once every *70 secs* it would turn on one light (the *'light-on event'*). The participant was required to identify which light was on and record this on the workstation computer by raising their

right arm. This would cause a small blue dot on the workstation computer screen to follow the movements of the participant's hand. The participant would attempt to place this dot over a round circle, of the same colour, on the monitor. The participant then clicked the mouse to complete the recording of which light was on. This is shown in Figure 4-8. The entire process took approximately *10 secs*. If a correct selection was made, the light went off and the participant continued playing computer games. If an incorrect selection was made, a miss was recorded and the workstation computer would direct the user to try again. The time between the participant turning a light off and the next light-on event was exactly *60 secs*.

When a light came on or was turned off by the participant, the workstation sent this information to the base computer, where it was recorded in the data file. When a light was on, the base computer sent the coordinates of the hand ETS sensor to the workstation computer via the network cable. The workstation computer used this information to move the dot on the monitor to show hand movement to the participant.

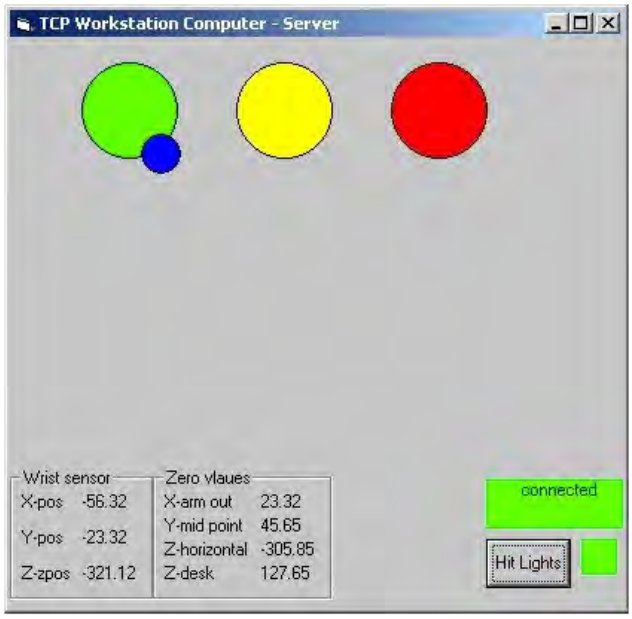


Figure 4-8 – Example of participant responding to the light-on event. The blue dot followed the motion of the right hand and has been placed over the green light 1

To move the dot over the colour circles, participants were required both to raise their hand above the height of the acromion process and to keep their forearm extended. If the hand was not far enough forward, the dot stopped moving and changed colour. This indicated to the participant that the hand had to be moved forward. This forced the participant into a simulated poor posture with an extended and controlled arm reach action.

Arm movements above the height of the acromion process have been associated with shoulder pain and tiredness in the shoulder, and stiffness in the neck [427]. Elevation of the shoulders from a work-surface above elbow height may increase the load level on the upper trapezius [428]. The upper part of the trapezius muscle, which originates in the neck, is an important muscle in the suspending mechanism of the shoulder. The descending part of the trapezius is one of the main muscles preventing downward rotation of the scapula when the arm is elevated [429]. Activity in the trapezius has been found to correspond closely to the shoulder joint load; a connection between repetitive arm flexion and residual neck pain in the descending part of the trapezius has been made [430-432].

4.3.5.5.2 Base computer

The base computer operated all other electronic equipment used for measurement purposes. These instruments included the master and slave Fastrak electromagnetic tracking system (ETS) units and the pressure pain threshold (PPT) measurement device (described in Ch. 6). The ETS was used for posture measurement and passive cervical ROM assessment.

For posture measurement, the base computer used custom written software to control the two Fastrak electronic ETSs. All communication with the ETSs was via the computer communication ports at a 19,200-baud rate. The software used the information provided by the six ETS sensors to determine the posture of the participant in real-time. This was displayed on the base computer as FWAP-Link angles in numerical format. The FWAP-Link angles could also be displayed graphically. These were displayed in real-time and followed the posture and actions of the participant. Timers were incorporated with the user interface. They indicated to the user how long each game had been played and when to pause the experiment for each hourly break. The base computer interface is shown in Figure 4-9.

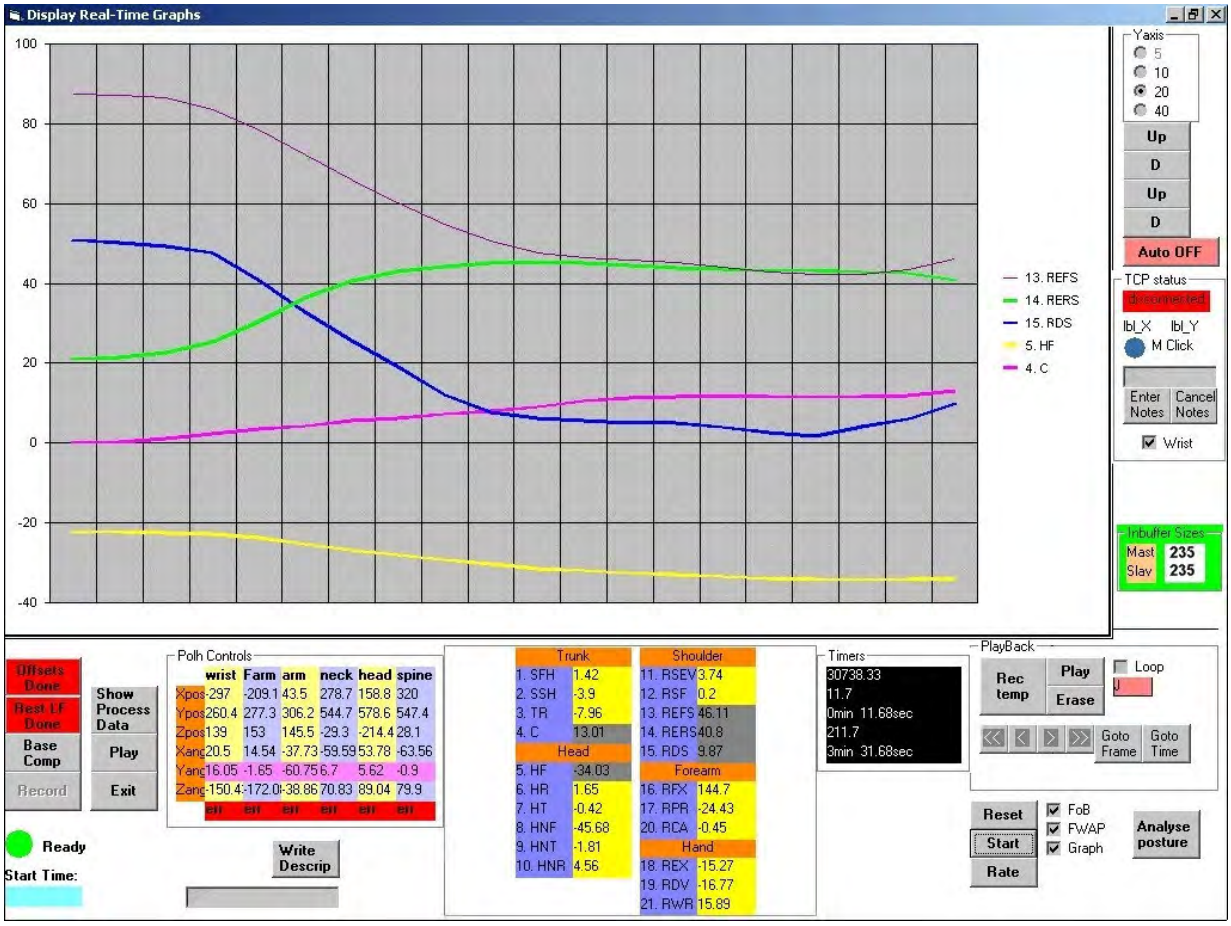


Figure 4-9 – Graphical and numerical user interface with the Fastrak electromagnetic tracking system. This program controlled and recorded all data from the Fastrak sensors.

The anatomical locations were measured before posture measurements took place. These three-dimensional (3D) locations were used to develop each segment's local reference system. An ETS sensor was mounted onto a stylus, the tip of which was placed at each anatomical location. A remote button connected to the base computer was used to activate measurement of the stylus tip. Each anatomical location was measured five times, with the average recorded to a database.

The author developed all code to conduct the investigation using Visual Basic (version 6.0) and a small proportion of Visual Designer[8] (version 3.0). This involved developing several programs to:

- measure the posture of the participants
- to control the workstation and base computers

[8] Intelligent Instrumentation Inc., Tucson, Arizona, USA

- develop the games on the workstation computer
- develop communication methods and triggers between the base and workstation computers
- to convert the ETS data via kinematic geometry to the FWAP-Link angles
- to store data in a database and computer hard drive
- to complete ROM measurements, and
- to complete post measurement statistical functions.

Except for some input to the games, the author completed all programming. In total there were approximately 25,300 lines of code.

4.3.5.6 POSTURE AND ACTION MEASUREMENT SYSTEM: FWAP-LINK

The FWAP-Link system was used to measure and record the posture of the participants. This posture and action measurement system used a Fastrak ETS[9] with six sensors to measure the posture of a participant's anatomical segments (see Table 4-3) at approximately twelve measurements per second. The angles of the trunk, head, cervical spine, upper thoracic spine, arm, forearm and hand were measured. This system is described in Ch. 3, Sec. 3.3 and App. A.

Anatomical Segment	Location Description
Hand	Dorsal surface of hand approximately over the second, third and forth metacarpals
Forearm	Superior surface of forearm, when forearm is oriented in the transverse plane and pronated. Approximately three-quarters of the distance between the elbow and wrist joints, from the elbow.
Arm	Lateral side of arm approximately half way between glenohumeral joint and elbow joint, between triceps brachii and biceps brachii
Head	In the middle of the forehead, above eyebrows
Neck	Over spinous process of C7
Spine	Over spinous process of mid point between T5 and T6.

Table 4-3 – Physical location of the Fastrak sensors on participants

The 3D coordinates of anatomical locations were measured with a sensor attached to a stylus. The anatomical locations of the elbow (mid-point between medial and lateral epicondyles) and the eye were used to determine the number of wooden spacers required to raise the mousepad and monitor, to required heights. The posture of the participant with the arm, forearm and hand held horizontally in front of the participant

[9] Polhemus Incorporated, 40 Hercules Drive, Colchester, VT, USA

was also recorded. This data was used by the workstation computer to guide the participant to turn the lights off as described in Sec. 4.3.2.

The sensors were mounted onto a flexible sensor 'holder'. The holder was constructed of a square piece of 1mm thick rubber, with wooden posts, and four rubber wings extending from the rubber square. When the sensor and 'holder' were placed onto the participant's skin, four pieces of skin tape were laid across the rubber wings. This fixed the sensor to the skin on a flexible 'holder' (see Figure 4-10). An elastic headband was used to mount the head Fastrak sensor onto the forehead. Velcro© was utilised to permit adjustability for different head diameters. This method proved to be a very successful method for securely fixing the sensors to participants for the entire duration of the four-hour measurement sessions.

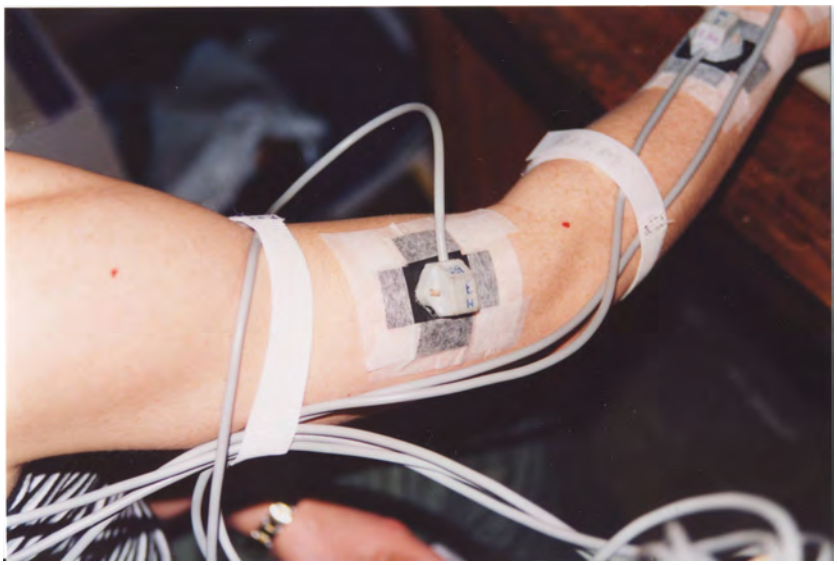


Figure 4-10 – Photo of Fastrak sensors mounted to arm and forearm with custom flexible rubber holders and skin tape

4.3.6 DATA ANALYSIS

A repeated measures analysis of variance (ANOVA) was applied to the dependant variables of posture data, the musculoskeletal sites and cervical PPT, the cervical ROM data and the body-part discomfort scores. Neck status (neck-mobile or neck-static), time (time 0hr, 1hr, 2hr, 3hr and 4hr) and the interaction of neck status and time were independent within factors in the ANOVA. It was assumed that the co-variates of different levels were the same for different pairs of levels. The Newman-Keuls post-hoc analysis method was conducted on significant outcomes. Significant outcomes are described as * $p<0.05$, + $p<0.01$ for the ANOVA and for the Newman-Keuls analysis.

A one-sided test was applied to the factor of neck status, which had only two levels, for the dependant variables of PPT, ROM and the pain visual analog scale (VAS). This halved the *p*-values for these variables, for this factor only. A one-sided test was used because it was hypothesised that the neck status results were directional; it was hypothesised that the neck-static results would be significantly greater than the results from the neck-mobile measurement session.

Pearson product moment correlation coefficients were also determined to examine the inter-relationship within and between the dependant variables of PPT, ROM and VAS scores. Correlations of less than 0.25, 0.25 to 0.5, 0.5 to 0.75, and 0.75 to 1.0 indicated little or no, low to fair, moderate to good, and good to excellent relationships, respectively [433].

4.3.6.1 POSTURE DATA ANALYSIS

4.3.6.1.1 Average posture

The average posture for each participant was determined by analysing the recorded posture during the times when the *lights were off*. The recorded posture was analysed for each light-off period for 50 secs, starting 10 secs after the light-off event, to the following light-on event. The pause of 10 secs before analysis began gave the participant to put the hand back on the mouse pad after the light-off event. The average, standard deviation, and the first, second and third quartiles were calculated for each neck status session (mobile and static) and also for each hour of measurement (time 1 - 4hrs). To explore the spread of each posture code data, a cumulative frequency distribution was determined for each posture code for all participants and each measurement session. Bin widths of 2 deg were used.

During the *lights on periods*, the maximum and minimum posture values for each FWAP-Link code were determined for each participant and then averaged, to examine how far the head, trunk and arm moved during these once-a-minute events.

4.3.6.1.2 Postural changes

The number of postural changes of each FWAP-Link posture code was also determined to gain some insight into the repetitiveness of each segment. The average number of

posture changes and the average time spent in each posture was determined for each 50 secs of posture data between the light-off and light-on event. A postural scale starting at zero degrees (0 deg), with increments of 2 deg, was used to define postural changes. This analysis was similar to postural information reported previously by others [347].

A 'FWAP for Windows©' analysis of one participant for one cycle during a neck-static and mobile session was completed. The MODular arrangement of predetermined time standards (MODAPTS) and posture analysis was completed with the FWAP-Link program described in Ch. 3.

To ensure that each participant had exactly the same recorded time available for the ANOVA, only 18 mins of posture data for each game was included. Four games were played, twice during each measurement session, which resulted in 36 mins of posture data per hour of measurement session. In addition, the Fastrak ETS did not always measure exactly the same number of posture measurements per second. It varied between 9 and 13 Hz. Therefore, the posture data was averaged per second. Only the 50 secs of data between the light-off and on events were used in the ANOVA.

4.3.6.2 PRESSURE PAIN THRESHOLD ANALYSIS

For the musculoskeletal tender point (TeP) and control point (CP) PPT results, the average and standard deviation of each measurement location was determined. A quadrant analysis was also undertaken. The TePs and CPs in the upper body quadrants were grouped together and analysis was undertaken on the combined scores. A total PPT score was also by adding the TeP and CP PPT values for each participant. The percentage change in the PPT score over time at each measurement location was determined by comparing the end PPT value (time 4 hr) with the start value (time 0 hr).

The cervical PPT results were analysed in a similar manner to the TeP and CP PPT results. In addition, the reliability (Intraclass Correlation Coefficient, ICC[2,1]) of the three consecutive cervical PPT measurements was assessed. ICC values between 0.90 to 0.99 were interpreted as indicative of high reliability; 0.8 to 0.89 as good reliability; 0.70 to 0.79 as fair reliability; and less than 0.70 as moderate to poor reliability [434,435].

For comparison purposes for Ch. 6, a trend analysis of the pain sensitivity in the cervical spine was completed on each side of the cervical spine.

The total PPT in the TeP and CP locations, and the total cervical PPT values were compared week to week. Only the first PPT values measured each week were compared before the posture experiment had begun. This was to test for any carry over effects of the experiment week on week. Box and whisker plots were used to examine differences between experiments week on week. Paired t-tests were conducted to examine for significant changes on the total PPT value for each participant.

4.3.6.3 RANGE OF MOTION ANALYSIS

Descriptive statistics were used to summarise the ROM data at the start and end of each measurement session. A total ROM value was derived for each participant by adding the ROM values for each movement plane.

The ICC(2,1) was used to assess the reliability of ROM measurements between the first and second measurement of ROM in each plane of motion, also for comparison purposes with results from Ch. 6. The change in ROM between the start and end of each measurement session was determined. The Fastrak ETS system permitted assessment of the conjunct motion in planes other than the primary movement plane. Conjunct motions were recorded for each movement plane.

4.3.6.4 SELF REPORTING INSTRUMENT (QUESTIONNAIRE) ANALYSIS

The average and standard deviations (SD) for each body-part discomfort VAS are reported. The body part (BP) Frequency, BP Severity and BP Frequency Severity were calculated for time 0 to 4hrs and averages and SD reported.

4.3.7 WORKSTATION LAYOUT

The exact workstation dimensions are described in this section. This was shown pictorially above in Figure 4-1 and Figure 4-2. In Sec 4.4 (next), the ergonomic risk factors associated with the workstation layout are discussed.

4.3.7.1 WORKSTATION AREA

The workstation layout was set at the maximum, or just greater than the maximum, recommended ranges for workstation dimensions. Participants were seated on a wooden chair on a cushion at a custom designed workstation, in front of a visual display terminal (VDT). The right hand was placed on a mouse that was located at a far reach location (see Figure 4-3). The left arm was placed comfortably in the participant's lap; it was not used during testing. The 'workstation' area consisted of a workstation desk, a workstation computer with a standard 17" CRT monitor, a standard two-button mouse, a standard foam mouse pad, and some wooden spacers that were used to raise the height of the monitor and mouse pad as required.

4.3.7.2 MONITOR

The *monitor height* was placed above the level of the sitting participant's eye. The middle of the monitor screen was *700 millimetres* (mm) away and *15 deg* above the participant's sitting eye location. The angle of 15 deg above the participant's sitting eye level has been used in previous ergonomic investigations [436]. Villanueva et al. [437] stated that posture is decided by the demands on the visual system, and the neck appears to be the most susceptible and most important area in adjusting its position to find the preferred viewing angle. Neck inclination supports eye inclination, especially at higher monitor heights. To a lesser extent thoracic bending has also been noted to contribute to setting the viewing angle [437]. Postures that involve an extended head or neck for prolonged periods are likely to lead to neck discomfort [427,438,439] and may be associated with neck/shoulder problems [131,440]. although it was contrary to the preferred monitor height of lower than sitting eye level [130,335,436-438], the high monitor location was chosen to encourage extension of the head and neck.

The high monitor location also necessitated greater muscle activity for stabilising the cervical spine, because the spine was relatively extended [436]. In addition, ranking of the stressfulness of non-neutral postures ranks neck extension as more stressful than flexion [125,441]. A viewing distance of 450 to 500mm with a maximum of 700mm has been recommended [442]. For this investigation, the maximum recommended *viewing distance of 700mm* was used.

4.3.7.3 MOUSE

All interaction with the computer was via the computer mouse with the right hand; there was no keyboard operation required of participants during either measurement session. The mouse was used on a standard sized foam mousepad.

For 'poor' ergonomic performance the mouse was the preferred option compared with the keyboard for this experiment, for the following reasons:

- The use of a computer mouse typified a significant portion of work normally completed by computer users. Research shows that the computer mouse is the most commonly used input device other than the keyboard [443], and mouse use can equal or exceed the time spent using a computer keyboard during personal computer operation [444].
- Previous investigations have shown that computer mouse usage usually involves unilateral shoulder flexion, abduction and external rotation [443,444]. Mouse position with respect to the body may be a critical factor in determining the extent of shoulder flexion and abduction and the resultant strain on the deltoid and trapezius muscles of the neck-shoulder complex [443].
- When compared with non-mouse operators, mouse operation has been associated with long periods of strenuous working postures [445]. This may be due to the concentrated fixation of the participant's eye on the screen for computer tasks that require a mouse for pointing, dragging and selecting [437]. Therefore, for 'poorer' ergonomic performance, the mouse was the preferred option compared with the keyboard.

4.3.7.4 ARM POSTURE

The location of the mousepad dictated the posture of the right arm, forearm and wrist. All participants were right-handed mouse operators. The bottom left corner location of the mousepad was moved for each participant, so that the hand was over this corner when the *arm* was *flexed and abducted* to approximately *45 deg*, and elbow was flexed to *135 deg*. Arm abduction can cause a considerable increase in the activity levels of the upper thoracic and cervical spine extensors and upper trapezius [446]. Grandjean et al. [130] reported a preferred arm abduction setting of 22 deg (range of 11 – 44 deg) and upper arm flexion of 23 deg (range 1 – 50 deg), at a workstation. In this experiment, a

value of 45 deg was selected for upper arm abduction and flexion. These values put the start posture of the arm in the 'moderate-to-high' angle categories based on previous posture classification models [335,447,448]. For elbow flexion, preferred workstation ranges between within 70 – 135 [130,335,442] have been reported. A start posture of *135 deg elbow flexion* was selected for this experiment.

4.3.7.5 ELBOW HEIGHT

The mousepad was set at a high level of *120mm* above the sitting elbow height. This was based both on previous reports of neck and shoulder discomfort associated with high levels of computer keyboard operating height, and on recommended heights considerably lower than 120mm [131,329,442,449]. Liao and Drury [404] investigated three keyboard heights and found that at the highest level of 120mm above sitting elbow height, the shoulder, elbow and trunk angles were significantly greater than those at the lower keyboard heights. Subjects reported the highest discomfort rating at this keyboard height [404].

4.3.7.6 WORK PERIOD

A four-hour session was selected as the 'work' period for the experiment, based on the findings of two previous studies:

- Winkel and Westgaard [428] showed that there is little difference in the prevalence rate of shoulder-neck complaints after four hours work in poor ergonomic conditions, compared with six hours work under the same conditions.
- Krueger et al. found that the number of reported musculoskeletal disorder complaints in cash desk workers after four hours work gave was the same as that reported after eight hours work [450].

4.4 ERGONOMIC RISK FACTORS

This section investigates some of the *ergonomic* risk factors associated with the posture and actions undertaken by the participants during the experiment, described above in Sec 4.3.7. The risk factors were identified from the ergonomic research literature in

order to develop an appreciation of particular aspects of the tasks and workstation layout that could represent a risk of developing musculoskeletal disorders.

4.4.1 STATIC LOAD AND CONSTRAINED POSTURES

The tasks and workstation layout were designed to ensure that the participant held a constrained working posture for a full 4 hours. This posture was characterised by a static 'forward head' posture and shoulders forward.

The ergonomic literature indicates that *computer work* is associated with high risk of developing shoulder-neck disorders that are mainly due to the effect of static tension in the shoulder-neck muscles [451]. Sitting at a computer workstation predominantly involves static work [449,452] and the lack of physical variation can become a major problem for workers [451]. The static muscular loading, biomechanical stress, and repetitive work contributes to the musculoskeletal discomfort associated with computer work [449]. Previous research has demonstrated an association between the incidence of shoulder-neck complaints and the duration of computer work [451].

VDT work is characterised by *constrained* and *non-neutral* body postures [130,452]. During the measurement sessions, the workstation layout forced participants to assume a static and non-neutral posture while playing the computer games. The static and constrained postures were characterised by the restriction of free movements and resulted in long-lasting postural efforts [126,127]. According to the ergonomic literature, deviations from a neutral posture are the major cause of musculoskeletal static loading [124,125], and are likely lead to long-lasting constriction of the muscles, muscular fatigue, discomfort and pain [81,126,128-131]. Static load and constrained postures are frequently associated with pain [81,131]. Awkward and static body postures, are key ergonomic risk factors associated with musculoskeletal disorders [80,83,125,134,331,440].

4.4.2 FLEXION AND ABDUCTION OF THE ARM

The flexed and abducted *posture of the arm***,** during the light-off periods, would have placed postural load on the shoulder and neck. Arm abduction has been shown to cause a considerable increase in the activity levels of the upper thoracic and cervical erector spinae muscles and the trapezius [446,453]. Flexion of the arm may increase the static

level of activity and fatigue in the neck and shoulder muscles [454], and repetitive elevation of the arm has been reported as a significant factor in shoulder-neck musculoskeletal disorders [429]. An association between musculoskeletal illness in the shoulder/neck region and postures with considerable static load on the shoulder and neck muscles has been reported [430,455,456].

The experimental requirement of once-a-minute raising the arm above shoulder height – to turn the lights off – would also have also placed postural load on the shoulder-neck region. Activity in the trapezius has been found to closely correspond to the shoulder joint load [430-432]. Work at or above shoulder height has been associated with fatigue, discomfort and pain in the shoulder and neck region [427,427,432].

4.4.3 EXTENSION OF THE WRIST

The use of the *mouse* and mouse button with the finger and palm would have involved exertion of force to overcome the mouse button and gravity, inertia and friction forces [6]. The small and precise repetitive side-to-side actions of the hand required radial-ulna deviations of the wrist and may have contributed to muscular fatigue, discomfort and pain in the region. Tasks that involve high repetition have been associated with musculoskeletal disorders [457]. The static posture of considerable wrist extension would have placed biomechanical load on the wrist [458]. The biomechanical wrist load probably stimulated nociceptors in the joint capsules or ligaments, and caused pain [6]. Wrist postures of significant flexion or extension have been shown to significantly increase carpal tunnel pressures [7] and are a risk factor for hand and wrist musculoskeletal disorders [459].

4.4.4 EXTENSION OF THE HEAD

Postures where the head is *extended* for prolonged periods of time are likely to lead to neck discomfort [427,439,460] and may lead to both neck and shoulder disorders [440]. Static tension in the shoulder-neck muscles has been associated with a high risk of shoulder-neck disorders [131,134,451].

4.4.5 POSTURAL LOAD ON THE CERVICAL SPINE

In this experiment, the *postural load* on the cervical spine (due to the static 'forward head posture') would have contributed to discomfort in the neck. This posture may be a major contributing factor to musculoskeletal disorders in VDT workers [461]. The forward head posture of the neck and head was characterised by some flexion in the lower vertebrae combined with extension in the upper cervical vertebrae (the atlanto-occipital joint) [438,461].

The biomechanical postural load placed on the cervical spine was probably mostly counterbalanced by muscle activity [410]. It is unlikely that the postural load would have involved significant biomechanical loading of passive structures. The ligaments and joint capsules are elastic, especially within the mid-range, and a large range of movement is possible without significant contribution from passive tissues [410,438,462] (passive structures normally maintain load at or near the limit of a joints extreme position [410]). Instead, it was likely that muscular activity of the cervical extensor muscles was required to maintain the equilibrium status of the head and neck [438]. Cervical extensor muscles would have been active to counteract the anterior neck and head centre of mass.

Harms-Ringdahl et al. [460] showed that a posture of lower cervical flexion and extension at the atlanto-occipital joint significantly increased the muscle activity of the trapezius and cervical erector spinae to a level that exceeded the recommended limit level for static activity [448,453,463].

In addition, Burgess-Limerick et al. [438] explained that the suboccipital muscles are capable of providing extensor torque about the atlanto-occipital joint only, while other muscles provide extensor torque about the cervical vertebrae as well as the atlanto-occipital joint (such as semispinalis capitis), and others provide extensor torque about the cervical vertebrae only. The posture of cervical flexion in the lower cervical spine in this experiment probably reduced the possible contribution to atlanto-occipital extensor torque from the muscles that extend over the cervical vertebrae, as well as the atlanto-occipital joint.

Consequently, the suboccipital muscles were most likely required to significantly contribute to extensor torque at the atlanto-occipital joint [438]. The upper cervical

suboccipital extensor muscles are short and it is possible that even a small increase in extension can place these muscles in an inefficient range of their length-tension relationship [436,461,462]. It is likely that these muscles are primarily responsible for vertical movements about axes in the upper cervical spine [438].

In this investigation, the head and neck posture adopted by participants to observe the high monitor location involved extension of the atlanto-occipital joint beyond the neutral position. This posture may have rapidly led to a decrease in the force-generating capability of the small suboccipital muscles. This may have also applied to the muscles that crossed both the cervical and atlanto-occipital joints, because the cervical spine was not held in extreme flexion [436], and contributed to increasing the muscular effort required to maintain a static equilibrium [462].

4.5 RESULTS

The average time that the lights were on was 7.7 secs (10.5 SD). This gave a *total cycle time of 67.7* secs: 60 secs of playing the computer games and an average of 7.7 secs responding to the light-on event.

4.5.1 POSTURE RESULTS[10]

4.5.1.1 THE POSTURE CODES

The posture of participants was measured using the codes set out in Table 4-4, and described in full in Sec. 3.3.2 and App. A.4.

10 As a result of technical difficulties, there was a small percentage of missing or corrupted data in nine out of the thirty measurement sessions. This was due to the Fastrak ETS system occasionally 'crashing' for unknown reasons. When this occurred, the participants continued playing the computer games while the ETS was rebooted. However, because the Fastrak was not operational, there was some missing posture data for these time periods. To maintain continuity and to assist in statistical analysis, the lost data was replaced with posture data recorded either before or after the missing posture measurements. In most cases, the ETS was not operational for only 1 or 2 minutes. In addition, through human error, one posture code for one participant during a measurement session was greatly distorted to the group mean. This was corrected by applying a correction factor so that the data for this posture code was similar to the group average.

Segment	No	Code	Description	Positive	Negative
Trunk	1	SFH	Shoulder forward of hips	Ventral	Dorsal
	2	SSH	Shoulder side of hips	Right	Left
	3	TR	Trunk rotation	Right	Left
	4	C	Trunk curvature	Flexion	Extension
Head	5	HF	Head flexion/extension	Flexion	Extension
	6	HR	Head rotation	Right	Left
	7	HT	Head tilt (lateral flexion)	Right	Left
	8	HNF	Head flexion/extension rel to neck	Flexion	Extension
	9	HNT	Head rotation relative to neck	Right	Left
	10	HNR	Head tilt (lateral flexion) relative to neck	Right	Left
Shoulder	11	RSEV	Right shoulder elevation	Superior	Inferior
	12	RSF	Right shoulder protraction	Protraction	Retraction
Arm	13	REFS	Right arm flexion/extension	Flexion	Extension
	14	RERS	Right arm abduction	Abduction	Adduction
	15	RDS	Right arm rotation	Right	Left
Forearm	16	RFX	Right elbow flexion		
	17	RPR	Right forearm pronation/supination	Pronation	Supination
Wrist	18	REX	Right hand flexion/extension	Flexion	Extension
	19	RDV	Right hand ulna/radial deviation	Ulna	Radial

Table 4-4 – Description of the FWAP-Link posture codes (from Ch. 3 at Table 3-2)

4.5.1.2 POSTURE

The posture of participants was characterised as poor and static during most of the experiment. The posture did not vary during the experiments (i.e. the posture was static), and there was virtually no difference in posture between the two sessions, for when the lights were off.

However, there were large differences in posture between the two sessions when participants were responding to the light-on event. This was an experimental objective of the investigation – the posture results showed that for this once-a-minute event, participants had significantly altered posture between the two sessions.

4.5.1.2.1 Posture when the lights were off

The average posture of participants for when the *lights were off* (i.e. not including data from when the participants were responding to a light on event) is shown in Table 4-5 and Figure 4-11 below. Head flexion (HF), right arm flexion (REFS), elbow flexion (RFX) and right hand extension (REX) were the posture angles that were most deviated from a neutral posture. These posture codes are indicated in bold in Table 4-5. The cumulative frequency analysis graphs of each posture code are shown in App. C.

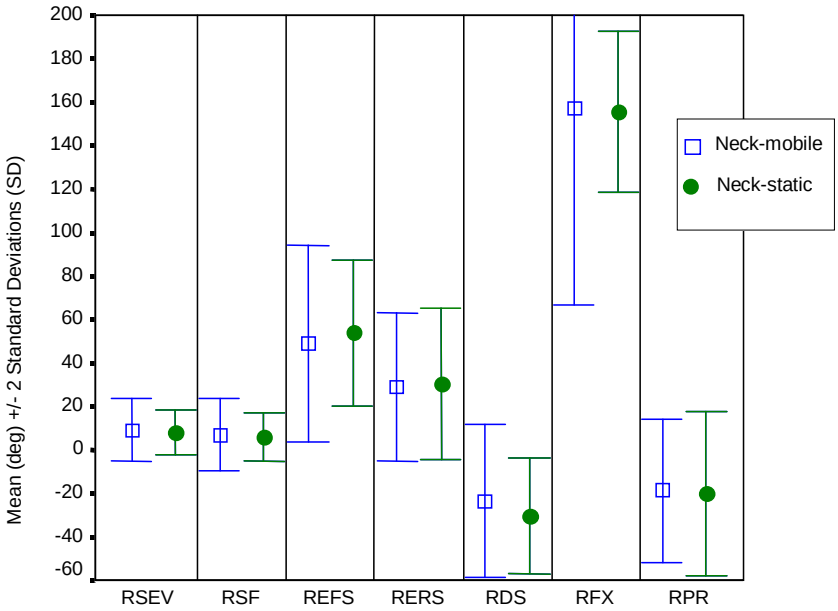
For the *light-off period*, there were no significant differences in posture *between* the neck-mobile and neck-static testing sessions. This is demonstrated in Figure 4-11, which shows that the posture deviated by only 1.9 deg (range 0 - 7 deg) between the

two measurement sessions (Table 4-7). Hence, posture was not a factor between the two sessions, when the lights were off.

The posture *during* the measurement sessions also did not vary. App. B Table B-1, shows that the posture of participants was similar at each hourly interval.

		Neck-mobile					Neck-static					Diff	All Posture Data				
No	Code	Mean	SD	Q1	Q2	Q3	Mean	SD	Q1	Q2	Q3		Mean	SD	Q1	Q2	Q3
1	SFH	8.1	8.1	4.1	8.1	13.4	7.1	8.7	2.8	8.5	12.8	1.0	7.6	8.4	3.6	8.3	13.1
2	SSH	2.9	4.7	0	2.7	5.3	1.8	5.2	-1.4	0.8	3.4	1.1	2.3	5.0	-0.8	1.7	4.5
3	TR	-0.7	8.5	-6	-1.2	4	1.7	9.1	-4.1	2.6	7.9	-2.4	0.5	8.9	-5.3	0.5	6.2
4	C	11.3	12.8	0.7	10.8	21.9	9.8	14.4	-0.1	7.4	19.3	1.5	10.6	13.6	0.4	8.6	20.9
5	**HF**	**-16.9**	**8.4**	**-22.9**	**-16.6**	**-11.6**	**-16.5**	**8.0**	**-21.9**	**-17.2**	**-11.9**	-0.4	**-16.7**	**8.2**	**-22.4**	**-16.9**	**-11.7**
6	HR	-2.8	11.4	-8.1	-1.9	2.8	-4.2	9.3	-9.9	-4.4	1.6	1.4	-3.5	10.5	-9.2	-3.1	2.3
7	HT	0.5	5.2	-2.5	0.3	3.5	1.0	5.2	-1.7	1.2	3.9	-0.5	0.8	5.2	-2.1	0.8	3.7
8	**HNF**	**-31.5**	**13.9**	**-41**	**-31.7**	**-22.5**	**-27.7**	**11.9**	**-35.2**	**-27.8**	**-21.1**	-3.8	**-29.6**	**13.1**	**-38**	**-29.5**	**-21.7**
9	HNT	1.1	8.0	-4.4	0.7	6.5	1.8	8.5	-3.3	2.1	7.2	-0.7	1.5	8.3	-3.9	1.4	6.9
10	HNR	-1.9	11.8	-8.1	-1.3	4.1	-3.0	10.6	-8.7	-2.8	3.1	1.1	-2.5	11.3	-8.4	-2.1	3.7
11	RSEV	9.0	6.2	4.6	9.5	13.3	8.1	5.1	4.9	8.3	11.7	0.9	8.6	5.7	4.7	8.8	12.5
12	RSF	6.7	8.0	0.6	7	10.8	5.9	5.7	1.7	5.3	10	0.8	6.3	7.0	1.3	6.1	10.4
13	**REFS**	**49.0**	**19.0**	**40**	**53.7**	**61.3**	**53.7**	**16.9**	**43.6**	**54.8**	**65.3**	-4.7	**51.4**	**18.1**	**42.2**	**54.2**	**62.6**
14	RERS	28.9	16.8	21.7	31.5	38.6	30.4	17.5	16.2	31.2	43.6	-1.5	29.6	17.2	18.4	31.4	40.7
15	RDS	-23.4	17.3	-34.7	-22.5	-11.5	-30.5	13.4	-38.5	-30.1	-21	7.1	-26.9	15.9	-37	-26.7	-16.4
16	**RFX**	**156.3**	**24.2**	**145.4**	**157.8**	**167.2**	**155.7**	**18.5**	**143.6**	**156.5**	**170.2**	0.6	**156.0**	**21.5**	**144.6**	**157.2**	**168.7**
17	RPR	-18.8	16.1	-29.1	-21.5	-13.9	-20.1	18.7	-32.4	-24.3	-6.6	1.3	-19.4	17.5	-30.5	-22.7	-10.9
18	**REX**	**-27.6**	**11.0**	**-34.3**	**-28.1**	**-20.6**	**-23.8**	**8.5**	**-29.6**	**-24.8**	**-18.1**	-3.8	**-25.7**	**10.0**	**-31.8**	**-26.3**	**-19.3**
19	RDV	5.6	9.0	-0.3	4.6	11.3	6.3	8.3	1	6.5	12.1	-0.7	5.9	8.7	0.3	5.6	11.8

Table 4-5 – Average posture in degrees, standard deviation (SD), and quartiles (Q1 to Q3) for each FWAP-Link posture code for each measurement session when the lights were off. The largest non-neutral postures are shown in bold and shaded.



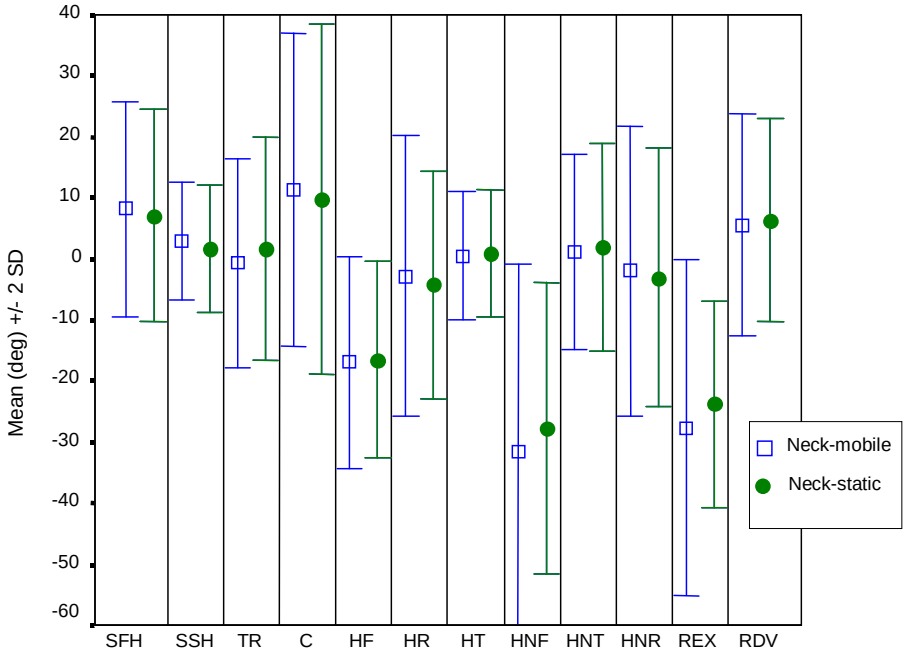


Figure 4-11 – Comparison between the neck-static and neck-mobile posture (+/- 2 SD) for the arm and forearm (top graph) and all other posture codes (bottom graph) for when the lights were off.

As discussed in Sec. 4.4, there *were ergonomic musculoskeletal disorder risks associated with the posture* assumed by the participants – the posture adopted was characterised as static and poor. Specifically, the poor posture assumed by participants in this experiment included (from Table 4-5 above):

- trunk flexed forward 8 deg (SFH) and slightly to the right 3 deg (SSH) and with no rotation (TR)
- upper thoracic spine region was ‘slumped’ by about 10 deg (C) (the ‘slumped’ trunk curvature posture (C) indicated that the angle between the hips, the upper thoracic spine and the base of the neck was curved down)
- large head extension (HF) with almost no tilt (HT) and small left rotation 3 deg (HR) (head extension (HF) was about 16 deg compared with the vertical, but this value increased to 30 deg relative to the base of the cervical spine (HNF))
- upper torso ‘slumped’ and lower cervical spine (C) flexed, which contributed to the large head extension value relative to the neck (HNF). The lower cervical spine demonstrated a flexed posture at C7 level. The upper cervical spine vertebrae were extended to accommodate the head posture of extension. This head and neck posture has been described as the ‘forward head posture’ [438,461].
- right shoulder glenohumeral location was elevated 8 deg (RSEV), and protracted 6 deg (RSF)

- right arm was held in a posture significantly altered from neutral – flexed forward 50 deg (REFS), abducted 30 deg (RERS) and rotated to the left 27 deg (RDS).
- forearm was flexed 156 deg about the elbow joint (RFX) and supinated 20 deg from a palm down orientation, or pronated 70 deg from a thumbs position (RPR).
- wrist extended by 26 deg (REX), and slightly ulnarly deviated by 6 deg (RDV).

4.5.1.2.2 Posture at the light-on event

For the once-a-minute light-on events, there were *significant differences* in posture between the neck-mobile and the neck-static sessions.

The *head and neck* were the body segments that displayed the largest difference in posture for the light-on event, as shown in Table 4-6. The head rotated between 60 – 72 deg during the neck-mobile session, compared with a small range of 11 – 7 deg during the neck static session.

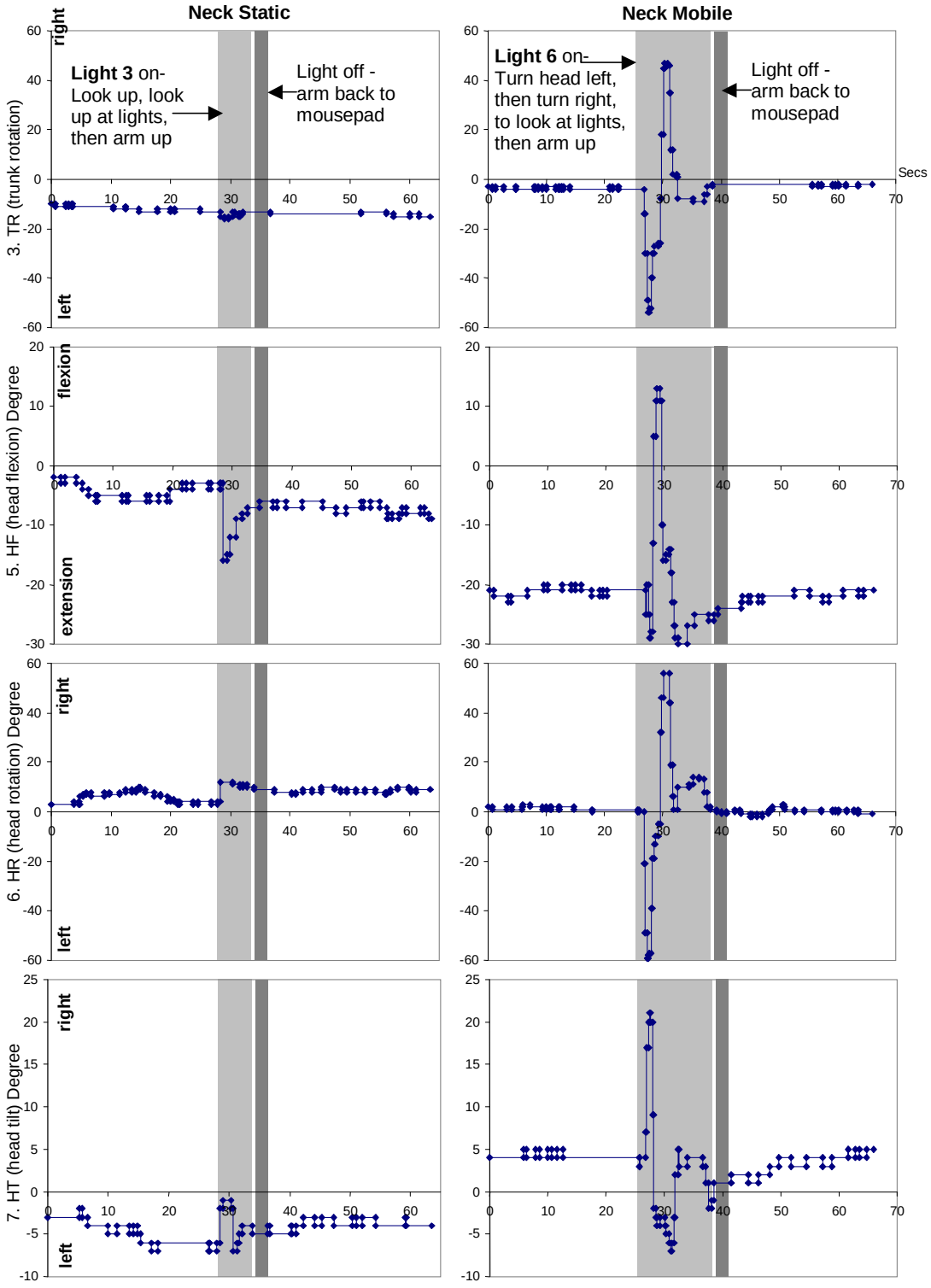
The different postures and actions undertaken by participants when they responded to the once-a-minute light-on event was ***the only difference*** between the neck-static and neck-mobile measurement sessions. It was surmised that the different postures assumed in the head and neck (for this once-a-minute light-on event) caused the differences in the measured variables.

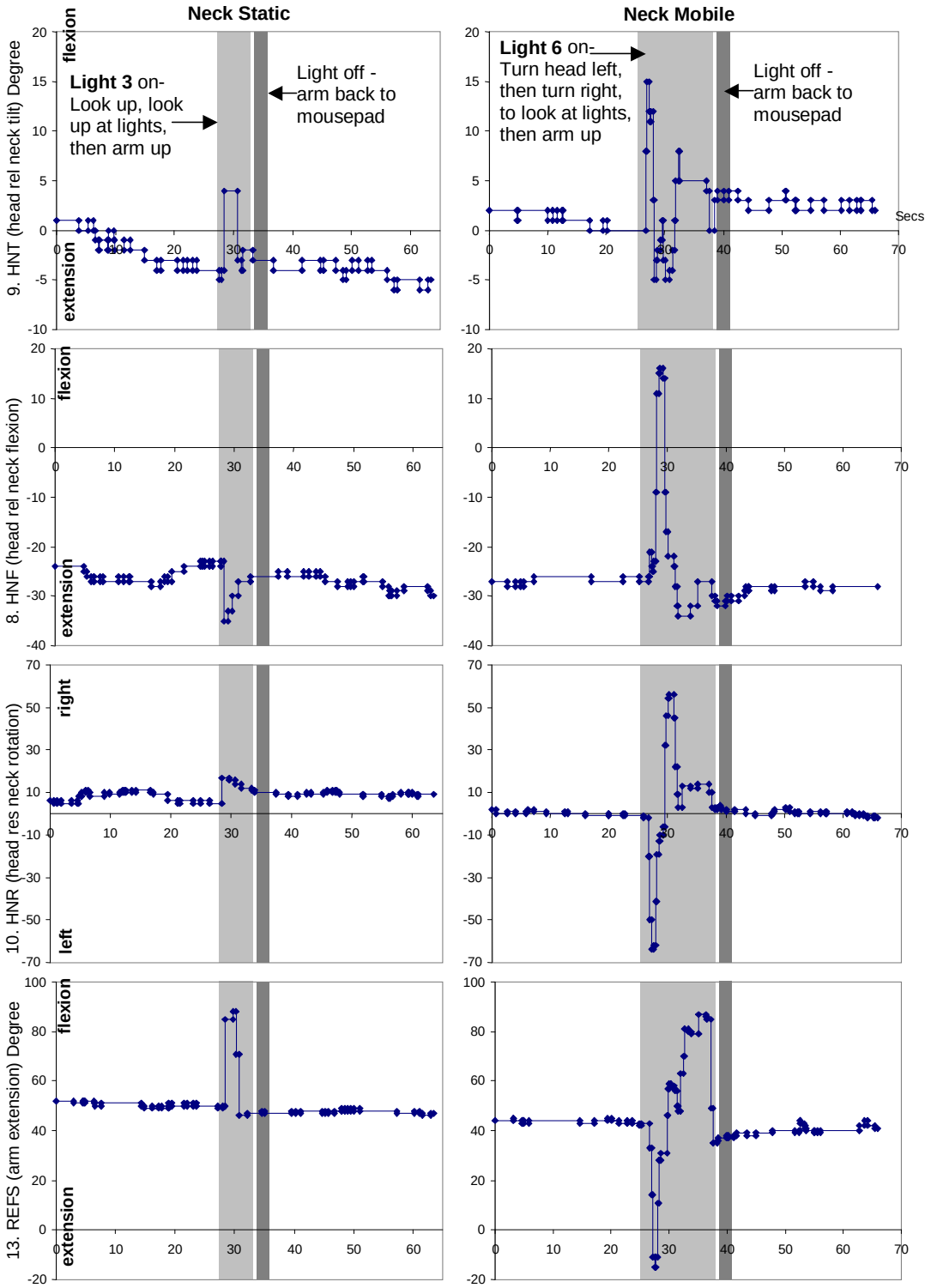
		Neck-mobile								Neck-static							
		Light 4		Light 5		Light 6		Total		Light 1		Light 2		Light 3		Total	
No	Code	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1	SFH	14	-0	14	-4	18	-3	18	-4	11	1	11	2	13	4	13	2
2	SSH	13	-3	13	-3	14	-5	14	-5	3	-4	3	-3	4	-2	4	-5
3	**TR**	**4**	**-48**	**4**	**-46**	**32**	**-47**	**32**	**-48**	**4**	**-10**	**3**	**-8**	**3**	**-9**	**9**	**-10**
4	C	16	-4	19	-4	20	-5	20	-5	12	-1	12	-1	12	-2	12	-2
5	**HF**	**-3**	**-24**	**17**	**-24**	**18**	**-25**	**18**	**-25**	**-11**	**-24**	**-11**	**-23**	**-11**	**-22**	**-11**	**-24**
6	**HR**	**17**	**-72**	**18**	**-70**	**60**	**-70**	**60**	**-72**	**9**	**-7**	**9**	**-6**	**11**	**-6**	**11**	**-7**
7	**HT**	**15**	**-10**	**13**	**-23**	**15**	**-25**	**15**	**-25**	**4**	**-6**	**4**	**-5**	**4**	**-5**	**4**	**-6**
8	**HNF**	**-7**	**-35**	**10**	**-34**	**9**	**-36**	**10**	**-36**	**-14**	**-32**	**-15**	**-31**	**-15**	**-31**	**-14**	**-32**
9	**HNT**	**10**	**-9**	**10**	**-17**	**11**	**-18**	**11**	**-18**	**9**	**-3**	**8**	**-3**	**7**	**-3**	**9**	**-3**
10	**HNR**	**20**	**-74**	**20**	**-71**	**62**	**-72**	**62**	**-74**	**14**	**-6**	**12**	**-6**	**14**	**-4**	**14**	**-5**
11	RSEV	16	3	16	2	17	0	17	0	16	5	16	6	16	5	16	5
12	RSF	11	-7	12	-7	16	-7	16	-7	10	2	10	2	10	2	10	2
13	**REFS**	**92**	**-12**	**90**	**-9**	**92**	**-13**	**92**	**-13**	**98**	**48**	**99**	**48**	**101**	**48**	**101**	**48**
14	RERS	50	7	50	13	50	-0	50	-0	36	3	36	11	42	21	42	3
15	**RDS**	**37**	**-55**	**33**	**-52**	**36**	**-55**	**37**	**-55**	**-23**	**-66**	**-23**	**-63**	**-23**	**-63**	**-23**	**-67**
16	RFX	164	117	164	119	166	117	166	117	168	134	168	136	169	137	169	134
17	RPR	-10	-33	-9	-33	-8	-34	-8	-34	-10	-29	-12	-28	-12	-29	-10	-29
18	REX	-10	-31	-12	-34	-10	-35	-10	-35	-6	-27	-7	-27	-9	-27	-6	-27
19	RDV	14	1	13	0	13	-0	14	-0	13	1	13	2	12	1	13	1

Table 4-6 – Average maximum (max) and minimum (min) posture during the light-on events. Data is shown for the neck-static (lights 1–3) and neck-mobile (lights 4-6) measurement sessions. Bold and shading indicates large postural differences.

4.5.1.3 FWAP FOR WINDOWS ANALYSIS OF ONE PARTICIPANT

A 'FWAP for Windows©' graphical outputs of *one participant only* (for one cycle) during a neck-static and neck-mobile session are shown in Figure 4-12. These graphs clearly show the differences in posture between the two sessions, particularly for the light on event. Only posture codes with large differences are shown (those in bold in Table 4-6). See App. D for all posture graphs, and App. E for the FWAP for Windows©' spreadsheets. These results were derived from the analysis of the posture data with the FWAP-Link program described in Sec. 3.3.


Neck Static
Neck Mobile
Light 3 on-
Look up, look up at lights, then arm up
Light off - arm back to mousepad
Light 6 on-
Turn head left, then turn right, to look at lights, then arm up
Light off - arm back to mousepad
Secs
3. TR (trunk rotation)
right
left
5. HF (head flexion) Degree
flexion
extension
6. HR (head rotation) Degree
right
left
7. HT (head tilt) Degree
right
left


Neck Static
Neck Mobile
9. HNT (head rel neck tilt) Degree
flexion
extension
Light 3 on-
Look up, look up at lights, then arm up
Light off - arm back to mousepad
Light 6 on-
Turn head left, then turn right, to look at lights, then arm up
Light off - arm back to mousepad
Secs
8. HNF (head rel neck flexion)
10. HNR (head res neck rotation)
right
left
13. REFS (arm extension) Degree

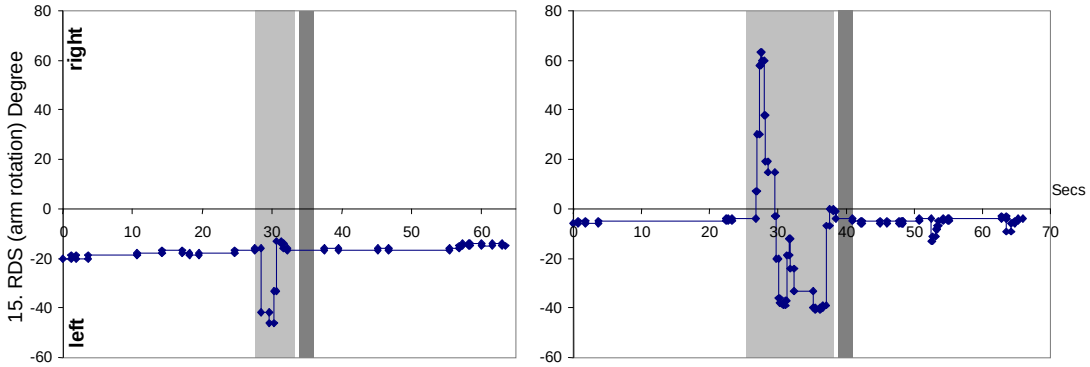


Figure 4-12 – 'FWAP for Windows©' graphical output for each posture code for one participant for the neck-static measurement session (left) and the neck-mobile session (right). App. D shows the remaining posture codes that are not shown above.

4.5.1.4 POSTURE RESULTS ANALYSIS OF VARIANCE

There were *no significant* differences in the posture data (when the lights were off) between the neck-static and neck-mobile measurement sessions (Table 4-7). However, some posture codes did demonstrate some change in posture over time. The post-hoc analysis is reported in App. B.1 in Table B-4.

FWAP-Link Code No	FWAP-Link code	Neck status	Time	Neck x time
5	HF		F(3,42) = 6.4+	
7	HT		F(3,42) = 3.4*	
12	RSF		F(3,42) = 3.3*	
13	REFS		F(3,42) = 4.6+	
15	RDS		F(3,42) = 4.0*	
16	RFX		F(3,42) = 7.0+	
18	REX		F(3,42) = 3.2*	
19	RDV		F(3,42) = 6.0+	

Table 4-7 – Significant outcomes from the ANOVA analysis for each FWAP-Link posture code for neck status and time. * $p<0.05$, + $p<0.01$.

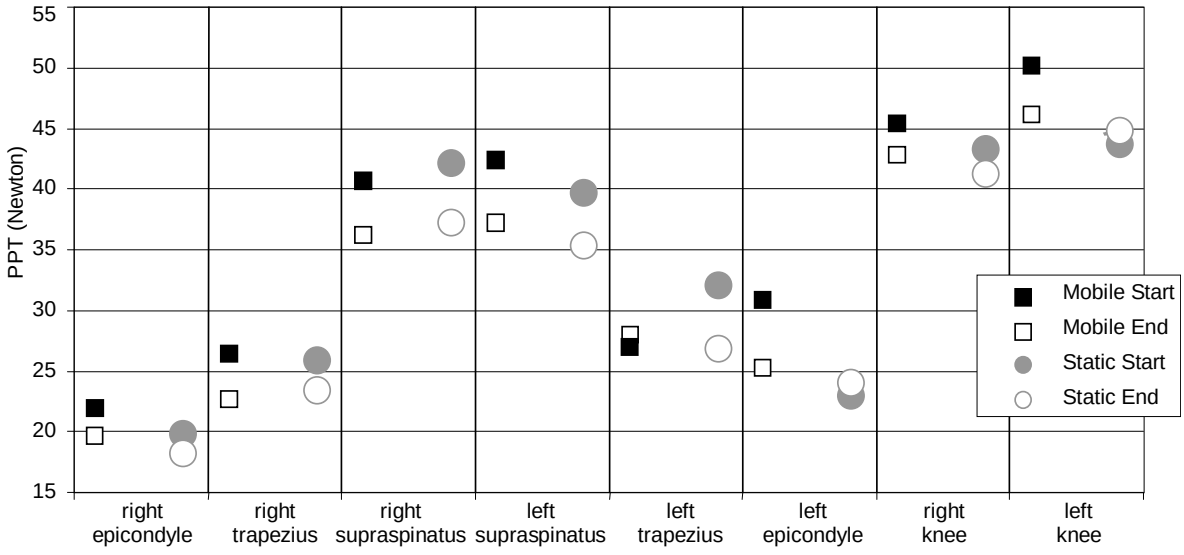
4.5.2 PRESSURE PAIN THRESHOLDS (PPT)

4.5.2.1 TENDER POINT (TEP) AND CONTROL POINT (CP) PRESSURE PAIN THRESHOLDS (PPT)

4.5.2.1.1 Summary of TeP and CP PPT results[11]

One thousand and eighty PPT measurements were taken at eight tender points (TeP) and four control points (CP). As demonstrated by Figure 4-13 and Figure 4-14 *the PPT decreased between the start and end of each measurement session* – at almost every measured site, the PPT decreased over time.

In addition, the PPT values in the neck-static session were lower than the values in the neck-mobile session. The PPT results of each site are shown in App. B in Table B-6.



[11] Two subjects were not measured at time 2 for a testing session (due to human error). The 24 missing data values represented 2.2% of all PPT data. To assist in data analysis, the PPT values at times 1 and 3 in the same testing session were averaged to estimate the missing data. Inclusion of the estimated missing data altered the group average by 0.09N and the SD by 0.09N, indicating that this statistical method of estimation did not greatly alter the PPT results.

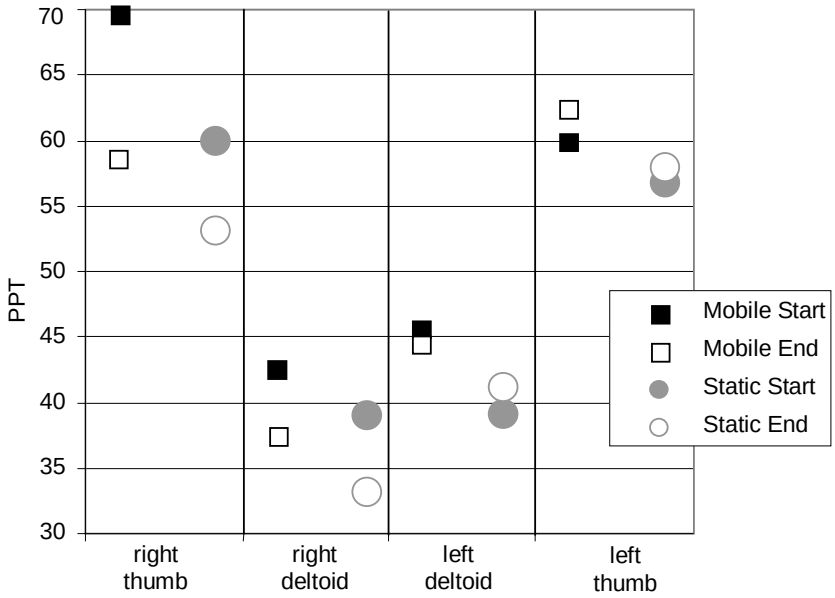


Figure 4-13 – Average PPT values for neck status (moving and static) and measurement times start and end for the tender points (top graph) and control points (bottom graph). The measurements at time 2hr are not shown for clarity.

4.5.2.1.2 Total tender point and control point PPT values

The total PPT values (derived by adding the PPT scores from each TeP and CP site) are shown in Table 4-8 and Figure 4-14. The *total PPT also decreased between the start and end* of both measurement sessions, by an average of 7.4%. The *neck-static results were lower than the neck-mobile values.* This represented baseline differences between the two groups (i.e. compared to a baseline of zero).

However, *the change* in total PPT was slightly larger during the neck-mobile session than the neck-static session.

Neck status		Measurement time			Mean	Total PPT	% change 0 hr – 4 hr
		0 hr	2 hr	4 hr			
Mobile	Mean	505.7	487.6	463.5	485.6	1456.7	-8.3%
	SD	132.2	123.1	106.0	119.4	345.4	
	No	15	15	15	45	15	
Static	Mean	469.4	446.1	439.7	451.7	1355.2	-6.3%
	SD	92.3	92.8	90.3	90.6	267.0	
	No	15	15	15	45	15	
Total	Mean	487.5	466.8	451.6	468.6	1405.9	-7.4%
	SPINAL DYSFUNCTION	113.5	109.2	97.5	106.8	307.7	
	No	30	30	30	90	30	

Table 4-8 – Total PPT value and percentage change in total PPT between the start and end of each measurement session

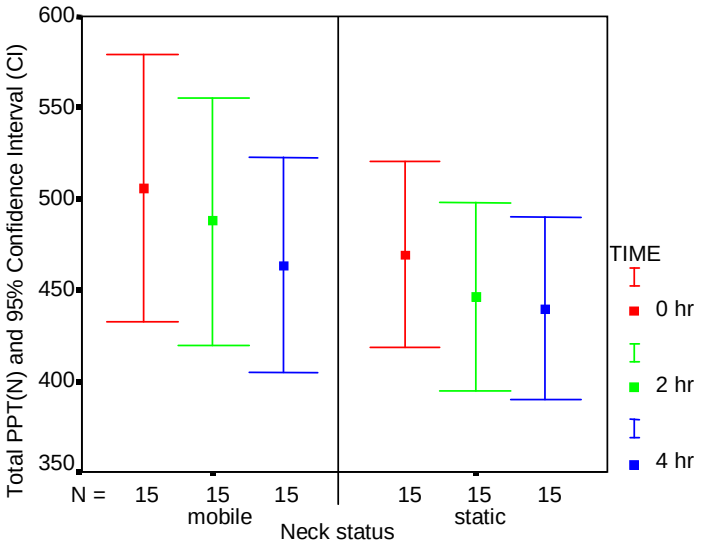


Figure 4-14 – Total PPT and 95% confidence interval (CI)

4.5.2.1.3 TeP and CP PPT analysis of variance

The PPT values from the *neck-static measurement session were significantly lower than the neck-mobile* PPT values. Table 4-9 shows that the PPT for all locations, the upper right quadrant and the upper left quadrant control points significantly differed between the two measurement sessions. This was also observed at some individual locations including the right lateral epicondyle, the right and left deltoids, and the right knee. There was also a strong trend in several other locations. This outcome supported the hypothesis that the postural and action characteristics of the head and neck influenced pain sensitivity.

There was also a *significant outcome for time of measurement*. For all measurement locations, in most quadrants and several individual measurement sites, the PPT values decreased (i.e. the pain sensitivity increased) significantly during the four-hour measurement sessions (Table 4-9). This outcome supported the hypothesis that the medium-term exposure to the ergonomic postural and action risk factors (discussed in Sec. 4.4) influenced pain sensitivity in the participants.

The post-hoc analyses of significant outcomes confirmed that the start, middle (2 hr) and end (4 hr) PPT values were significantly different – the pain sensitivity had increased by the end of the measurement sessions (see App. B in Table B-9).

LOCATION	TeP or CP	Neck status	Time	Neck x time	Location	Neck x Loc	Time x Loc
All locations	TeP + CP	$F_{(1,14)} = 3.54$*	$F_{(2,28)} = 5.5^{+}$		$F_{(11,154)} = 35.4^{+}$		$F_{(22,308)}=2.4^{+}$
U right quad	TeP + CP		$F_{(2,28)} = 10.0^{+}$		$F_{(4,56)} = 39.6^{+}$		
U right quad	TePs only		$F_{(2,28)} = 9.9^{+}$		$F_{(2,28)} = 34.3^{+}$		
U right quad	CPs only	$F_{(1,14)} = 4.06$*	$F_{(2,28)} = 7.9^{+}$		$F_{(1,14)} = 21.9^{+}$		
U left quad	TeP + CP				$F_{(4,56)} = 38.3^{+}$	$F_{(4,56)} = 2.9$*	
U left quad	TePs only		$F_{(2,28)} = 4.8$*		$F_{(2,28)} = 23.7^{+}$	$F_{(2,28)} = 3.5$*	
U left quad	CPs only	$F_{(1,14)} = 4.27$*			$F_{(1,14)}) = 25.2^{+}$		
RThb	CP		$F_{(2,28)} = 7.7^{+}$				
REpi	TeP	$F_{(1,14)} = 3.97$*					
RDel	CP	$F_{(1,14)} = 3.42$*					
RTra	TeP						
RSup	TeP		$F_{(2,28)} = 4.4$*				
LSup	TeP		$F_{(2,28)} = 3.9$*				
LTra	TeP		$F_{(2,28)} = 3.8$*	$F_{(2,28)} = 3.8$*			
LDel	CP	$F_{(1,14)} = 3.83$*					
LEpi	TeP						
LThb	CP						
RKne	TeP	$F_{(1,14)} = 4.55$*	$F_{(2,28)} = 4.9$*	$F_{(2,28)} = 3.7$*			
LKne	TeP						

Table 4-9 – Significant outcomes from the ANOVA analysis for PPT are shown. U quad, TeP and CP refers to upper quadrant, tender point and control point respectively. * $p<0.05$, + $p<0.01$.

4.5.2.1.4 Change in PPT

The change in PPT at each site between the start-to-end (0 hr - 4 hr) is shown in Table 4-10. Full results are shown in App. B, Table B-7.

There was an average decrease in PPT of 3 Newton (N) across all sites (i.e. an *increase in pain sensitivity*). Some sites demonstrated a large change in PPT, while others demonstrated a small change. Interestingly, the neck-mobile PPT results demonstrated a greater change in pain sensitivity than the neck-static PPT results, although the difference was small. This was not consistent with the PPT results described above, which did show a lower PPT value in the neck-static session compared to the neck-mobile session. This made interpretation of the pain sensitivity results difficult and is discussed further in Sec. 4.6.4.

Neck Status	ΔTime	Measurement Location												Mean
		Right Upper Quadrant					Left Upper Quadrant					Lower		
		RThb	REpi	RDel	RTra	RSup	LSup	LTra	LDel	LEpi	LThb	RKne	LKne	
Neck Mobile	Δ 0 hr – 4 hr	-11.3	-2.2	-5.9	-3.2	-4.2	-5.6	1.2	-0.9	-5.4	2.1	-3.4	-3.7	-3.5
Neck Static	Δ 0 hr – 4 hr	-6.8	-1.7	-4.9	-2.9	-5.2	-4.1	-5.4	1.9	-0.2	1.4	-1.3	-0.2	-2.5
Mean	Δ 0 hr – 4 hr	-9.0	-2.0	-5.4	-3.1	-4.7	-4.8	-2.1	0.5	-2.8	1.8	-2.4	-1.9	-3.0

Table 4-10 – Average change in PPT at each measurement location for each time segment

The percentage change in PPT results demonstrated similar outcomes. These are shown in App. B in Table B-7. In the working regions of the musculoskeletal system the percentage change was greatest. These locations included the right arm and right shoulder. The *percentage change in PPT results did not support* a significant difference in pain sensitivity change between the two measurement sessions.

4.5.2.1.5 Quadrant PPT results

Average PPT values for the upper left and right quadrants and changes within these quadrants, between each measurement time, are shown in App. B in Table B-9.

There was a reduction in PPT in the upper left and right quadrants, and the lower quadrant. This included a *decrease in PPT in the upper left quadrant and the lower quadrant*, even though *these quadrants did not undertake any work* during the measurement sessions. The change in PPT was greatest in the upper right quadrant, which was not unexpected given that the right arm was active during the measurement sessions.

4.5.2.2 CERVICAL PRESSURE PAIN THRESHOLD (PPT)

In the cervical region, 2,160 PPT measurements were completed (see Figure 4-15 and App. B, **Table B-13**). The PPT *decreased between the start and end of each measurement session* – the PPT at almost all cervical locations decreased during the measurement sessions.

In addition, there was a greater decrease in PPT in the neck-static session compared with the neck-mobile session. However, the difference between two measurement sessions was small.

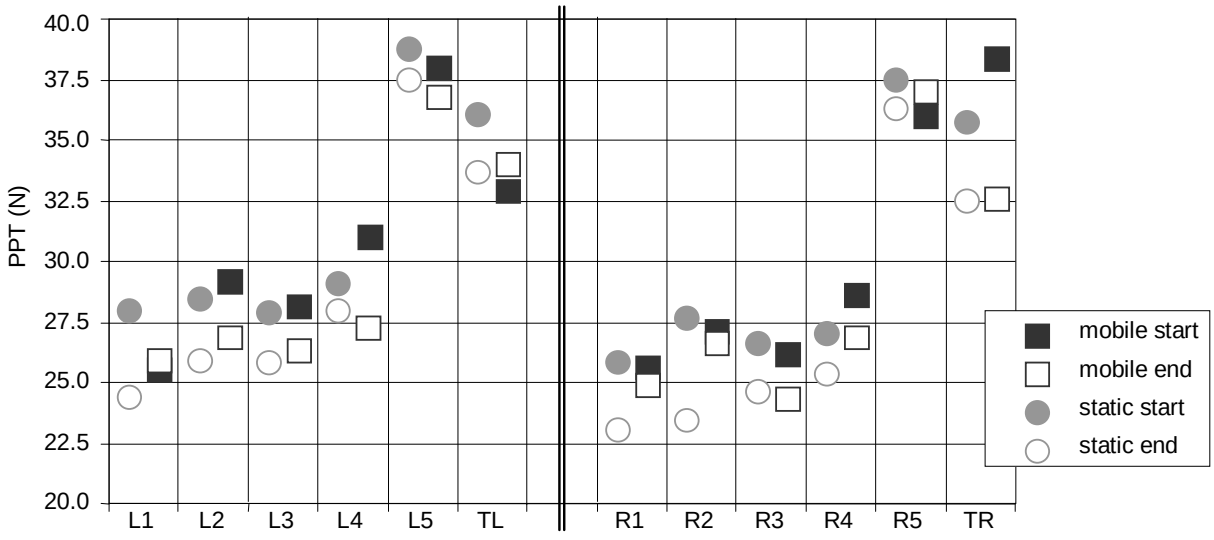


Figure 4-15 – Average PPT at each cervical measurement location for neck status (mobile and static). The consecutive measurements were averaged.

4.5.2.2.1 Total cervical PPT values

The total cervical PPT values (derived by adding the PPT scores from the measurements in the cervical region) are shown in Table 4-11 and Figure 4-16. The average was calculated from the measurements 1, 2 and 3. For both measurement sessions, there was an *average decrease in total PPT of 6.1%* between the start and end.

The change in total PPT was slightly larger during the neck-static session (-7.5%), compared with the neck-mobile session (-4.7%).

Neck status	Start or End	Average cervical total PPT	SD	No	% change Δ 0 hr – 4 hr
mobile	start	368.1	48.5	45	-4.7%
	end	350.8	59.8	45	
	mean	359.4	54.8	90	
static	start	369.0	54.4	45	-7.5%
	end	341.3	48.1	45	
	mean	355.1	52.9	90	
mean	start	368.5	51.2	90	-6.1%
	end	346.0	54.2	90	
	mean	357.3	53.8	180	

Table 4-11 – Average, standard deviation (SD) and number (no) of cervical total PPT values

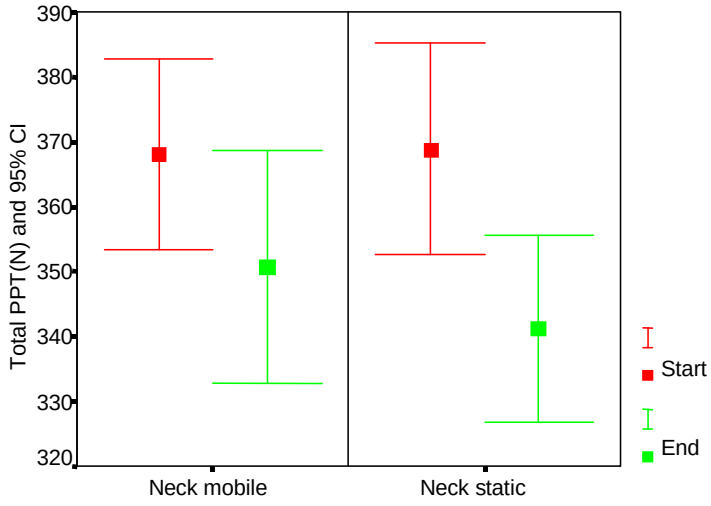


Figure 4-16 – Total PPT for all cervical measurement locations

4.5.2.2.2 Cervical PPT analysis of variance

Although the neck-static measurement session did have lower PPT values and a greater decrease in PPT during that session, when compared with the neck-mobile measurement session, the outcomes for *neck status were not significant* (Table 4-12). This outcome *did not support the hypothesis* that the different postural and action characteristics of the neck-static and neck-mobile computer tasks influenced pain sensitivity in the neck.

There was a *significant outcome for time of measurement* (between the start and end of the measurement tasks). For all cervical PPT data, the right side locations and several individual locations the PPT decreased significantly during the four-hour measurement sessions. This outcome supported the hypothesis that the medium-term exposure to the ergonomic postural and action risk factors influenced pain sensitivity in the neck.

There was also a significant difference in PPT between the cervical measurement locations. The upper cervical spine was significantly more sensitive to mechanical pressure than the lower spine. This is shown in the post-hoc analysis in App. B in Table B-14.

Location	Neck status	Time	NeckXTime	Location	NeckXLoc	TimeXLoc	NeckXTimeXLoc
all locs		$F_{(1,14)}$=7.26*		$F_{(11,154)}$=34.8+			
right locs		$F_{(1,14)}$=7.29*		$F_{(5,70)}$=45.0+		$F_{(5,70)}$=3.1*	
left locs				$F_{(5,70)}$=32.6+			$F_{(5,70)}$=3.1*
L1							
L2		$F_{(1,14)}$=4.85*					
L3							
L4		$F_{(1,14)}$=12.64+					
L5							
TL							
R1		$F_{(1,14)}$=9.14+					
R2	$F_{(1,14)}$=4.21*	$F_{(1,14)}$=17.07+	$F_{(1,14)}$= 5.6*				
R3							
R4							
R5							
TR		$F_{(1,14)}$=18.65+					

Table 4-12 – Significant outcomes from the ANOVA analysis for cervical pressure pain threshold based on neck status (mobile or static), time (0 hr, 4 hr) and location (locations L1 to TR). * p<0.05, + p<0.01.

4.5.2.2.3 Percentage change in cervical PPT

The average percentage change in cervical PPT between the start and end of the neck-static and the neck-mobile measurement sessions, for each location, is shown in Table 4-13 and Figure 4-17. The average percentage change was similar for each measurement session, although the neck-static session had a slightly larger change in pain sensitivity (-5.8%) compared with neck-mobile (-3.9%). There was also large variability in the percentage change between the measurement locations.

Neck status	L1	L2	L3	L4	L5	TL	R1	R2	R3	R4	R5	TR	Average
Neck-mobile	1.7%	-6.8%	-4.8%	-12.1%	-3.2%	5.9%	-2.7%	-1.7%	-6.0%	-5.8%	3.1%	-14.8%	-3.9%
Neck-static	-10.2%	-6.4%	-4.0%	-2.5%	-2.2%	-5.1%	-9.6%	-14.1%	-5.0%	-4.2%	0.6%	-7.6%	-5.8%

Table 4-13 – Average percentage change of each cervical measurement location PPT between the start and end of each measurement session

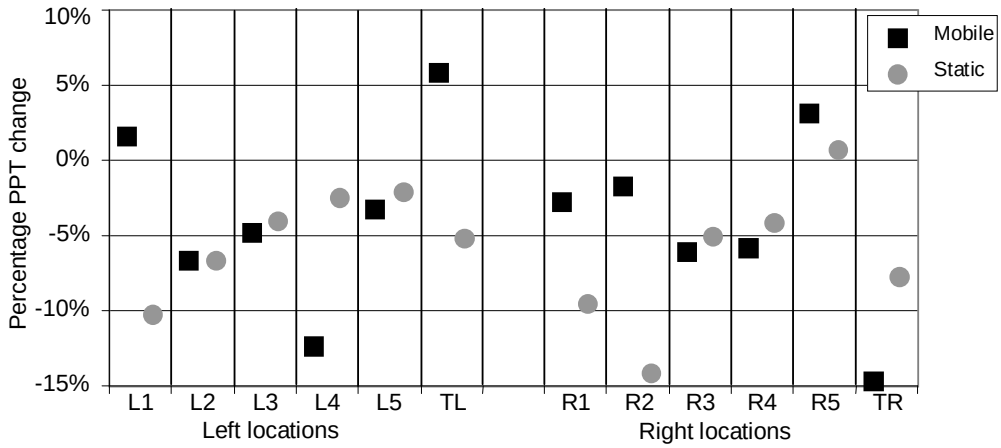


Figure 4-17 – Average percentage change of each cervical measurement location PPT between the start and end of each measurement session

4.5.2.3 WEEK ON WEEK PPT COMPARISON

The total PPT in the TeP and CP locations, and the total cervical PPT values were compared week to week. Only the first PPT values were compared before the posture experiment had begun. This was to test for any carry over effects of the experiment between weeks. The paired t-tests were not significant, indicating that the total PPT values week on week were not significantly different.

The box and whisker plots in Figure 4-18 show that there were similar PPT values in the TePs and CPs and in the cervical spine week to week, indicating there was minimal carryover between experiments. If anything, the total PPT slightly increased.

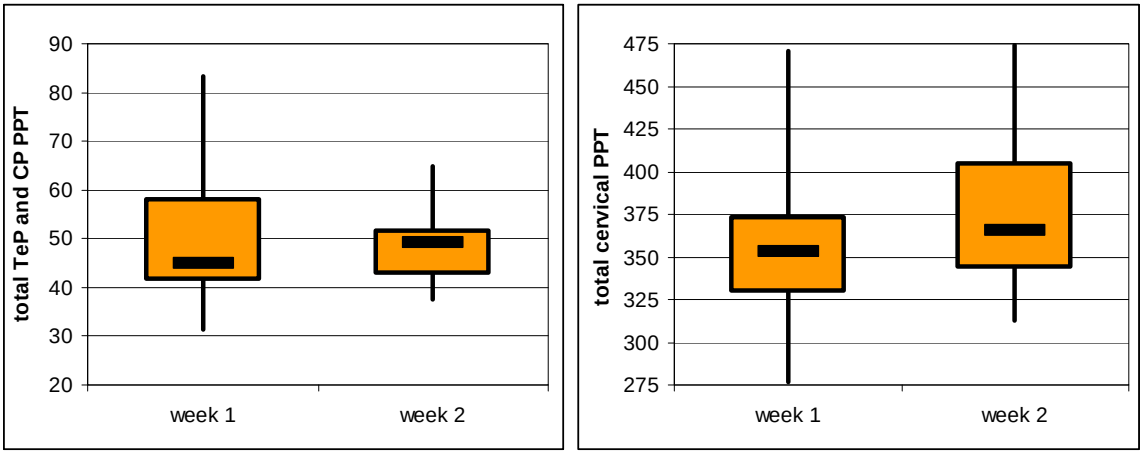


Figure 4-18 – Box and whisker plots comparing the pain sensitivity week on week, to examine an carryover effects. The left chart compares TeP and CP total PPT, and the right chart compares cervical total PPT.

4.5.3 BODY-PART DISCOMFORT SCORES

4.5.3.1 SUMMARY OF BODY-PART DISCOMFORT SCORES

Super-imposed body-maps at times 0 hr to 4 hr are depicted in Figure 4-19 and Figure 4-20. These shaded body-maps show (for all participants combined) the regions where participants indicated discomfort that they felt discomfort. The body-maps were super-imposed on top of each other and therefore show more regions of discomfort than that reported by any one participant alone.

After completing the end of the neck-static session, all participants shaded more of each body part than after completing the neck-mobile session – particularly in the cervical region (body parts RN, LN). This indicated that the neck-static session caused more discomfort for participants than the neck-mobile session.

It was clear from the filled in body maps that the postural load placed on the musculoskeletal system during the four-hour sessions *did cause musculoskeletal discomfort*. The discomfort was experienced predominantly in the working regions of the musculoskeletal system, including the *neck, right arm (including the shoulder, arm, forearm and hand), and the upper, middle and lower back*. These regions had the highest discomfort scores (Figure 4-21).

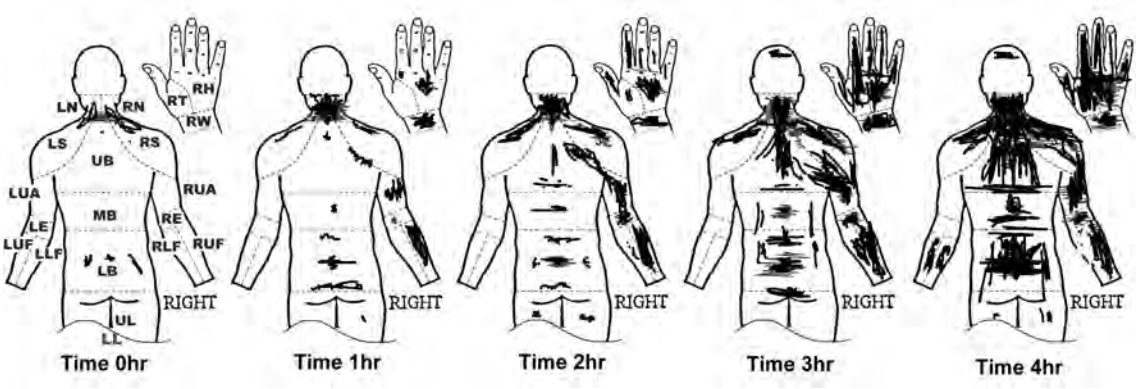


Figure 4-19 – Body-part (BP) discomfort maps from the neck-static session for all participants at times 0hr to 4hr showing where participants experienced discomfort. All body-maps were combined.

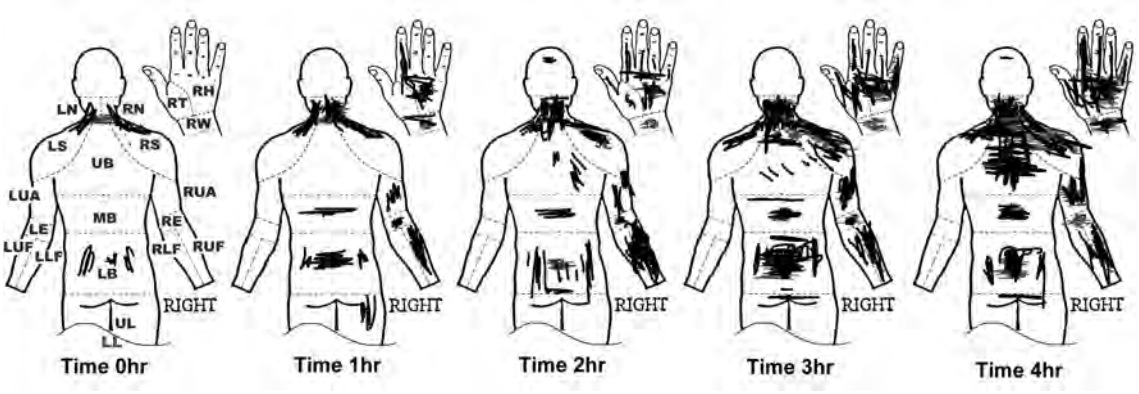
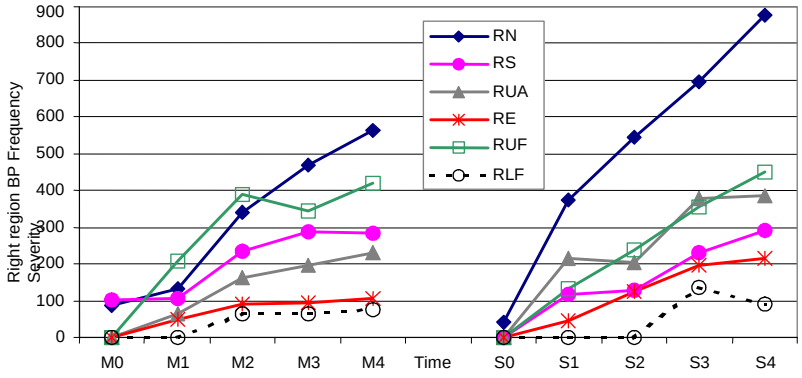


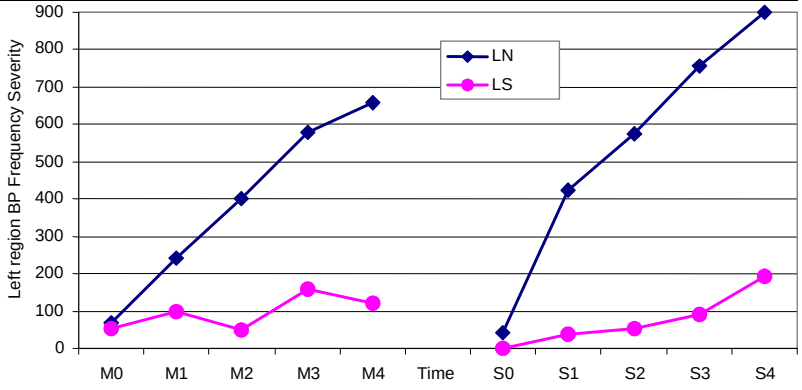
Figure 4-20 – Body-part (BP) discomfort maps from the neck-mobile session for all participants at times 0hr to 4hr showing where participants experienced discomfort. All body-maps were combined.

The average BP Severity, BP frequency and BP Frequency Severity for each body-part is shown in Figure 4-21. The tables below each graph show the number of subjects included in the BP Frequency Severity charts, as only non-zero data is shown. The full results are reported in App. B in Table B-17.

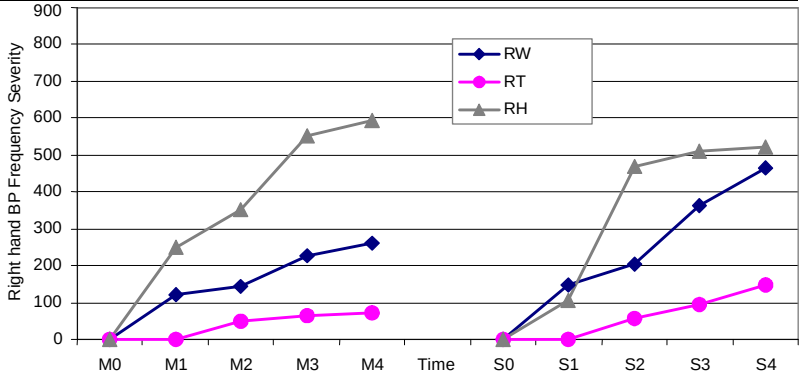
Figure 4-21 clearly shows that in almost all of the body parts in which musculoskeletal discomfort was reported, the discomfort was greater during the neck-static session compared with the neck-mobile session. This was most evident in the cervical spine region. Furthermore, it was evident that the BP Frequency Severity steadily increased during the four-hour measurement tasks, indicating that the participants were experiencing more discomfort and pain during the experiment in most body-parts.



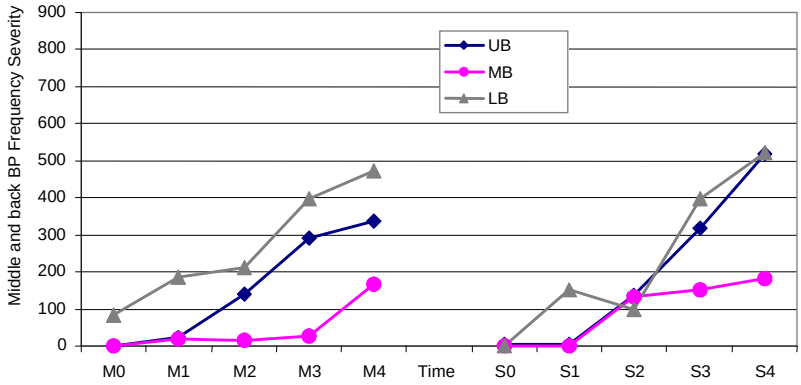
	M0	M1	M2	M3	M4		S0	S1	S2	S3	S4
RN	3	4	8	9	11		1	9	12	13	15
RS	2	2	4	6	6			2	2	4	6
RUA		1	3	3	5			5	5	6	5
RE		1	2	2	3			1	3	4	4
RUF		5	6	5	6			3	5	5	7
RLF			1	1	1					2	1



	M0	M1	M2	M3	M4		S0	S1	S2	S3	S4
LN	3	6	9	13	12		1	11	13	13	14
LS	2	2	1	3	2			1	1	2	4



	M0	M1	M2	M3	M4		S0	S1	S2	S3	S4
RW		3	3	5	6			3	5	7	9
RT			1	2	2				2	2	3
RH		7	9	11	12			6	10	10	9



	M0	M1	M2	M3	M4		S0	S1	S2	S3	S4
UB		1	3	5	7		1	1	4	7	9
MB		1	1	1	3				2	3	3
RLB	3	4	4	8	9			3	4	9	11

Figure 4-21 – Average body-part (BP) Frequency Severity for each body-map region for neck status of mobile (M) and static (S) at times 0 hr to 4 hr (0-4) (only non-zero scores are shown). Tables show the number of subjects represented in each group.

4.5.3.2 WHOLE OF BODY DISCOMFORT SCORES

The whole of body BP Frequency, BP Severity and BP Frequency Severity scores are shown in Figure 4-22. Full results are reported in App. B, Table B-18. These average musculoskeletal discomfort scores for all body parts confirmed the trends shown above in Figure 4-21; there was, on average, greater musculoskeletal discomfort and pain in the neck-static session than the neck-mobile session, and this pain and discomfort increased steadily during the four-hour sessions in response to the imposed postural load.

The BP Frequency Severity was calculated by the multiplication of the BP Frequency by BP Severity (i.e. the number of all non-zero VAS ratings multiplied by the average VAS score for the non-zero values). This value has been used previously [404] and helps interpret both number and severity of body part discomfort scores in one figure.

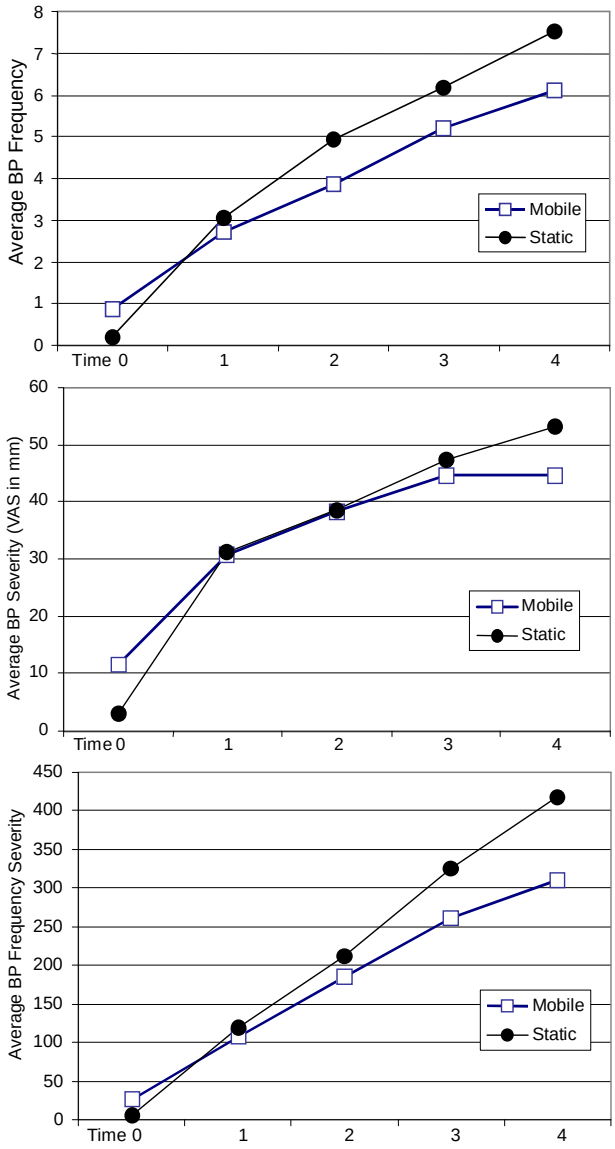


Figure 4-22 – Average body-part (BP) Frequency, BP Severity and BP Frequency Severity for neck status of mobile and static at times 0 hr to 4 hr (0-4)

4.5.3.3 BODY-PART DISCOMFORT ANALYSIS OF VARIANCE

The body part discomfort scores were *significantly greater in the neck-static measurement session than in the neck-mobile session*. This outcome was significant for all body part discomfort data, the right neck, right upper arm, BP Frequency and BP Frequency Severity (Table 4-14). For each individual body part participants reported more discomfort and pain in the neck-static session, than the neck-mobile session, although many of the differences were not significant. This outcome supported the hypothesis that the postural and action characteristics of the head and neck influenced the musculoskeletal discomfort and pain in the neck and at other musculoskeletal sites.

There was also a *significant outcome for time of measurement*. For all discomfort data, including most individual body parts and the overall discomfort scores (BP Frequency, BP Severity, BP Frequency Severity), the musculoskeletal discomfort and pain increased significantly during the four-hour measurement sessions (Table 4-14). This outcome supported the hypothesis that the medium-term exposure to the ergonomic postural and action risk factors influenced the musculoskeletal pain in the participants (the post-hoc analysis of significant outcomes is reported in App. B, Table B-19, Table B-20 and Table B-21).

Body-part	Neck status	Time	Neck x Time	Location	Time x Loc
All data	$F_{(1,14)} = 3.24$*	$F_{(4,56)} = 29.6$+	$F_{(4,56)} = 5.8$+	$F_{(22,308)} = 10.2$+	$F_{(88,1232)} = 5.8$+
EY		$F_{(4,56)} = 3.4$*			
RN	$F_{(1,14)} = 3.59$*	$F_{(4,56)} = 22.5^{+}$	$F_{(4,56)} = 2.8$*		
LN		$F_{(4,56)} = 24.4^{+}$			
RS		$F_{(4,56)} = 4.3^{+}$			
RUA	$F_{(1,14)} = 4.81$*	$F_{(4,56)} = 5.5^{+}$	$F_{(4,56)} = 3.0$*		
RE		$F_{(4,56)} = 3.1$*			
RUF		$F_{(4,56)} = 6.7^{+}$			
RW		$F_{(4,56)} = 8.1^{+}$			
RH		$F_{(4,56)} = 16.2^{+}$			
UB		$F_{(4,56)} = 8.5^{+}$			
MB		$F_{(4,56)} = 3.6$*			
LB		$F_{(4,56)} = 12.3^{+}$			
BP Frequency	$F_{(1,14)} = 3.82$*	$F_{(4,56)} = 47.6^{+}$	$F_{(4,56)} = 3.6$*		
BP Severity		$F_{(4,56)} = 40.5^{+}$	$F_{(4,56)} = 3.5$*		
BP Frequency Severity	$F_{(1,14)} = 3.24$*	$F_{(4,56)} = 29.6^{+}$	$F_{(4,56)} = 5.8$+		

Table 4-14 – Significant outcomes from the ANOVA analysis for body-part and body region discomfort scores (only significant outcomes are shown). * $p<0.05$, + $p<0.01$

4.5.4 CERVICAL RANGE OF MOTION (ROM) RESULTS

4.5.4.1 SUMMARY OF CERVICAL ROM RESULTS[12]

Cervical ROM *decreased* between the start and end of each measurement session in all measurement planes (flexion/extension, lateral flexion and rotation), except for rotation in the neck-mobile session (see Figure 4-23 and Table 4-15). The first and second ROM measurements were averaged. Rotation most likely increased during the neck-mobile session because participants were required to rotate the head once every minute to observe the lights placed in difficult to see positions.

[12] Through technical error, two participants were not measured for some movement planes at one of the participants' measurement sessions. The missing data was 2.8% of all ROM data. To assist in the ANOVA statistical analysis, the missing data was imputed using SPSS (SPSS for Windows, Release 11.5.0) with the entropy method.

Neck Status	Time	Flex/Extension			Lateral Flexion			Rotation			total ROM		
		Mean	SD	No	Mean	SD	No	Mean	SD	No	Mean	SD	No
mobile	start	113.4	13.1	30	78.8	8.7	28	140.7	11.4	28	332.3	25.8	28
	end	106.5	15.7	28	76.4	11.4	28	146.8	12.6	28	329.7	32.0	28
	mean	110.1	14.7	58	77.6	10.1	56	143.8	12.3	56	331.0	28.8	56
static	start	113.8	15.9	30	79.4	10.6	30	141.0	11.0	30	334.2	28.7	30
	end	108.4	16.6	30	76.9	11.2	30	139.6	13.1	30	324.9	35.3	30
	mean	111.1	16.3	60	78.2	10.9	60	140.3	12.0	60	329.5	32.2	60
Mean	start	113.6	14.4	60	79.1	9.7	58	140.9	11.1	58	333.3	27.1	58
	end	107.5	16.1	58	76.7	11.2	58	143.1	13.3	58	327.2	33.5	58
	mean	110.6	15.5	118	77.9	10.5	116	142.0	12.2	116	330.2	30.5	116

Table 4-15 – Average whole-plane cervical range of motion (ROM) in degrees for each movement plane.

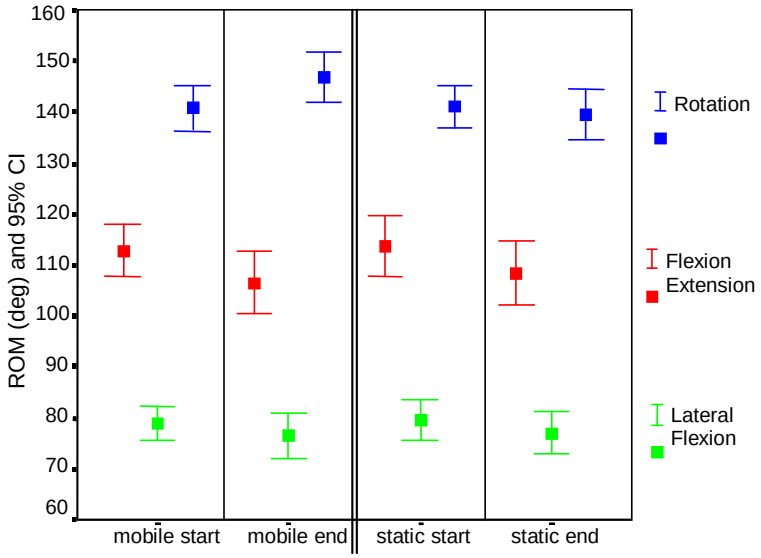


Figure 4-23 – Average cervical range of motion values for each movement plane

Table 4-16 shows ROM in each measurement plane *from a neutral position* with conjunct motions (conjunct motions are movements in planes other than the primary movement plane). Except for flexion/extension, movements in most planes were relatively symmetrical. As noted above, the ROM in each plane and in each direction decreased between the start and end of each measurement session.

		Neck-mobile						**Neck-static**					
		Start			End			Start			End		
		Rot	LF	FE	Rot	LF	FE	Rot	LF	FE	Rot	LF	FE
		Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean
primary movement	Right Rot	**69.3**	12.3	5.6	**71.6**	10.9	4.4	**68.1**	13.9	5.4	**67.7**	10.6	3.8
	Left Rot	**-71.5**	-11.9	0.0	**-75.2**	-8.1	-4.1	**-72.9**	-13.3	-0.6	**-71.9**	-8.2	-2.4
	Right LF	1.9	**39.5**	0.1	2.7	**37.6**	0.4	3.5	**37.3**	-1.8	6.6	**32.7**	-3.1
	Left LF	-2.7	**-39.4**	-4.3	-2.6	**-38.8**	-3.8	-4.5	**-42.1**	-2.9	-4.7	**-33.2**	-1.9
	Flexion	0.8	-1.1	**41.7**	0.6	-1.6	**39.6**	0.4	-1.5	**42.5**	1.2	0.0	**41.6**
	Extension	6.8	3.5	**-71.7**	5.6	6.8	**-66.8**	7.8	0.4	**-71.3**	5.2	3.2	**-66.8**

Table 4-16 – Average cervical range of motion of primary movement from the neutral position and conjunct motion in planes other than the primary movement plane. Bold text indicates ROM values in the primary movement plane [Rotation (Rot: +right, -left), Lateral Flexion (LF: +right, -left), Flexion/Extension (FE: +flexion, -extension)]

4.5.4.2 TOTAL ROM

Total ROM (derived by adding the values of flexion/extension, lateral flexion and rotation) also *decreased between the start and end* of each measurement session. The decrease in ROM was *larger in the neck-static session* than the neck-mobile session (Table 4-15 and Figure 4-24).

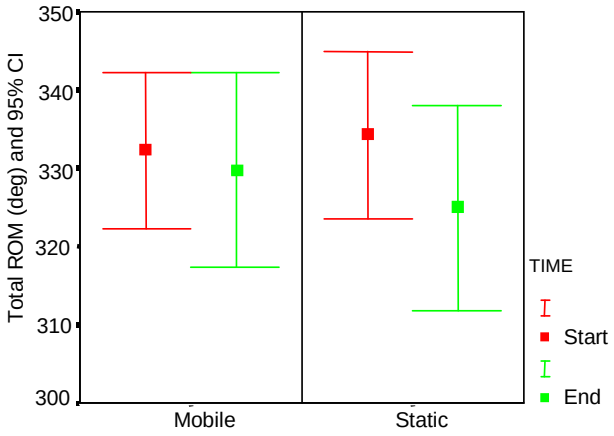


Figure 4-24 – Total cervical range of motion values for the neck-static and neck-mobile measurement sessions

4.5.4.3 CHANGE IN ROM OVER TIME

Table 4-17 shows the change in ROM in degrees between the start and end of the measurement sessions. In almost all planes cervical ROM decreased. The change in ROM was greater during the neck-mobile session than the neck-session static for flexion/extension and lateral flexion, although the difference between the two sessions was small.

Neck Status	Flex/Ext			Rotation			Lateral Flexion			Mean			total ROM		
	Mean	SD	No	Mean	SD	No	Mean	SD	No	Mean	SD	No	Mean	SD	No
Mobile Δ end-start	-6.1	8.5	26	7.6	8.4	26	-2.5	5.6	26	-0.4	9.5	78	-1.1	17.3	26
Static Δ end-start	-5.4	12.3	30	-1.5	8.9	30	-2.4	7.2	30	-3.1	9.7	90	-9.3	23.2	30
Mean Δ end-start	-5.7	10.6	56	2.7	9.7	56	-2.5	6.4	56	-1.8	9.7	168	-5.5	20.9	56

Table 4-17 – Average change in ROM between the start and end of the measurement sessions

4.5.4.4 CERVICAL ROM ANALYSIS OF VARIANCE

There were *no significant differences* in cervical ROM between the neck-static and neck-mobile measurement sessions. There were also no significant differences in ROM between the start and end of each measurement session in all measured planes, except for flexion/extension. Flexion/extension decreased by an average of 5.7 deg during the measurement sessions. This was a significant change (Table 4-18).

Plane of motion	Neck status	Time	Neck status x Time
Rotation			$F_{(1,74)} = 22.23^{+}$
Flexion/Extension		$F_{(1,14)} = 6.97^{*}$	
Lateral Flexion			
total ROM			$F_{(1,74)} = 6.96^{+}$

Table 4-18 – Significant outcomes from the ANOVA analysis for cervical range of motion. * $p<0.05$, + $p<0.01$

The post-hoc analysis of the interaction between neck status and time (Table 4-19) shows some interaction between the variables: total ROM at the end of the neck-static session was significantly lower than at the start of the same session, and also lower than the start and end of the neck-mobile session.

Total ROM		static end	mobile end	mobile start	static start
	Mean	324.9	331.5	333.4	334.2
static end	324.9	--	6.54+	8.45+	9.28+
mobile end	331.5		--	1.91	2.74
mobile start	333.4			--	0.83

Table 4-19 – Post-hoc analysis of total range of motion data for interaction between neck status (mobile or static) and measurement time (start or finish)

4.5.5 SELF-REPORTING INSTRUMENT RESULTS

A summary of the questionnaire variables is shown in Table 4-20. There were no significant differences in scores between the two measurement sessions.

	Session 1		Session 2		Average	
	Average	SD	Average	SD	Average	SD
Age	24.5 yrs	2.1	not measured			
Region Count	2.9	2.7				
Static postures	5.8 hrs	2.3				
Manual labour postures	0 hrs	0				
Total Exercise	4.3 hrs	3.3				
NDI	9.0	6.1	9.0	6.6	9.0	6.2
POMS_TA	11.3	8.1	8.8	5.0	10.1	6.8
POMS_DD	6.2	6.8	4.3	3.5	5.3	5.4
POMS_AH	5.5	4.4	6.0	4.1	5.7	4.2
POMS_VA	14.9	4.9	14.2	5.9	14.6	5.3
POMS_FI	9.9	7.1	8.7	6.2	9.3	6.6
POMS_CB	8.1	4.7	6.5	2.8	7.3	3.9
POMS_TMDS	26.1	27.7	20.0	18.2	23.1	23.4
STAI-S	35.0	8.5	38.6	9.9	36.7	9.2

Table 4-20 – Summary table of questionnaire variables including psychological questionnaires

The self-reporting questionnaire results indicated that the participants of this study were *comparable to normal adult populations*. The neck disability index (NDI) was in the mild disability range [421], the Spielberg State Anxiety (STAI-S) scores were similar to working adults [423] and most Profile of Mood States (POMS) values were lower than those reported from adult normative samples [422]. In addition, these results were similar to the asymptomatic participant reports from Ch. 6.

4.5.6 MEASURES CORRELATION ANALYSIS

A correlation analysis was completed to better understand if the different measurement variables were varying together in some manner during the measurement sessions. Full results are reported in App. B, Sec. B.5.

Correlation analysis of the cervical range of motion (ROM), pressure pain threshold (PPT) data for the cervical and musculoskeletal regions, neck disability index (NDI) scores, total region count, the profile of mood states TMDS score and the Spielburger anxiety score is shown in Table 4-21. There were poor correlations between most variables, except between the total PPT in the cervical spine and the total PPT in the tender points and control points (R = 0.72).

There were also some significant negative correlations between the neck disability index (NDI) and some cervical range of motion (ROM) motions (R=-0.62). This negative association is shown in Figure 4-25, which indicates that as the NDI increases (or as the self-reported neck disability increases) the ROM decreases (R=-061).

	Total region count	POMS TMDS	NDI	Spielberg	Total cervical PPT	Total TeP & CP PPT
POMS TMDS		--				
NDI			--			
Spielberg		0.60*		--		
Total cervical PPT					--	
Total TeP & CP PPT					0.72+	--
Flex/Ext			-0.62*			
Lat Flex						
Rot						
total ROM			-0.61*			

Table 4-21 – Pearson's R correlation coefficient values between the cervical range of motion results, neck pain and headache visual analogue scale scores, pressure pain threshold, and some questionnaire results. * $p<0.05$, + $p<0.01$.

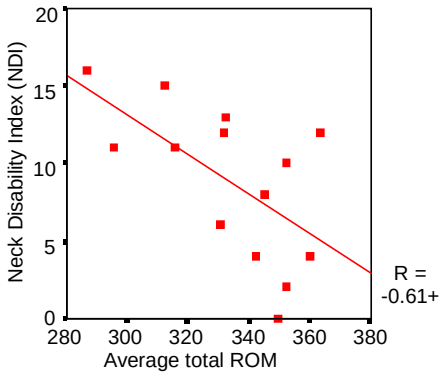


Figure 4-25 – Scatter plot of average total cervical range of motion (ROM) and the neck disability index (NDI) scores (+ $p<0.01$)

There were good correlation outcomes between the total PPT scores from the TeP and CP locations and most cervical locations. In addition, the total PPT scores from the cervical spine measurement locations had good correlation with the total PPT score from the TeP and CP sites (R=0.72). As evident from Figure 4-26, as pain sensitivity increased in the cervical spine, the pain sensitivity also increased in the TePs and the CPs.

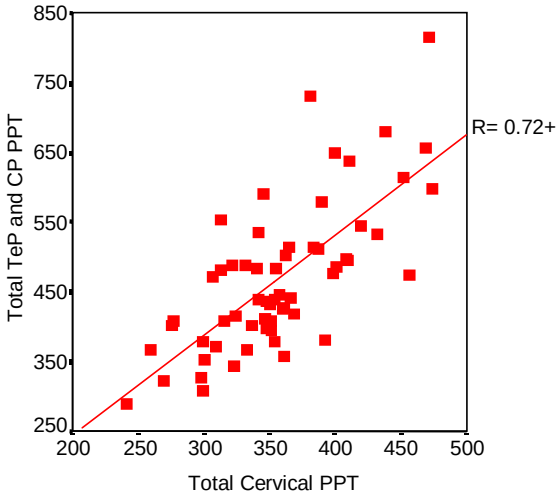


Figure 4-26 – Scatter plot of total tender point (TeP) and control point (CP) pain pressure threshold (PPT) vs total cervical PPT for all measurements (+ p<0.01)

4.6 DISCUSSION

The discussion will explore the literature and the results of the current investigation, and will compare the results against the hypotheses outlined in Sec 4.2 of this chapter.

4.6.1 THE ERGONOMICS COMMUNITY AND RPS

The ergonomics community has not accepted the potential neurobiological basis for the chronic musculoskeletal pain disorder RPS. This has limited investigation of the relationship between ergonomic exposures, such as posture and repetitive actions, and pain manifestations such as hyperalgesia, referred hyperalgesia, referred pain and allodynia, all of which play an important role in chronic musculoskeletal pain syndromes. *Prospective studies*, of an association between ergonomic risk factors and pain variables (such as this investigation) would be of benefit to employees who are engaged in sedentary based work. There exist very few investigations exploring the association of ergonomic risk factors and changes in pain sensitivity.

The rheumatology and pain fields have also not extensively investigated the putative association between ergonomic risk factors (such as poor posture and repetitive actions) and features of RPS and FM. Workplace ergonomic exposures that may act as aetiological factors in chronic musculoskeletal pain syndromes are unclear. Specific guidelines regarding ergonomic workplace factors and hypersensitivity of the peripheral and/or central pain system, which may manifest as tenderness, allodynia and referred tenderness and pain, are presently at their very early stages. *This investigation was conducted to elucidate some of these issues and to promote links* between the research fields of pain physiology and rheumatology, and the fields of ergonomics and occupational health and safety.

4.6.2 SUMMARY OF MAIN FINDINGS

The occupational environment used in this investigation exposed participants to ergonomic risk factors that caused musculoskeletal discomfort in several body regions. The work environment required participants to assume a static and constrained posture that was characterised by a 'forward head posture' and 'rounded shoulders'. It also required repetitive actions of the body-parts that interacted with the work environment. *Short-term exposure to these ergonomic risk factors resulted in medium-to-high musculoskeletal discomfort* in the working regions of the musculoskeletal system and an *increase in pain sensitivity* at several musculoskeletal locations. There was also a *reduction in cervical ROM*.

In all measured variables the values were *greater when the task was performed with a static neck* posture (neck-static measurement session) than when exactly the same task was performed with variations made to the posture and actions of the head and neck at least once a minute (neck-mobile measurement session). The posture and action characteristics of the current investigation are discussed in Sec. 4.6.3.

These outcomes lent some support to the hypothesis that the ergonomic risk factors of poor posture and repetitive actions may have some influence the function of the pain system, and in a relatively short period of time. However, as will be discussed below in Sec. 4.6.10, measurements from a baseline group of participants in good working postures was not established. Hence, it was not possible to discount either a time factor associated with the conduction of work, or some other factor. The pain sensitivity, self-

reported musculoskeletal discomfort and cervical range of motion results are discussed below in Secs. 4.6.4, 4.6.5 and 4.6.6, respectively.

The postural and action characteristics of the *cervical spine* most likely affected the pain-processing function of the nociceptive system, during the computer based tasks. The pain sensitivity and body-part discomfort results were significantly increased when the cervical spine was held in a static posture, compared with a neck posture that included regular large postural changes. Some locations remote from the cervical spine were also significantly affected by the posture and action characteristics of the neck, including the right arm. Given that postures of the cervical spine were varied between the two measurement sessions, the results supported the hypothesis that the posture and action characteristics of the neck can influence pain sensitivity and musculoskeletal discomfort in the cervical spine and upper limbs. However, not all aspects of the PPT results supported this hypothesis. These outcomes supported general ergonomic advice that tasks involving non-static postures are more optimal than prolonged static postures [81]. This is further discussed in Sec. 4.6.7.

In this investigation it was hypothesised that poor occupational posture (particularly of the neck), combined with repetitive arm actions, disturbed the function of the cervical spine and *pain-modulation of the nociceptive system*. Nociceptive afferent stimuli from the cervical spine and other working regions of the musculoskeletal region may have contributed to hypersensitivity of the pain system via peripheral sensitisation and possibly also including central mechanisms. The dorsal horn neurons have shown an ability to become hypersensitive from a sustained afferent barrage from mechanisms such as wind-up and central sensitisation. Hence, it was possible that the increased pain sensitivity and discomfort in the musculoskeletal system may have represented manifestations of both peripheral and central mechanisms. However, it was not possible to determine if central hyperexcitability was a contributing factor or not. The pain sensitivity changes, either of peripheral and/or central origin, and altered cervical spinal function may have characterised the first manifestations of RPS. *It was clear that peripheral, and possibly central, augmented pain processing contributed to changes in the clinical variables that were associated with pain assessment***,** during the measurement sessions. This is further discussed in Sec. 4.6.8.

The cervical spine is a region of the musculoskeletal system that appears to be more susceptible than others to initiating possible aetiologic factors related to the onset of RPS and FM. Given that the postural load imposed on participants during the measurement sessions was focused on the cervical spine, which caused a change in the pain-processing function in the peripheral pain system, and possibly the central nervous system, and that the putative phenomena involved in the increased pain sensitivity are also factors in the pathogenesis of RPS and FM, the *postures and actions undertaken in this experiment may be risk factors for these pain syndromes*. It is recommended that the postures and actions described in this experiment should not be undertaken as part of daily work.

However, for FM this risk is probably low. Prevalence rates of FM are low in the general population averaging about 2% of the population. Considering many workers undertake computer based work on a daily basis, and do not proceed to develop FM, the risk factor is regarded as low. This is further discussed in Sec. 4.6.9.

4.6.3 POSTURE RESULTS

The postures adopted by participants during the measurement sessions represented a compromise between the visual and task requirements, and musculoskeletal discomfort. The posture adopted was generally static, constrained and poor, due to the high monitor location and distant and high location of the mouse pad. When compared with the zero or neutral posture, the posture assumed was a ‘slumped’ flexed torso posture with a slightly flexed trunk, flexed lower cervical spine, extended upper cervical spine and head, flexed and abducted arm, extended forearm and extended wrist (see Table 4-5).

The posture of the trunk, head and neck has been described in the ergonomic literature as ‘forward head posture’, which involves a combination of lower cervical flexion, upper cervical extension (head tilt) as well as ‘rounded shoulders’ (shoulder protraction and elevation) [461]. These postural characteristics are commonly adopted by office workers [461], making the outcomes of this investigation relevant to many office based workers who use computers. The ergonomic risk factors associated with this posture were discussed above in Sec. 4.4.

The posture of all body segments in the neck-static measurement session compared with the neck-mobile session was *not* significantly different when the *lights were off* (see

Table 4-5). However, *there were large variations in posture* between the neck-static and neck-mobile sessions, during the *light-on* events (see Table 4-6). In the neck-mobile session, when participants had to look for the light, the trunk and head were both rotated and flexed, the arm was raised, abducted and rotated, the elbow was flexed and the wrist placed in a neutral posture. In contrast, for the neck-static session during light-on periods, only head flexion, arm flexion, abduction and rotation, and wrist posture, were noticeably different than during the light-off periods. From these results (Table 4-6), when participants were looking for a light (the light-on periods (~10 secs)), there were different postures between the neck-static and neck-mobile sessions in the *trunk, arm and particularly the head and cervical spine*.

The different postures adopted in the neck-static session during light-on periods, compared with postures in the neck-mobile session during light-on periods, *represented the only difference* between the two measurement sessions. Hence, the differences in the dependant variables of 1. pain sensitivity, 2. cervical range of motion and 3. body-part discomfort between the neck-static and neck-mobile measurement sessions *were a consequence of this once-a-minute light on postural differences.*

There were also considerable *differences* in the average postures *between participants* during the measurement sessions (see Table 4-5). Although the workstation computer dimensions were adjusted for each participant with the aim of minimising the effect of each participant's anthropometry, considerable variation was found in the postures adopted by participants. This outcome was consistent with previous posture investigations that demonstrated large inter-individual working postures [86,331,464] and supported general ergonomic advice that preferred postures vary considerably from person to person [465].

To examine how often each body-part was moved during the light-off periods, the number of times each posture alternated (when the lights were off) within a scale of 2 deg widths, was determined. This was to gain some insight to the *repetitiveness* of each segment (see App. B, Table B-2 and Table B-3). Posture codes associated with the head and hand had the highest number of postural changes, and the arm and trunk posture codes had the lowest. There were large differences between the posture codes that were highly repetitive, compared with other posture codes.

The head interacted directly with the workstation via the eyes with the computer monitor, and the hand with the computer mouse, whereas the trunk and arm were held in static postures as support for the distal segments of the head and hand. The head and hand were moved repetitively in response to the task requirements of the computer games, which explained why these segments had highly repetitive action characteristics.

The use of the posture measurement system developed in this thesis (see Ch. 3) was successful and allowed an in-depth investigation of the possible contribution of the factor of posture to the pain outcomes reported by participants. The analysis of one participant's posture and action results provided thorough analysis of the action characteristics of the two tasks (see Figure 4-12, E and D). This analysis was revealing in terms of the work action differences between the two measurement sessions.

4.6.4 PRESSURE PAIN THRESHOLDS (PPT)

The PPT results indicated that of the tender points (TeP) and control points (CP), the right epicondyle and right trapezius TePs were the most sensitive mechanical pressure (see Figure 4-13). These sites were located in regions of the musculoskeletal system that had significant postural load placed on them as a consequence of the workstation layout.

The upper cervical spine locations were significantly more sensitive to mechanical pressure than the lower cervical spine. The top four locations on the left and right sides the cervical spine were significantly lower than the measurement sites near C7 (locations L5 and R5) and in the trapezius (locations TL and TR) – see Figure 4-15. This outcome confirmed the findings from the investigation reported in Ch. 6, where the pain sensitivity assessments in the upper cervical spine were also significantly greater than in the lower cervical spine.

In almost all sites where PPT measurements were conducted, the pain sensitivity increased during both the neck-static and neck-mobile measurement sessions. The increase in pain sensitivity was greater for the neck-static than the neck-mobile session.

Hypothesis – $H0_1$-A: There was no change in the pressure pain threshold (PPT), or pain sensitivity, at the tender points, control points or at the cervical spine after performance of two four-hour computer-based tasks with poor ergonomic characteristics – ***REJECTED.***

There was a *significant outcome for time of measurement* in the tender point (TeP) and control point (CP) pain sensitivity measurements. The total PPT, the upper right quadrant TePs and CPs, the upper left quadrant TePs, and several individual locations, significantly decreased in value during the measurement sessions (see Table 4-9). This indicated that the postural load imposed on participants during the four-hour measurement sessions significantly influenced the PPT in most regions of the musculoskeletal system.

There was also a *significant outcome* for time of measurement in the cervical spine measurement locations. The total cervical PPT, and the PPT of the left and right sides, and most individual locations demonstrated a significant change in scores between the start and end of the measurement sessions (see Table 4-12). Based on these outcomes, the *hypothesis $H0_1$-A was rejected*; the pain sensitivity increased significantly in the tender points, control points and in the cervical spine during performance of the computer-based tasks.

As noted above in Sec. 4.4, the static and constrained postural load (particularly in the cervical spine), the small and precise repetitive actions of the head and hand, and the once a minute raising of the outstretched arm above shoulder height, represented ergonomic risk factors of musculoskeletal discomfort and pain. *These ergonomic risk factors were most likely associated with the changes observed in the PPT scores* of most locations in participants. This is discussed further in Sec. 4.6.8 and Sec. 4.6.7.

The results of the current investigation were consistent with previous prospective ergonomic investigations that showed a positive association between time spent engaged in work with poor ergonomic task characteristics and change in pain sensitivity. Ergonomic factors including repetitive [363,378], forceful actions and static muscle work [369] have been associated with changes in pain sensitivity. Nakata et al. [378] showed that in healthy participants, perceived musculoskeletal discomfort and muscular activity from light repetitive work was associated with a change in pain sensitivity. Farrell and Littlejohn [363,368] demonstrated that tasks that required less variety of action and static muscle work were associated with decreases in PPT values in FM patients and healthy participants. Repetition frequency, static muscle work and force influenced the pain sensitivity in the body regions active during specific work tasks and also in the contralateral side [368].

Hypothesis – $H0_2$-A: The PPT at the tender points and control points was not significantly decreased after performance of the task that had a static cervical spine posture (the neck-static measurement session), as compared with the task that had more dynamic work actions in the cervical spine (the neck-mobile measurement session) – ***REJECTED.***

The PPT in the TePs and the CPs *differed for neck status* between the neck-static and neck-mobile sessions. The PPT was *significantly lower* in the neck-static session compared with the neck-mobile session. The PPT values were lower in the neck-static session when compared with the neck-mobile session at all measurement locations, (except for the right supraspinatus and left trapezius).

A significant difference in PPT for neck status was observed at several individual locations, and for the upper right and left quadrant control point PPT values. Some sites were significantly lower during the neck-static session, than during the neck-mobile session. Based only on the pain sensitivity measurement in the tender points and the control points, the *hypothesis $H0_2$-A was rejected*, indicating that the postural and action characteristics of the neck and head most likely influenced pain sensitivity in the musculoskeletal system.

Hypothesis – $H0_2$-B: The PPT in the cervical spine was not significantly decreased after the neck-static measurement session, compared with the neck-mobile measurement session – ***NOT REJECTED.***

At the *cervical spine* measurement locations, the PPT was *not significantly different for neck status* between the neck-static and neck-mobile measurement sessions. The majority of cervical measurement locations demonstrated a lower PPT during the static compared with the mobile sessions, but the difference was small and not significant. Therefore, *hypothesis $H0_2$-B was not rejected* for the pain sensitivity measurements conducted in the cervical spine.

The *percentage change* in PPT in the tender points, control points and cervical spine measurement locations during the neck-static measurement sessions compared to the neck-mobile session was *not significantly different* (see Figure 4-17 and Table 4-13). The percentage change in PPT was not consistent with increased pain sensitivity in the neck-static compared with the neck-mobile session. Although the PPT in the neck-static

sessions was significantly lower than the neck-mobile session in the tender points and the control points, suggesting that the posture and action characteristics of the neck-static session had a greater impact on pain system sensitivity, this was not supported by the percentage change of PPT results. Instead, during each measurement session the percentage change in results was similar. Therefore, for the *percentage change in PPT, the hypothesis $H0_2$-B was not rejected*.

In summary, the PPT results from the tender points and control points were significantly different between the neck-static and neck-mobile measurement sessions (hypothesis $H0_2$-A rejected). In contrast, the cervical PPT results and the percentage change in PPT were not significantly different between the two measurement sessions (hypothesis $H0_2$-B not rejected). Furthermore, the one-sided statistical test used in testing the hypotheses $H0_2$-A and $H0_2$-B increased the possibility of Type I statistical error, which increased the chance of rejecting these hypotheses. These outcomes made interpretation of the pain sensitivity results difficult.

However, the next section (Sec. 4.6.5) shows that the self-reported pain and discomfort results were significantly greater in the neck-static measurement sessions than the neck-mobile session. This outcome, combined with the PPT results, lended support to the hypothesis that the static nature of the cervical spine during the neck-static computer task did significantly influence pain sensitivity in the cervical spine and other musculoskeletal sites, compared with the computer task where the cervical spine was more mobile (during the neck-mobile session). This is discussed further in Sec. 4.6.8 and Sec. 4.6.7.

Correlation analysis showed that there was good to high correlation between most cervical measurement locations, suggesting that most neck locations varied together (see App. B, Table B-24). This indicated that although there was large variability in PPT between some of the measurement sites, what the sites were measuring was most likely common to each site. The measurement sites were in close proximity to each other, which probably contributed to the good correlations.

There were poor correlations between the cervical spine PPT measurements and the PPT measurements at other musculoskeletal sites at the TePs and CPs, except for the sites that were in close proximity to the neck. In App. B at Table B-26 the left and right

trapezius and supraspinatus TeP locations (RTra, RSup, LSup and LTra) had good to high correlations with most cervical spine measurement locations. This lended support to the notion that PPT measurement sites in close proximity will predominantly measure the same thing.

4.6.5 BODY PART DISCOMFORT RESULTS

The BP discomfort VAS scores indicated that participants experienced discomfort in several body regions during the measurement sessions. The highest discomfort at the conclusion of the measurement sessions was felt in the neck and right body-parts (including the shoulder, arm, forearm, wrist and hand) and the upper and lower back (see App. B at Table B-17 and Figure 4-21). These regions included areas where the posture was greatly deviated from the neutral posture.

Hypothesis – $H0_1$-B: There was no change in the self-reported body-part discomfort after the two four-hour computer-based tasks – ***REJECTED.***

In the body regions where postural load was applied the increase in discomfort between the start and the end of the measurement sessions was statistically significant. These areas were the neck, right arm to wrist, and upper, middle and lower back. There was also a significant increase in the average body part (BP) Frequency [number of body-parts rated greater than zero], average BP Severity [average of all non-zero ratings], and the average BP Frequency X Severity [derived from BP Severity multiplied by BP Frequency] during the measurement sessions (a description of the derivation of these 'whole of body region' scores is described above in the methodology in Sec. 4.3.5.4).

This outcome indicated that the postural load placed on the musculoskeletal system, due to the workplace layout and the resultant static and constrained postures, did significantly influence the self-reported musculoskeletal pain and discomfort. Therefore, the hypothesis $H0_1$-B was rejected.

The self-reports of high discomfort in the neck, shoulders, arm, wrist and back concurred with previous ergonomic investigations of musculoskeletal complaints in VDT work. Musculoskeletal discomfort of VDT users most commonly includes pain in the back, neck and shoulders [130,451,452].

Hypothesis – $H0_2$-C: The self-reported body-part discomfort was not significantly increased after the neck-static measurement session, as compared with the neck-mobile measurement session – ***REJECTED****.*

Participants reported pain and discomfort in more body-parts, and of greater severity, at the end of the neck-static session, compared with the neck-mobile session. For all body-part discomfort data, this difference was significant at the right neck, and the right upper arm, and there was a strong trend in the left neck and right wrist. There was also a significant outcome for the 'whole of body region' scores for the BP Frequency, and BP Frequency Severity (see Table 4-14).

There was also significant interaction between neck status and time of measurement for the whole of body scores and for the right neck (RN) and the right upper arm (RUA). In App. B, Table B-20 in the neck-static session at the third and fourth hours, the values were significantly higher than all other cell combinations, including all neck-mobile measurement times.

Based on these outcomes the hypothesis $H0_2$-C was rejected; participants reported significantly increased musculoskeletal pain and discomfort in the neck-static session compared with the neck-mobile session (although, this significant difference was not observed at all body part locations).

In addition, the one-sided statistical test used in testing the hypotheses $H0_2$-C increased the possibility of Type I error, which increased the probability of rejecting this hypothesis. Therefore, further investigation is warranted to better understand the association of spinal and ergonomic factors and self-reported musculoskeletal discomfort and pain.

4.6.5.1 VARIABILITY IN SELF-REPORTED DISCOMFORT BETWEEN PARTICIPANTS

There was *large variability between participants for the self-reports of pain and discomfort*. Each individual participant reported relatively similar levels of discomfort in each measurement session (although this was higher in the neck-static session than the neck-mobile session). Participants who reported high discomfort in the neck-mobile session also reported high discomfort in the neck-static session, and participants who reported low discomfort scores did so for both sessions.

It was of interest to explore why some participants were inexplicitly immune to the imposed postural load and reported low discomfort, while others experienced high discomfort at multiple regions. The following factors were examined:

4.6.5.1.1 Postural factors

The *posture* assumed by participants during the measurement sessions was greatly varied during the measurement sessions and this difference may have contributed to the amount of musculoskeletal discomfort. To explore this theory, a simple t-test was undertaken. Participants were placed into a 'high' or 'low' group based on their BP Frequency Severity score. Each posture code was then examined by unpaired t-test for significant differences.

The results showed a significant outcome for shoulder protraction. The 'high' group had an average of 6 deg more shoulder ventral protraction than the 'low' group. While there were no other significant differences, the 'high' discomfort group also displayed larger average posture values for head extension, head extension relative to the neck and right elbow flexion than the 'low' group. The postural differences between the 'low' and 'high' groups in neck flexion and shoulder protraction were in accordance with previous ergonomic studies [461].

4.6.5.1.2 Psychosocial factors

It has been suggested that factors such as emotion, attention levels and motivation may influence pain perception, probably via modulation of various descending sensory neurons [105]. In the current study, psychosocial factors may have played a role in the pain outcomes of the experiment, although this was unlikely based on the psychological and neck disability index tests results. The psychological results indicated that the participants were in general *comparable to normal adult populations.* In the NDI, STAI-S, and POMS results values were comparable to normal adults or lower (see Sec. 4.3.5.4 for a description of the questionnaires used).

To further investigate the possible contribution of psychosocial factors participants' psychosocial scores were placed in 'high' and 'low' BP Frequency Severity groups, as described above. The paired sample t-tests were not significant indicating that between the two groups there were no psychological differences. However, the NDI displayed a

strong trend between the high and low BP Frequency Severity groups (but this was not significant). The difference in the NDI scores between the groups could indicate that a pre-existing neck condition was a contributing factor to the large differences in self-reported pain and discomfort experienced by participants.

4.6.5.1.3 Other factors

It cannot be assumed, however, that the variance in participant discomfort scores was based on ergonomic and psychosocial factors alone. Other unknown factors may also have contributed to the variability in a participant's response to the physical demands of the two measurement sessions [168,466].

Armstrong et al. [467] proposed a *'dose-response' conceptual model* for work-related neck and upper-limb musculoskeletal disorders. A component of this model was the 'capacity', or the ability, of a participant to resist destabilisation due to 'exposure' to external work requirement factors. The capacity of an individual may depend on physical factors, such as the ability of the body's tissues to resist deformation, and/or non-physical factors such as self-esteem and a capacity to resist mental stress. Capacity may also be reduced or enhanced by previous exposure to work factors [467].

In this investigation, the capacity of the participants to resist the effects of the postural load on the musculoskeletal system may have been influenced by factors such as general health condition, ability to tolerate prolonged muscle load, individual differences in muscle load [455], generation of muscle load in excess of that necessary to maintain postural stability [468], individual work postures and techniques [86,331,464] and an awareness of increased muscle tension [444]. The individual contribution of these factors was unknown.

4.6.6 CERVICAL RANGE OF MOTION

Cervical ROM decreased between the start and end of the neck-static and neck-mobile measurement sessions in all measurement planes (flex/ext, lateral flex, rotation) and in total ROM, except for rotation in the neck-mobile session (see Table 4-15). Also, ROM and the change in ROM was relatively symmetrical. Table 4-16 shows that the ROM in each plane was similar on the left and right sides at both the start and end of the

measurement sessions. This indicated that the ROM was reduced in a symmetrical manner and did not develop asymmetrical properties.

During the measurement sessions, the head was held in a posture of extension for extended periods. This posture placed considerable postural load on the cervical spine and caused discomfort in this region. The increased discomfort in the neck and putative change of function of cervical structures, may have contributed to the reduction in ROM. The significantly reduced ROM in flexion/extension, and total ROM in the neck-static session, supported the use of cervical ROM measurements for describing impairment [320]. However, it was not possible to identify whether the reduced ROM was due to mechanical changes in the tissues, spinal dysfunction, pain inhibition or other unknown factors [320,416].

The ROM results in this investigation were lower than the ROM results reported in the subsequent investigation reported in Table 6-14 in Ch. 6. This was due in part to the different methodologies used in each investigation. In Ch. 6, ROM measurements were recorded with one ETS sensor placed on the head, and hence the results likely included movements from the thoracic spine and trunk. In contrast, this investigation used two sensors, with one placed on the head and the other at the base of the cervical spine at the spinous process of the seventh cervical vertebra (C7). Movements of the sensor at C7 were subtracted from the movements of the sensor at the head to remove potential movements of the thoracic spine and trunk from the ROM results. There was an average of 18.7 deg difference in total ROM between asymptomatic participants in Ch. 6 and the ROM measurements in this investigation. Based on this outcome, the use of a second sensor at C7 to limit purported extraneous movement of the thoracic spine and trunk in cervical ROM measurements was successful.

Hypothesis – $H0_1$-C: There was no change in the cervical range of motion (ROM) after the two four-hour computer-based tasks – ***NOT REJECTED****.*

The cervical range of motion (ROM) scores decreased between the start and end of the measurement sessions for lateral flexion, flexion/extension and total ROM (derived from the addition of ROM in the three primary movement planes). For flexion/extension this change was significant (see Table 4-18). These results provided some support for rejecting the hypothesis $H0_1$-C, because the cervical ROM was reduced during the

measurement sessions in some planes. However, the total ROM was not significant reduced over time and so the hypothesis was not rejected.

Rotation ROM increased during the neck-mobile session. The once a minute requirement to turn the head considerably to observe which light was on would have contributed to this outcome.

Hypothesis – $H0_2$-D: The cervical ROM was not significantly decreased after the neck-static measurement session, as compared with the neck-mobile measurement session – ***NOT REJECTED****.*

The cervical ROM was *not significantly* reduced in the neck-static measurement session, compared with the neck-mobile session. However, there was some interaction between neck status (neck-static or neck-mobile) and time. The total ROM was significantly lower at the end of the neck-static session compared with the start of that session, and also lower than at the start and end of the neck-mobile session. This outcome provided some support for rejecting the hypothesis $H0_2$-D that the cervical ROM was significantly reduced in the neck-static session, compared to the neck-mobile, but the hypothesis was not rejected due to a non-significant result based on total ROM.

4.6.7 CERVICAL POSTURE, PAIN AND SPINAL DYSFUNCTION

During the measurement sessions, the postural status of the neck (either neck-static or neck-mobile) was a *significant factor* associated with changes in pain sensitivity, self-reported body-part discomfort, and to some extent cervical range of motion. As noted above in Sec. 4.6.4 (PPT discussion) and Sec. 4.6.5 (body-part discomfort discussion), there was significantly increased pain sensitivity and higher self-reports of body-part discomfort during the neck-static session, than during the neck-mobile session in the *neck and also other regions of the musculoskeletal system*.

The *different action characteristics* of the neck-static and neck-mobile measurement sessions, during the once a minute light-on events, did influence the pain sensitivity and self-reported discomfort. Based on these outcomes, *the action and posture characteristics of the cervical spine did influence the function of the pain system* during the computer-based tasks.

The posture results indicate that the posture was the same for both sessions during the light-off periods. Hence, the *only postural differences between the two measurement sessions were during the once a minute light-on events*, when the head and neck either moved considerably to observe which light was on (during the neck-mobile session) or not at all (during the neck-static session). The greatly different action characteristics of the head and neck during the neck-mobile session at light-on events, would have significantly altered the postural load on muscles in the cervical spine and permitted muscle length changes. This most likely reduced muscle pain in the cervical muscles (particularly in the suboccipital muscles) and other structures (this is discussed further in Sec. 4.6.8.1.2).

The putative reduced activity in the nociceptors of the cervical spine during the neck-mobile measurement session, compared with the neck-static session, would have lessened the peripheral nociceptive barrage on the dorsal horn neurons, thereby decreasing the risk of central pain-modulation changes. As will be discussed further in Sec. 4.6.8, this barrage of nociceptive afferent input from the neck could have initiated changes in the pain-processing function of the central nervous system (CNS). A change in the *pattern* and/or *reduction of the barrage of afferent nociceptive stimulus* (as observed in the neck-mobile session) may have reduced any putative change in the excitability in the dorsal horn cells.

However, there was not a significant increase in pain sensitivity between the measurement sessions at most cervical spine measurement locations and some musculoskeletal sites. For example, remote sites such as the knee, epicondyles and thumb showed no change in the static group. A characteristic of a substantive central sensitisation feature could be claimed if these remote points also showed change, which they did not.

As well, there was no carry-over effect between the two measurement sessions separated by a week. The week one initial PPT measurements in the cervical spine, TePs and CPs showed no significant difference for the week two initial PPT measurements. A substantive central sensitisation would possibly have increased the PPT over this period, which was not the case. However, the experiment methodology had a large time difference between the measurement sessions to avoid carry over

effects, so it was also plausible that any central mediated changes decreased over this time period.

In addition, the *percentage change* in pain sensitivity was not consistent with increased pain sensitivity in the neck-static compared with the neck-mobile session. Hence, it remained unknown if there was a change in the sensitivity of the central pain system or not.

Therefore, this experiment provided support for the notion that the posture and actions of the cervical spine may increase *the risk* of pain sensitivity change in the dorsal horn neurons in this region, which in turn, could influence tenderness and discomfort in remote musculoskeletal regions, such as the arm. However, in this experiment it remains unknown if central pain changes contributed to the pain and discomfort reported by participants. Due to the small number of participants, further investigation is warranted.

4.6.8 PAIN MODULATION MECHANISMS

Peripheral pain mechanisms play an important role in increased somatic pain sensitivity [372], and also in driving altered pain modulation phenomena in the CNS [188,215,220,224]. Augmented central pain-processing is believed to contribute to the persistence of pain in musculoskeletal pain syndromes, manifesting clinically as muscle hyperalgesia, referred pain, referred hyperalgesia and widespread hyperalgesia [372]. These phenomena are important aspects of chronic musculoskeletal pain [372,469]. Both peripheral and central pain mechanisms may play important roles in the pain manifestations related to non-specific musculoskeletal disorders [32,60,74,469].

Based on the results of this investigation, peripheral and possibly central pain mechanisms contributed to the increased pain sensitivity and self-reported discomfort described by participants. However, it was not possible to conclusively establish whether central pain mechanisms were involved in the change in pain sensitivity during the measurement sessions. Therefore, peripheral and/or central pain factors were thought to be associated with the changes in the clinical variables that were related to pain. These peripheral and central pain phenomena are discussed in this section with regard to the pain sensitivity and self-reported discomfort results from the current investigation.

4.6.8.1 PERIPHERAL PAIN FACTORS

4.6.8.1.1 Muscular pain

The posture adopted by participants during the measurement sessions was characterised as static and constrained. These ergonomic risk factors may have restricted the blood flow to the working muscles, thereby activating muscle nociceptors [190] (muscle pain is frequently experienced during sustained muscular contractions [230]).

Muscle pain was reviewed in Ch. 2, Sec. 2.3.2. Briefly, nociceptors are found throughout skeletal muscle and the majority have non-myelinated afferents [190,197]. Some nociceptors respond maximally under *ischaemic conditions*, which is muscle contraction when the blood supply has been compromised [202]. This situation occurs in normal muscle as a result of an increase in intramuscular pressure during muscular activity [202]. This type of muscle pain is believed to be due to the accumulation of metabolites that stimulate muscle nociceptors [190,200,202], which also has a strong sensitising effect on muscle nociceptors [185,190]. Local muscle pain is usually associated with central phenomena [190].

In the trapezius muscle in particular, it has been shown that low-force contractions can cause a local muscle metabolic response [42,43]. Inhomogeneous activation of muscle fibres can result in local metabolic changes that could sensitise nociceptors. The parts of the muscle working the most under the low-force conditions may have had impeded blood flow, forcing them to work in part anaerobic conditions. The heterogeneous activation of the trapezius muscle, which might activate nociceptors under these low-threshold work conditions. Resting levels of nociceptive substances in the trapezius has been reported in patients with trapezius myalgia supporting this hypothesis [44,45]. In the current experiment, the poor posture task was characterised by low-force repetitive motions. The raised right arm would have placed a consistent load on the trapezius muscle throughout the tasks.

4.6.8.1.2 Spinal factors

As noted above in Sec. 4.4, the static and constrained posture of considerable *head extension* placed significant postural load on the neck, particularly on the neck extensor muscles and possibly on the passive cervical support structures as well. As a

consequence, most participants reported mild to significant discomfort at the end of the measurement sessions in this region. The increased cervical pain sensitivity and the significant discomfort experienced by some participants in the neck suggested that the static postural load placed on this region might have contributed to some form of dysfunction of either muscular and/or passive structures.

The neck and head posture was characterised by some flexion of the lower cervical spine and extension of the upper cervical vertebrae, particularly at the atlanto-occipital joint, during the light-off periods in both measurement sessions. This 'forward head posture' placed considerable load on the cervical spine muscles over the four-hour measurement periods [461]. Extensor moments about both the atlanto-occipital and cervical joints were required to counteract the anterior centres of mass of the head, and the head and neck combined [438]. The cervical extensor muscles, particularly in the deep sub-occipital muscles, would have acted to counteract the load moments [427,436], rather than passive tissues. In addition, significant muscle activity would have occurred in the trapezius and cervical erector spinae, probably to a level that exceeded the recommended limit level for static muscular contractions [460].

The posture and actions of the arm and trunk would have also contributed to postural load on the cervical muscles [410,453,453,454]. The posture of the arm and hand required stabilisation of the shoulder girdle and the glenohumeral joint. The load on the glenohumeral joint was transmitted to the scapula and further to the upper trapezius, cervical erector spinae and the thoracic erector spinae muscles [428,454]. The upper trapezius acts as the principle anti-gravitational muscle for the arm [428] and activity in this muscle has been found to closely correspond to shoulder joint load [430]. An association between arm and shoulder load, and neck pain has been reported [81,429,430,432]. In addition, the 'slumped' or flexed posture of the trunk (derived from FWAP-Link posture code C, see Ch. 3, Table 3-2) would have also placed postural load on several cervical and shoulder muscles [453].

These ergonomic factors would have contributed to the discomfort reported from the muscles and/or passive structures in the cervical spine during the measurement sessions. The prolonged isometric contractions of the cervical extensor muscles, and subsequent activation of nociceptors in these deep spinal muscles, may have characterised spinal dysfunction in the cervical region. Tension in passive structures of the cervical spine

including the ligaments, discs and facet joints, may have also contributed to dysfunction in these passive structures during the prolonged measurement sessions [449], although the postural load was mostly placed on the cervical muscles [410,438]. From the manual therapy literature, muscular abnormalities are believed to be an important component of spinal dysfunction [103,366] and some authors [94,112] have stated that muscular abnormalities, combined with spinal articular dysfunctions, may be responsible for spinal pain syndromes.

Unfortunately, it is very difficult to identify structural and muscular abnormalities in patients with neck pain [110,111]. Therefore, in the current investigation it was not possible to determine exactly the cervical spine structures that contributed to the neck pain reported by participants. None the less, the significant self-reported pain from this region indicated that the nociceptors in either the cervical muscles and/or passive structures were stimulated.

4.6.8.2 CENTRAL AND PERIPHERAL PAIN FACTORS

Alterations of peripheral and central pain-processing mechanisms may manifest as a reduction in the pressure pain threshold (PPT) [386]. Sensitisation of the peripheral and central pain pathways can cause a decrease in the pain threshold and an increased response to mechanical stimuli, with the clinical outcome of tenderness [65,66,287,385].

During the measurement sessions there was a significant increase in pain sensitivity (or tenderness) at most measured locations (see Sec 4.6.4 for discussion). Peripheral and/or central pain modulation phenomena were factors associated with the increased responsiveness of the nociceptive system to the applied mechanical stimuli. This was an expected outcome based on the musculoskeletal discomfort reported by participants as a consequence of the poor posture and action characteristics of the computer tasks.

The increased pain sensitivity involved peripheral pain mechanisms [61]. The preceding discussions indicate that pain in the spinal muscles, zygapophysial joints or related structures, or muscles, tendons and joints in the upper limbs would have been consequent upon the ergonomic risk factors identified in Sec. 4.4. In particular, the static and prolonged nature of the computer tasks may have caused repeated stimulation of the nociceptors and, in turn, caused them to become sensitised. Repetitive stimulation

of nociceptors will cause sensitisation [61], such that there is a reduction in the activation threshold of nociceptors [66]

4.6.8.2.1 Wind-up

In combination with peripheral mechanisms, sensitisation of pain pathways in the central nervous system may have contributed to the increased pressure pain sensitivity observed during the measurement sessions, although this was less clear. Central pain hypersensitivity can be induced by persistent muscle pain that is of moderate or high intensity [72]. Repeated stimulation of dorsal horn cells will cause the central phenomenon of *wind-up*. Wind-up manifests as a summation of action potentials from repetitive nociceptive stimulation, generating a progressively increasing and longer-lasting depolarisation of the dorsal horn neurons [66]. This homosynaptic central pain event may also be an important factor for establishing longer-term increased excitability in the dorsal horn cells, or central sensitisation [64].

4.6.8.2.2 Central sensitisation

Central sensitisation manifests as a prolonged pain threshold reduction, an increased responsiveness to afferent inputs and an expansion of the peripheral receptive field of dorsal horn neurons [63-67]. In addition, central sensitisation alters sensory processing in the spinal cord such that non-nociceptive input from low-threshold afferents can gain access to the central pain-pathways and begin to produce pain, something that never normally occurs [63]. These characteristics are expressed clinically as abnormal or heightened sensitivity with a spread of hypersensitivity to uninjured sites (secondary hyperalgesia) and the generation of pain by low-threshold mechanoreceptors (allodynia) [64,220]. This was discussed in Ch. 2, Sec. 2.3.3.3.

Central sensitisation can spread extra-segmentally within the dorsal horn cells. Some volume neurotransmitters involved in pain transmission, released by C-fibre afferents, have demonstrated an ability to diffuse over long distances in the spinal cord (e.g. substance P). These neurotransmitters evoke slow synaptic potentials and are believed to be involved in unmasking latent connections that could be involved in the referral of pain and tenderness. This means that C-fibre afferent activity, such as from prolonged muscle nociceptor activation, has the potential to influence large populations of dorsal

horn neurons in the vicinity of the release site at the dorsal horn [198,224]. Studies of pain in animals have shown that a persistent nociceptive input from a muscle can increase the population of dorsal horn neurons that could be activated by the muscle afferents. The increase in excitability, or the central sensitisation, spread within the dorsal horn for a few spinal segments, due to the strong peripheral source [75,198].

4.6.8.2.3 Peripheral and central factors at TePs

The reduction in PPT at most measured locations suggested that the generalised pain reduction may not have been exclusively a localised phenomenon, although this was not clear from the results. As noted in Sec. 4.3.5.1.1, the tender points are considered sites of the musculoskeletal system that are most densely supplied with receptors for noxious and also non-noxious stimuli [185]. A hypersensitive TeP may represent a site of primary and secondary hyperalgesia [185], which could be due to peripheral (primary) or central (secondary) mechanisms. Some measured sites were in regions that were probably not active during the measurement sessions, suggesting that the lowering of PPT in these regions could have been characteristic of secondary hyperalgesia, implying central mechanisms. The TePs in the lower regions and the left side of the body displayed increased pain sensitivity, even though minimal work was undertaken by these quadrants. The increased tenderness displayed in these non-working regions may have be indicative of an alteration of afferent processing of non-nociceptive mechanical stimuli by second-order neurons in the dorsal horn [385].

Farrell [352] also established that PPT, and change in PPT, at TeP sites is mostly a common outcome. Farrell [352] showed that repeated PPT measurements at several sites over several weeks consistently demonstrated high correlations between the different sites. Principal component analysis showed that approximately 68% of what was being measured in PPT at each measurement site was common to each site in healthy participants, and that what was being measured could be summarised in a single value.

However, in the current experiment, it was not possible to conclusively establish whether the increased pain sensitivity, or tenderness, resulted from only primary (peripheral) mechanisms, or also included secondary (central) mechanisms [55,385-387]. There was not a significant increase in pain sensitivity between the measurement

sessions at most cervical spine measurement locations (although as a whole there was a significant change) and at some TeP and CP sites. For example, remote sites such as the knee, epicondyles and thumb showed no change in the static group, yet others did. A characteristic of a substantive central sensitisation feature could be claimed if these remote points also showed change, which they did not. As well, the *percentage change* in pain sensitivity was not consistent with increased pain sensitivity in the neck-static compared with the neck-mobile session. Hence, it remained unknown if there was a change in the sensitivity of the central pain system or not.

In summary, the outcomes of this investigation support the hypothesis that the increased pain sensitivity at most measured sites involved peripheral factors. A possible contribution from central pain modulation factors was not clear. It was possible that the persistent musculoskeletal pain from the working regions of the musculoskeletal system (particularly in the neck) may have induced long-term changes in the excitability of the dorsal horn cells in the cervical spine, but this was speculative. Nonetheless, putative central changes would have been an important factor in the development of primary and secondary hyperalgesia [64]. In this investigation, the spread of tenderness to some regions of the musculoskeletal system, including the left arm and the lower regions, may have represented regions of secondary hyperalgesia, which implied a perturbation of central mechanisms. Whereas, in the right arm and cervical spine a combination of peripheral and possibly central factors may have been involved. Therefore, this experiment provided support for the notion that the posture and actions of the cervical spine may increase *the risk* of pain sensitivity change in the dorsal horn neurons in this region, which in turn, could influence tenderness and discomfort in remote musculoskeletal regions, such as the arm.

4.6.9 POSTURAL RISK FACTORS OF FM AND RPS

4.6.9.1 ERGONOMIC FACTORS AND INCREASED PAIN SENSITIVITY

As discussed in Ch. 2, Sec. 2.4.5.2, central sensitisation of the dorsal horn nociceptive neurons and disturbance of the descending pain modulatory system are the main mechanisms of central pain hypersensitivity [72-74]. These mechanisms of altered central pain-processing are believed to be likely aetiological factors in RPS and FM

[52,53,60,75]. Persistent and strong musculoskeletal pain can trigger such central pain modulation changes and, therefore, may be a risk factor for RPS and FM [60,179,188].

In the current investigation, the postural and action characteristics of the computer-based tasks caused musculoskeletal pain that may have included a peripheral and/or central pain processing changes. Altered central pain-processing mechanisms are believed to be factors involved in the pathogenesis of RPS and FM. Therefore, in this investigation, the poor ergonomic postural and action characteristics of the computer-based tasks may have represented risk of augmented pain-processing (possibly including central mechanisms and associated central pain manifestations), and hence, in the long-term, possible development of RPS. The potential association between ergonomic risk factors and development of a non-specific chronic musculoskeletal pain syndrome is discussed in this section.

In Ch. 2, Sec. 2.2.3, it was discussed that FM and RPS may exist as part of a continuum of pain and pain behaviours, and not as a discrete disorders [34,470-474]. Investigations of localised musculoskeletal pain, RPS, widespread musculoskeletal pain and FM reveal that a continuum may exist between different pain status groups. The process of deterioration within the pain groups may begin with localised pain and end with generalised pain. In this regard, it is believed that *self-reported pain of any severity* confers risk for deterioration and development of FM and RPS [186]. This conclusion is supported by the fact that most FM patients indicate that the generalised pain was preceded by chronic localised pain, usually in the axial musculoskeletal system [20,35,72,73,93,185-187].

In the current investigation, the persistent musculoskeletal pain reported by participants during the measurement sessions may have represented the very initial aspects of the pain continuum, and characterised a much lesser form of pain symptoms associated with these syndromes.

However, for FM this risk is probably low. Prevalence rates of FM are low in the general population averaging about 2% of the population. Considering many workers undertake computer based work on a daily basis, and do not proceed to develop FM, the risk factor is regarded as very low.

4.6.9.2 SPINAL FACTORS

In this investigation, participants consistently reported pain in several regions of the musculoskeletal system, but particularly in the cervical spine. Pain sensitivity of the cervical spine significantly increased during the measurement sessions, and this was also the region with the highest level of self-reported pain. Spinal factors have been highlighted as one of many factors involved in the aetiology of RPS and FM [17,20,78,93-99]. Hence, the musculoskeletal pain reported during the measurement sessions, particularly from the nociceptor rich region of the paraspinal region in the cervical spine, represented a possible *risk factor for RPS* and FM. This is further discussed and investigated in Ch. 6, Sec. 6.2.1,

The sensitised pain-processing function of the nociceptive system, observed during the measurement sessions, was a short-term phenomenon. Most participants reported no pain or discomfort as a result of the measurement sessions within a day, although some reported mild pain for a few days. However, it is plausible that in a situation where workers adopt the postures and actions of this experiment on a daily basis (e.g., as a part of an employee's normal work), long-term implications could include an ongoing and persistent peripheral nociceptive barrage to the CNS, and induce long-term changes the function of the nociceptive system via central neuronal plastic alterations. Permanent neuronal plasticity changes could represent the pathological component of the ensuing pain disorder such that normal non-nociceptive stimuli may be interpreted as tissue threatening due to the amplification of the pain signal in the CNS [60,220]. Permanent neuronal plasticity changes involve neuroanatomical restructuring in the CNS via altered synaptic connections and other structural changes, following long-standing noxious stimulation [72,74,220]. These long-term neuronal changes in the pain-processing function of the CNS are probably involved in RPS and FM [52].

The putative peripheral and central pain-processing changes that contributed to the pain sensitivity and self-reported discomfort results, may also be risk factors associated with the onset of RPS and FM. Participants reported high musculoskeletal discomfort in the cervical spine region, which has been previously identified as an area of the musculoskeletal system that is susceptible to initiating aetiological factors associated with RPS and FM. Therefore, the poor ergonomic characteristics of the task undertaken in this study may represent a risk factor of RPS. The postures and actions characteristics

of this experiments computer-based tasks should not be undertaken on a long-term or regular basis.

However, as discussed in the literature review in Ch. 2, several structures of the musculoskeletal system are believed to contribute to the onset of chronic musculoskeletal pain, and *not only spinal factors*. The trapezius muscle in particular has received much attention, and investigations conducted support the hypothesis that in some patient groups, peripheral nociception in the muscles is present, and that there is a muscle defect in the pain groups [51]. Other studies include tendon entrapment of the dorsal wrist compartments (tenosynovitis), peritendinitis (inflammation of the paratenon), elbow (e.g. lateral epicondylitis), and the wrist (e.g. carpal tunnel syndrome) [136], to name a few. The proponents of other musculoskeletal aetiologies of upper quadrant RPS in office workers is not refuted by the current study. Instead, this study has focused on spinal factors, rather than other regions of the musculoskeletal system.

4.6.10 STUDY LIMITATIONS AND FUTURE RESEARCH

A fundamental research assumption was that the change in pain sensitivity was entirely due to the poor posture participants assumed for the research. It was assumed that if the same participants had been involved in a similar work environment and for a similar amount of time, but in a good working posture, the pain sensitivity would have remained consistent; i.e. there would be no change over time. However, the question is how much of the change shown in this study could be attributed to the poor posture rather than just the time of the computer task? A baseline measurement group who were set up in good working postures could have answered this question. Therefore, for future studies it is recommended that a baseline group be assessed for similar time periods to the research design, but in a good working posture. Analysis of the poor working postures results could then be compared to the baseline good working posture results. This would provide assurance that any changes observed in the study were entirely due to the impact of the poor working postures rather than from a time factor.

The PPT measurements at each TeP and CP site were only measured once per session. Current research practice is to test three times consecutively and take the average of the three results as the PPT value. Three measurements per site may have provided more

accurate data, as there may be variation in any one application. This was not applied due to the large number of sites tested within each participant, three times over, and the inconvenience to the participants. For future studies it is recommended that TeP and CP sites are assessed three times consecutively per measurement time and the average calculated.

The author undertook all measurements due to time constraints and understanding of the operation of the equipment. Future studies would benefit from having blinded examiners to remove the possibility of participant status bias within the results.

This investigation added to the limited understanding of the relationship between specific ergonomic risk factors (static and poor posture, and repetitive actions) and change in pain sensitivity. The ergonomics community should consider pathophysiological pain mechanisms when examining risk factors for chronic musculoskeletal pain. Future studies are now required to better elucidate this relationship and for the development of better ergonomic guidelines regarding non-specific musculoskeletal disorders.

4.7 CONCLUSION

This investigation was undertaken to utilise knowledge from the fields of ergonomics, rheumatology and pain physiology. The ergonomics community has not recognised the potential neurogenic basis for chronic musculoskeletal pain. Hypersensitivity of the pain system, including changes in the function of the dorsal horn cells, has not been greatly discussed by this discipline. The rheumatology and pain physiology fields have not investigated to a great extent the potential contribution of workplace ergonomic risk factors to the onset of non-specific pain syndromes, including RPS and FM. The current investigation reported here, has utilised knowledge from these different disciplines to explore the association between workplace risk factors and pain manifestations associated with RPS.

There was a significant change in the measured variables that were associated with pain and discomfort. The pain sensitivity and self-reported discomfort significantly increased during the two four-hour computer based tasks with poor ergonomic characteristics. This outcome supported the hypothesis that workplace *ergonomic risk factors can*

influence the sensitivity of the pain system. The results demonstrated that there was a change in the function of the pain system at a peripheral level and possibly central pain modulation changes, although this was unknown. The ergonomics community should consider pathophysiological pain mechanisms when examining risk factors for chronic musculoskeletal pain.

The action characteristics of the cervical spine were also a significant factor for pain sensitivity and self-reported discomfort. The pain sensitivity and self-reported discomfort results were significantly increased after performance of the computer based task that had a static cervical spine posture (the neck-static measurement session), as compared with the task that had more dynamic work actions in the cervical spine (the neck-mobile measurement session). In addition, the cervical range of motion results were different between the measurement sessions in some planes (although not significantly). These outcomes supported the hypothesis that the cervical spine was a region of importance in driving pain sensitivity changes.

From the results of the investigation it was concluded that the postural and action characteristics of the cervical spine are important ergonomic factors for musculoskeletal discomfort and pain, both in the cervical spine and at some other musculoskeletal sites. The posture and action characteristics of the neck should be measured in workplace ergonomic investigations for two reasons. Firstly, because this research has shown that this region can influence pain sensitivity in the neck and some distal sites. Secondly, previous research over the past decade has supported the hypothesis that spinal factors are associated with the onset of chronic musculoskeletal pain.

The augmented pain processing of the pain system, due to peripheral and/or central mechanisms, was a short-term phenomenon. However, long-term exposure to the postures and actions described in this experiment (e.g. as part of a persons daily work) could eventually induce permanent aberrant function of the nociceptive system. Central neuronal plastic alterations may become permanent, representing the pathological component of an ensuing chronic non-specific musculoskeletal pain syndrome. In this situation, normally non-nociceptive stimuli may be interpreted as tissue threatening due to augmentation of afferent stimulus in the dorsal horn neurons, manifesting clinically as tenderness and referred pain. Therefore, the postures and actions described in this experiment should not be undertaken as part of daily work.

Only a small number of participants were tested in this investigation, and the test period was short-term. Any long-term conclusions based on the results of this investigation are hypothetical. However, this work adds to the limited understanding of the ergonomic risk factors of posture and repetitive actions, and an association with changes in the function of the pain system, which may be representative of the first manifestations of RPS. The results of this investigation lend support for further such studies in the future.

CHAPTER 5

MEASUREMENT OF CERVICAL RANGE OF MOTION

- **CHAPTER SUMMARY**

This chapter presents a new measurement instrument for assessing cervical ROM. This new device utilised a direct current (DC) Electromagnetic Tracking System (ETS) to measure passive cervical ROM in three movement planes (sagittal, transverse and frontal). A series of tests were completed to assess inter and intra-examiner reliability of the instrument. This instrument was used as an instrument to investigate cervical spine function in chronic pain syndromes in the next chapter, and hence the reliability of the device was tested. As well, the research investigated other techniques of ROM assessment, firstly for a criterion standard, and to confirm previous reports of poor reliability in a manual technique known as visual estimation (VE).

Cervical range-of-motion (ROM) measurement is utilised frequently in clinical practice as an assessment tool for the identification of disorders of the cervical spine, to assist in the decision making process for therapeutic intervention and to document the outcome of intervention. Decreased cervical ROM may be indicative of disorders of the cervical spine and spinal dysfunction.

The new ETS ROM device was compared with another established cervical ROM measurement device, the Cervical Range of Motion device (CROM®). The CROM has demonstrated good reliability and accuracy for the measurement of active and passive cervical ROM and was taken as a criterion device.

The new ETS ROM device was found to be an efficient system for the measurement and recording of passive cervical ROM. The ETS had high intra-examiner and fair-to-high inter-examiner reliability. The ETS compared well with the CROM in most measurement planes. The ETS had the advantage above the CROM device in that it was a true three-dimensional measurement device, and hence could assess ROM in all planes concurrently.

5.1 INTRODUCTION

5.1.1 CLINICAL ASSESSMENT OF CERVICAL RANGE OF MOTION

Cervical range of motion (ROM) measurement is a common assessment tool employed in clinical practice during clinical examination of patients [475]. It is applied by practitioners because it may provide an overall assessment of neck function by estimating the ability of the soft tissues to reach their extremes of movement [476].

It has been hypothesised that cervical ROM describes the limits of motion due to increased tension in the soft tissues, obstruction of motion, or discomfort [417]. Disorders of the cervical spine are considered to alter the normal ROM of the neck [435], with results including unequal bilateral range or gross deficits in range considered to indicate abnormality [414]. As a workplace analysis instrument, cervical ROM has been described as a useful tool to describe impairment [320].

Most ROM measurement systems provide assessment of the total neck motion, considering the atlanto-occipital and cervical spine joints as a whole [477]. Only radiographic systems enable assessment of the separate contribution of single joints to the overall global movement [477]. In this regard, measurement of cervical ROM, either with goniometers or a measurement system that assesses gross ROM, fundamentally describes the range of movement of the head. These measurement systems do not reveal what is actually happening inside the neck, although they do implicitly provide data on the *global function* of the neck [478].

Cervical ROM measurements have demonstrated a discriminate ability between asymptomatic participants and participants with disorders of the cervical spine. Patients with chronic neck pain, including whiplash-associated disorders, have demonstrated a reduced cervical ROM compared with healthy controls [416,476,479]. See also Ch. 6, Sec. 6.2.

Dall'Alba et al. [416] showed that patients with whiplash-disorders had reduced ROM in all primary movement planes compared with control participants. The reduction in ROM was relatively symmetrical; motions in planes other than the primary movement plane (conjunct movements) were not significantly different between patients with whiplash disorders and controls. The results also showed that ROM was a significant

discriminator between asymptomatic persons and patients with whiplash associated disorders. Dall'Alba et al. [416] concluded that the discriminative ability of cervical ROM strengthened the case for this assessment tool as an indicator of physical impairment.

Others [476,480] have also demonstrated a significant difference in cervical ROM between participants with whiplash-disorders and healthy controls. Bono et al. [480] showed that whiplash patients had an impairment of cervical spine mobility. Braun and Schiffman [481] demonstrated a strong association of self-reported neck pain in participants with whiplash-disorders and cervical ROM results. They [481] stated that ROM provided an objective measure of cervical status and that their results support the interrelationship between self-reported pain and dysfunction of the neck. Olson et al. [482] found that decreased neck retraction and cervical rotation ROM was associated with higher disability in participants with neck pain. Gargan et al. [483] showed that cervical ROM of patients three months after a whiplash injury was a good predictor of the severity of symptoms two years later. In the workplace, forest machine workers with present neck pain have demonstrated a reduced ROM in some measurement planes, when compared with workers without pain [320]. As will be discussed in Ch. 6, patients with fibromyalgia and chronic neck pain demonstrated significantly reduced ROM in all measured planes, compared with healthy participants. From these outcomes, ROM is a useful tool for describing neck impairment [320].

5.1.2 CERVICAL ROM ASSESSMENT TECHNIQUES

ROM can be assessed by active and passive techniques. *Active ROM* involves patients completing required movements unassisted by the examiner. *Passive ROM* involves the examiner assisting the patient and on the basis of end-feel, the examiner decides when 'full' range is attained [418,419]. Wong and Nansel [484] investigated cervical ROM using active and passive techniques. They found that active ROM significantly underestimated end-range asymmetry that was identified from passive ROM techniques. They concluded that active ROM measures may be more idiosyncratic and therefore more difficult to interpret than those obtained using passive ROM techniques, particularly when end-range asymmetry information is considered to be of primary clinical importance. As well, passive ROM has less variability than active ROM [475], is a more reliable technique [485] and for investigating total possible range of motion, is

regarded a more suitable option than active ROM [475]. However, Lantz et al. [486] demonstrated that active ROM was more reliable than passive ROM when assessed in healthy participants with an electrogoniometer measurement instrument. From these previous studies, it is unclear which method demonstrates a more optimal assessment technique for the measurement of cervical ROM, although *passive ROM appears to be the preferred method* for assessment of end-range asymmetries [484].

Many instruments are described in the literature for the measurement of cervical ROM. Examples range from intricate *electrogoniometric equipment* [487] to the most commonly used assessment tool, simple hand operated *goniometers* [488,489]. Several authors provide overviews of cervical spine ROM measurement techniques with various instruments [321,490,491]. A common method employed in the clinical setting is *visual estimation* (VE) [477]. VE has obvious inherent inaccuracy and it is virtually impossible to blind examiners during intra-examiner reliability tests [490]. Youdas et al. [435] compared VE with the CROM device (described below) and results demonstrated poor inter-technique reliability. They cautioned therapists against attributing changes in cervical ROM to treatment because of inherent measurement error when using VE and did not advocate its use by therapists.

The Cervical Range Of Motion[13] device (CROM) is a commercially available instrument for the measurement of cervical ROM. This instrument has been used in several investigations and has demonstrated high intra and inter-examiner reliability for active ROM [434,435,492,493] and acceptable reliability for passive ROM when measurements are made from one extreme to the other in a plane (whole plane motion) [418]. The criterion validity for flexion and extension [494] and lateral flexion [495] measurements has been established by comparing CROM results with radiographs. The CROM can be mounted consistently by different examiners without the need for locating specific anatomic landmarks [435], is easy to use and relatively affordable [494]. However, the CROM can only measure ROM in the primary plane, it cannot measure conjunct motion in other planes [490].

[13] Performance Attainment Associates, 3550 LaBore Rd, Suite 6, St. Paul, MN, USA

Electromagnetic tracking [336] is another technology that has a capability of measuring cervical ROM. Electromagnetic tracking is one of the few instruments suitable for measurement of relative three-dimensional joint rotation and is well suited for spinal kinematics [496]. This technology can track angular and positional data and has been used in several investigations of cervical ROM [414-417,497-499]. These investigations were conducted with alternating current (AC) electromagnetic tracking systems.

Buchalter et al. [415] investigated mean values of lumbar, thoracic and cervical ROM from four electromagnetic tracking sensors attached to the skin at the inion, C7, T12 and the sacrum. Participants of different age, weight and height categories were measured. Ordway et al. [417] investigated the effect of head position on cervical uniaxial rotation ROM. Pearson et al. [497] studied the effects of repeated neck retraction movements on a participant's retraction ROM and resting neck posture. Walmsley et al. [414] used two electromagnetic tracking sensors (one on the head and the other the sternum) to measure active axial ROM and sagittal translation with the head in different starting positions. Ordway et al. [498] measured cervical flexion/extension and sagittal translation with an AC electromagnetic tracking system and compared results with lateral cervical radiographs and the CROM device. Jordan et al. [499] investigated the reliability of measurement of cervical spine and shoulder ROM. Dall'Alba et al. [416] measured ROM in asymptomatic persons and those with whiplash. ROM was capable of discriminating between the two groups. Two sensors were used, on the forehead and the spinous process of C7.

Several investigations [414,416,417,498] mounted their AC electromagnetic tracking systems to measure only cervical spine motions, by attempting to exclude contribution from the upper thoracic segments to the measured ROM. This is dissimilar to the CROM device which cannot isolate cervical motion from the upper thoracic segments [498] – measurement of ROM with the CROM device potentially includes extraneous contribution from the thoracic spine [500] and trunk. Ordway et al. [498] demonstrated significant differences between their AC electromagnetic tracking system results and the CROM, possibly due to the isolation and inclusion of upper thoracic motion in ROM measurements, respectively.

5.2 OBJECTIVE

In this chapter, an investigation of passive cervical ROM was undertaken using a CROM device, visual estimation (VE) and a direct current (DC) electromagnetic tracking system[14] (ETS). The DC electromagnetic tracking technology was similar to AC electromagnetic tracking used in previous cervical ROM investigations, but has not been previously used to measure cervical ROM. The purpose of this study was to assess the use of the new DC electromagnetic tracking system for the measurement of passive cervical ROM in asymptomatic participants. Passive cervical ROM was measured in the transverse (rotation), frontal (lateral flexion) and sagittal (flexion/extension) planes, from one extreme to the other (whole plane motion). Whole plane motion has been shown to be more reliable than measuring ROM from a neutral position [418,499,500].

Two examiners undertook all measurements. An experienced clinician used the ETS and VE and an inexperienced examiner used the ETS and the CROM.

5.3 MATERIALS AND METHODS

5.3.1 INSTRUMENTATION

5.3.1.1 THE ELECTROMAGNETIC TRACKING SYSTEM (ETS)

The ETS consists of an 'electronics card' which drives a 'transmitter' and a 'sensor'.

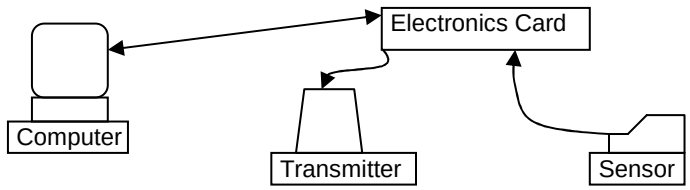


Figure 5-1 – Schematic diagram of the Ascension electromagnetic tracking system (ETS)

Three orthogonal coils are contained within both the transmitter and the sensor. The transmitter is controlled by the electronics card and generates an electromagnetic field. The electromagnetic field is detected by the sensor (see Figure 5-1). The signal from the sensor is processed by the electronics card and the position and orientation (elevation,

[14] Ascension Technology Corp: 'Flock-of-Birds', P.O. Box 527, Burlington, VT, USA

roll, azimuth) of the sensor *relative* to the transmitter is determined [336]. The range of the transmitter is approximately 1 metre and a transmitter-to-sensor distance of greater than this value may introduce error. Metal objects placed near the transmitter and sensor may potentially introduce error to ROM measurements. However, if metal items are at least 33 cm from the source and sensor, accuracy should not be compromised [501].

The author developed a custom computer program using Microsoft Visual Basic v6.0 that enabled communication between the ETS and a personal computer (PC), and the electronic storage of ROM measurements on the PC hard disk drive. Recording of a particular head position took less than 60 milliseconds.

The orientation and positional accuracy of the ETS was better than 0.75 deg and 1.68 mm root mean square for the X, Y and Z-axis. The procedure used and full results obtained are described in App. F. The results confirmed the manufacturers data regarding accuracy.

The sensor was firmly affixed to the top of the plastic internal support lining of a safety helmet. The plastic headpiece was adjustable and designed to be positioned securely and comfortably on a participant's head. The headpiece was adjusted on the participant's head to ensure the sensor was approximately horizontal and facing forward. A chinstrap helped reduce extraneous movements (see Figure 5-2).

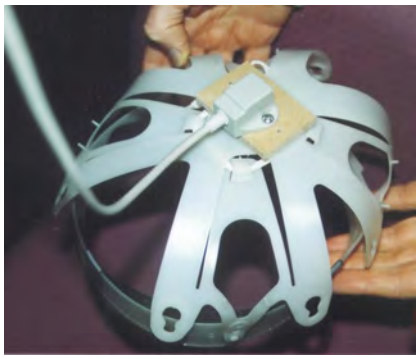


Figure 5-2 – Sensor of the electromagnetic tracking system attached to the plastic headpiece

As noted above, previous investigators [414,416,417,498] mounted their ETS's to exclude movement within the upper thoracic segments from cervical ROM measurements. The CROM device (described next) cannot isolate the cervical spine ROM in this manner and therefore, the ETS was mounted to measure cervical ROM similar to the CROM in this investigation. The ETS transmitter was fixed in front of the seated participant on a horizontal wooden beam above head height. The mounting

location was chosen to ensure measurements were completed within the operational range of the ETS – approximately 1m [502].

5.3.1.2 THE CERVICAL RANGE OF MOTION DEVICE (CROM)

The CROM device consisted of a plastic frame that was mounted on the participant's head in a similar manner to wearing optical glasses. An inverted 'V' section was supported by the bridge of the nose and cushioned by soft pliable rubber. Two arms extended posteriorly and were joined by a Velcro® strap and supported by the wearers' ears. The CROM consisted of three orthogonal dial angle meters, two of which were gravity meters. The side meter measures flexion and extension, and the front meter measures lateral flexion. The third meter, mounted in the transverse plane on top of the CROM, was a compass goniometer that measured rotation. A magnetic yoke mounted on the participant's shoulders reinforced the compass goniometer. The CROM was used as a criterion device.

5.3.2 EXAMINERS

Two examiners, an experienced clinician with 18 years experience measuring passive ROM (Examiner 1 [CC]), and an inexperienced examiner (Examiner 2 [AM]) undertook all measurements.

5.3.3 PARTICIPANTS

Participants were excluded from the study if any metallic items (except dental amalgam) or electronic circuitry were contained in the body. Three participants indicated present neck pain before testing. All other participants reported no or minimal neck pain before testing. Some participants made themselves available to all three studies; however, not all participants were available to all three studies. The age and sex of participants included in the three studies is given in Table 5-1.

STUDY	No. Female	Age: Mean (SD)	Range	No. Male	Age: Mean (SD)	Range
1	12	44.8 (10.9)	29-64	16	37.2 (11.0)	23-56
2	2	37.0 (11.3)	29-45	7	38.9 (10.5)	25-49
3	3	41.0 (10.4)	29-47	11	43.6 (14.5)	25-67

Table 5-1 – Age and sex of participants

5.3.4 DATA ANALYSIS

The Intraclass Correlation Coefficient (ICC[2,1]) was used to assess reliability [433,503]. The ICC(2,1) is the recommended method of reliability analysis for cervical ROM investigations [490,504]. The Pearson correlation coefficient, the paired Student T-Test and repeated measures ANOVA have problems in measuring reliability which suggest they are inappropriate for ROM reliability studies [490,499,504]. Jordan [490] explained that, provided variation among participants is not particularly small, a form of the ICC should be the analysis tool used. 0.90 to 0.99 was adopted as indicative of high reliability; 0.8 to 0.89 as good reliability; 0.70 to 0.79 as fair reliability and below 0.69 as poor reliability [434,435].

Confidence intervals for the ICC were also calculated. Jordan [490] discussed the importance of providing confidence intervals if no sample size calculations were completed, which in this investigation they were not. Jordan [490] also explained that if the confidence interval lower limit is greater than previously acceptable reliability figures, this would provide confidence in the reliability of the tool.

Intra-instrument and intra-examiner reliability results were based on the first ROM measurement in a plane compared with the second. For inter-instrument and inter-examiner reliability and change in ROM over a 24-hour period only the first measurement taken in a particular plane was compared.

5.4 PROCEDURE

5.4.1 PASSIVE ROM MEASUREMENTS

Participants were measured in the seated position on an upright wooden chair with feet flat on the floor and the lower back touching the back of the chair. Hands and forearms were placed in a relaxed position resting on the participant's thighs. All head and neck jewellery were removed to eliminate any potential interference with the ETS. The CROM and/or ETS were then placed on the participant's head.

Participants were seated in front of a mark on the wall, at approximately eye level, upon which they were requested to focus to attain a neutral starting posture. There was no real-time output from the ETS to assist with this. It was assumed between measurements

that participants could attain a similar neutral position by focusing on the same mark on the wall. Whenever a neutral position was required the examiner asked the participant to focus on the mark on the wall.

When recording with the ETS, the examiner standing behind the seated participant advised the PC operator that the neutral posture was attained and a recording of the participant's head orientation was made. The examiner then guided the head to full right rotation on the basis of end-feel [418]. This position was determined by the examiner taking the head to the limit of normal passive motion where a firm resistance was felt [418-420]. A recording of this head position was made. The head was then moved from full right rotation to full left rotation and again the position was recorded. The head was returned to the neutral posture and the same measurements were made again but in reverse order, i.e. neutral, left rotation and right rotation. The same procedure was used for lateral flexion and for flexion and extension; a total of eighteen ROM measurements. Warm-ups did not occur. Participants were seated in front of the ETS transmitter, their sagittal plane aligned approximately with the X-axis of the transmitter.

The same procedure was used with the CROM except the frontal plane of the participant was oriented in the electromagnetic north-south axis. The examiner using the CROM and VE noted and recorded his own results. The procedure is described in the CROM user manual [505].

All participants were required to sign an informed consent form before testing. The testing procedure and instruments involved were demonstrated to participants and any questions answered. Two examiners conducted studies 1 and 3. One of these examiners, the experienced clinician (CC), also completed study 2.

5.4.2 STUDY 1: INTRA-INSTRUMENT AND INTER-INSTRUMENT RELIABILITY

Participants were tested with the ETS, CROM and by VE. Participants were randomly assigned for assessment by Examiner 1 (CC) or Examiner 2 (AM) first. CC completed all ETS and VE measurements. CC also visually estimated passive ROM while completing the ETS movements and recorded the VE results manually on paper.

AM undertook all CROM measurements and recorded results after each ROM assessment on paper. Both examiners were blinded to the ETS results and CC was blinded to the results obtained by AM from the CROM. Measurements by both examiners were completed in less than ten minutes. The intra-instrument and inter-instrument reliabilities were determined.

5.4.3 STUDY 2: CROM AND ETS INTER-INSTRUMENT RELIABILITY

Participants were tested with the CROM and the ETS at the same time. The small dimensions of the ETS sensor (25 x 25 x 20mm) and the slim plastic headpiece upon which it was affixed permitted the ETS and the CROM to be mounted on participants at the same time. The electromagnetic yoke of the CROM was removed as it interfered significantly with the operation of the ETS. The experienced clinician, Examiner 1 (CC), completed all ROM measurements and recorded his own CROM results. The CROM still worked adequately well without the yoke attached.

This study permitted direct comparison of the ETS and the CROM. Inter-instrument reliability was determined.

5.4.4 STUDY 3: INTER-EXAMINER AND INTRA-EXAMINER RELIABILITY

Inter-examiner reliability of the ETS only was investigated in a non-randomised order. CC measured participant's ROM followed approximated 30 sec later by AM. Intra-examiner reliability was also determined.

5.5 RESULTS

Calculations were based on whole plane movements (i.e. from one extreme to the other) for the three planes: transverse (rotation), frontal (lateral flexion) and sagittal (flexion/extension).

5.5.1 STUDY 1: INTRA-INSTRUMENT AND INTER-INSTRUMENT RELIABILITY

A summary of ROM for the three measurement methods and measured planes is given in Table 5-2. Only one examiner's data was averaged for each measurement tool, as

only one examiner applied each tool. Hence, the data in this table is not an average of the two examiners.

PLANE	ETS (CC)	VE (CC)	CROM (AM)
Rotation	152.51 (17.71)	155.89 (22.98)	140.29 (15.08)
Lateral flexion	77.97 (13.50)	82.86 (13.91)	88.57 (14.61)
Flexion + Extension	107.08 (16.78)	116.25 (18.59)	117.25 (22.83)

Table 5-2 – Average and standard deviation for cervical range of motion (ROM) measurements with the electromagnetic tracking system (ETS), visual estimation (VE) and the Cervical Range of Motion (CROM) device for whole plane motion; *n=28*

The *intra-instrument reliability* was assessed by comparing the first measurement with the second measurement for each measured plane. Reliability ranged from fair-to-high for the CROM and VE. The ETS demonstrated good-to-high reliability for the three planes (see Table 5-3).

PLANE	Examiner 1		Examiner 2
	ETS	VE	CROM
Rotation	0.94 (0.84-0.98)	0.94 (0.86-0.97)	0.83 (0.66-0.92)
Lateral flexion	0.89 (0.77–0.95)	0.76 (0.51-0.89)	0.90 (0.80-0.95)
Flexion + Extension	0.90 (0.79-0.95)	0.83 (0.66-0.92)	0.75 (0.53-0.87)

Table 5-3 – Intra-instrument intraclass correlation coefficient (ICC) reliability and 95% confidence interval (CI) for the CROM, ETS and VE; *n=28*

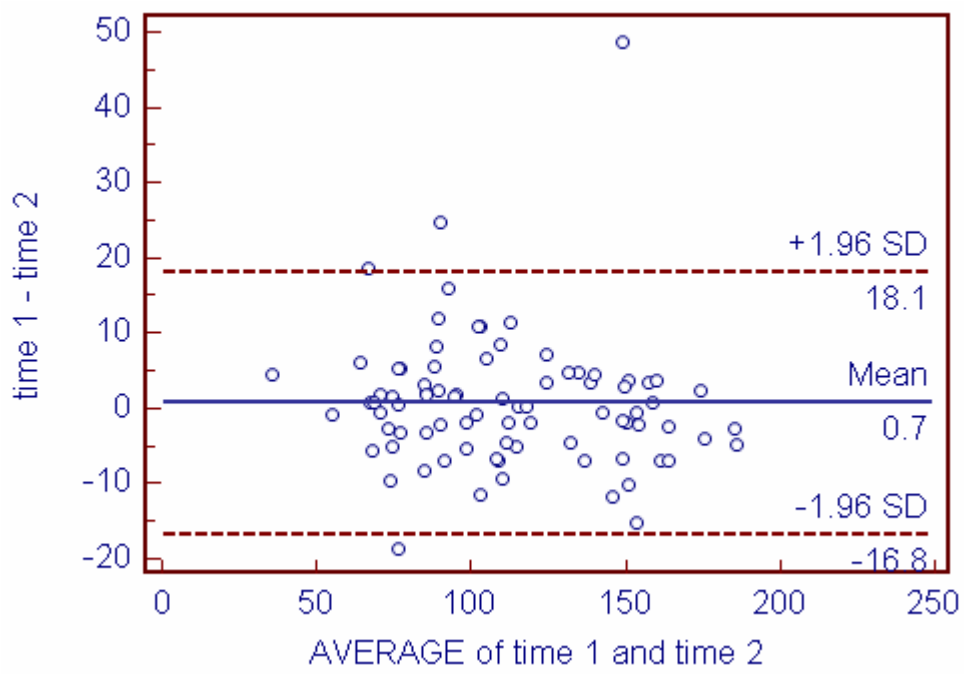


Figure 5-3 – Bland Altman plots of ETS comparison of first measurement with the second measurement total ROM results

For *inter-instrument reliability*, the first measurement in a particular plane was compared. Results indicated poor reliability (ICC < 0.69) for all three planes between all instruments, except for ETS compared with VE for rotation, ICC = 0.81 (0.63-0.90).

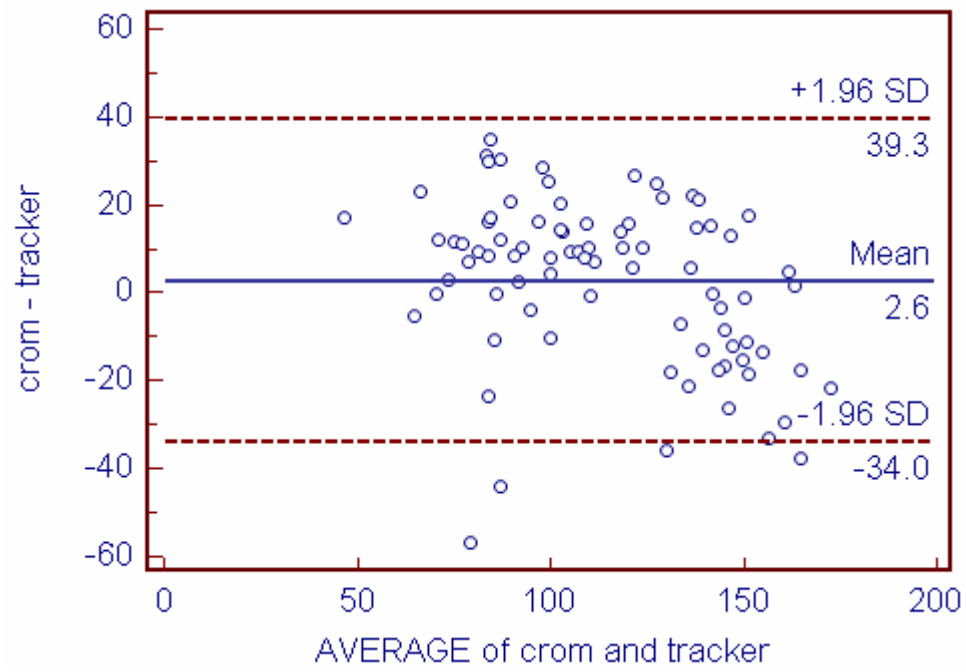


Figure 5-4 – Bland Altman plots of CROM vs ETS total ROM results

5.5.2 STUDY 2: CROM AND ETS INTER-INSTRUMENT RELIABILITY

The *inter-instrument reliability* of the CROM compared with the ETS, when both instruments were mounted *on the same participant at the same time,* was determined by comparing the first measurement taken in a plane. Results indicated high reliability for measurements in rotation and flexion/extension and fair for lateral flexion (see Table 5-4).

PLANE	Inter-instrument
Rotation	0.91 (0.62-0.98)
Lateral flexion	0.78 (0.33-0.94)
Flexion + Extension	0.94 (0.76-0.99)

Table 5-4 – Inter-instrument reliability (ICC and 95% CI) between the CROM and ETS; *n=9.*

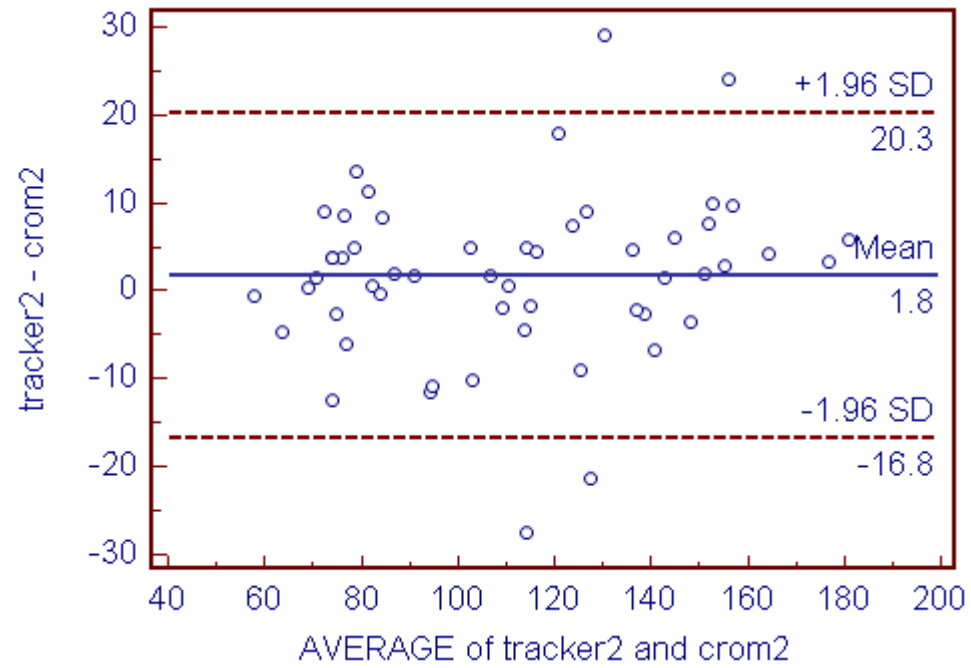


Figure 5-5 – Bland Altman plots of CROM and ETS at same time

5.5.3 STUDY 3: INTER-EXAMINER AND INTRA-EXAMINER RELIABILITY

Inter-examiner reliability for the ETS with some delay between examiners was determined. Rotation, lateral flexion and flexion/extension inter-examiner reliability was high, good and fair respectively (see Table 5-5).

PLANE	Inter-examiner
Rotation	0.94 (0.75-0.98)
Lateral flexion	0.80 (0.00-0.95)
Flexion + Extension	0.78 (0.44-0.92)

Table 5-5 – Inter-examiner reliability (ICC and 95% CI) with the ETS only; *n=14*

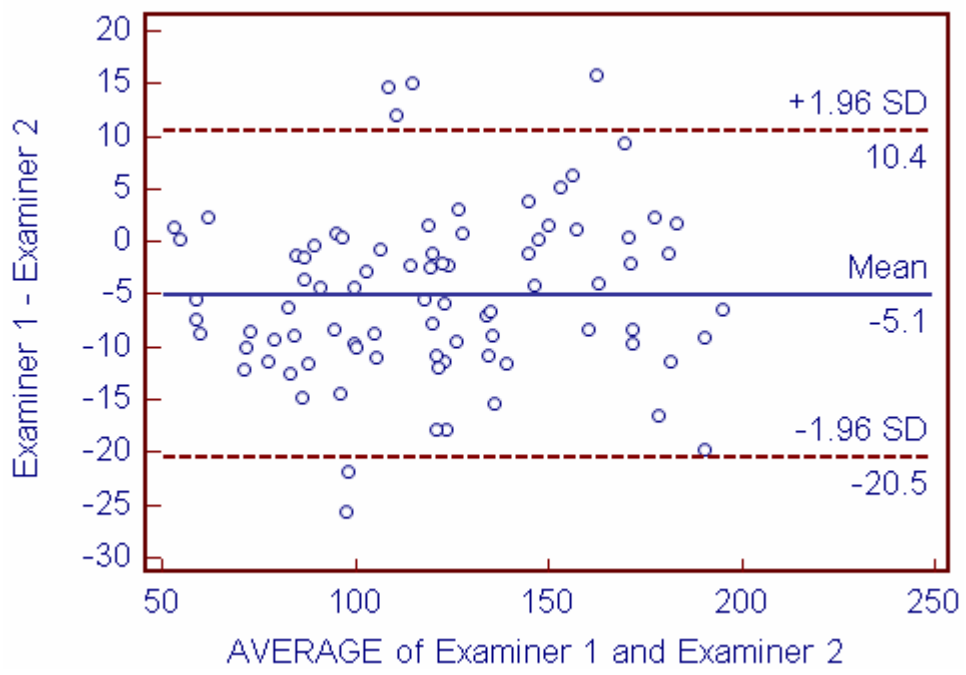


Figure 5-6 – Bland Altman plots of Examiner 1 vs Examiner 2 with ETS

Intra-examiner reliability was also determined. The two examiners had high intra-examiner reliability for all three planes (see Table 5-6).

PLANE	Examiner - CC	Examiner- AM
Rotation	0.97 (0.63-0.99)	0.96 (0.88-0.99)
Lateral flexion	0.94 (0.84-0.98)	0.95 (0.84-0.99)
Flexion + Extension	0.96 (0.89-0.99)	0.96 (0.88-0.99)

Table 5-6 – Intra-examiner reliability (ICC and 95% CI) with the ETS only; *n=14*

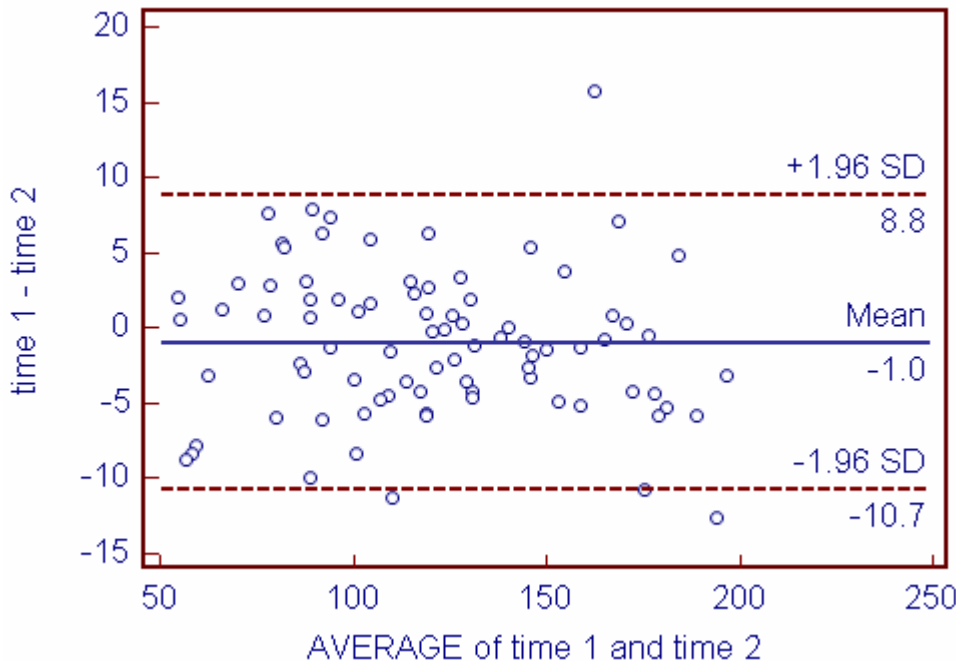


Figure 5-7 – Bland Altman plots of time 1 vs time 2 with ETS for all total ROM results

5.6 DISCUSSION

5.6.1 STUDY 1: INTRA-INSTRUMENT AND INTER-INSTRUMENT RELIABILITY

Results from **Study 1** indicated that the ETS had good-to-high intra-instrument reliability and the CROM fair-to-high. The measurement protocol used for the CROM may have accounted for the lower ICC confidence intervals for rotation and flexion/extension. This is discussed further below.

Comparison between these two instruments demonstrated poor inter-instrument reliability. This was most likely due to different examiners applying the ETS and the CROM; the different methods and experience levels of the examiners contributed to the low inter-instrument reliability values. Also, variation in the application method of the ETS and CROM may have contributed to differences in ROM results. This is further discussed below in Study 3.

The VE intra-instrument reliability was fair-to-high but blinding of the examiner was not possible during measurement. It was likely that this significantly influenced results and therefore the positive reliability results must be cautiously interpreted.

VE compared reasonably with the ETS in the transverse (rotation) plane only. The lack of anatomical landmarks on the head makes cervical ROM VE measurements difficult [435]. In the transverse plane however, the examiner can use the tip of the nose relative to the left and right acromion processes as an indicator of axial rotation. The good reliability for VE in this plane when compared with the ETS supports the use of VE for this plane. For lateral flexion and flexion/extension there are not such easily identifiable anatomical landmarks and in these planes reliability between VE and the ETS was poor.

5.6.2 STUDY 2: CROM AND ETS INTER-INSTRUMENT RELIABILITY

Study 2 permitted direct comparison between the CROM and the ETS. There was high inter-instrument reliability for ROM measurement in rotation and flexion/extension, and fair for lateral flexion. The lower ICC confidence interval would likely be improved with a larger sample size.

Occasionally during testing, the indicator needle of the CROM's gravity angle meter for measuring lateral flexion (frontal plane) was slightly offset from vertical and would rest against the clear face or back surface of the goniometer's case. This was due to slight head rotation and/or flexion/extension during lateral flexion measurements. This deviation from vertical potentially introduced error into results and may have contributed to the lower reliability value.

Conjunct movement in planes other than the primary plane of movement during ROM measurements has been reported [416,477]. Ferrario et al. [477] reported significant out-of-plane components for lateral bending when measuring ROM. To avoid out-of-plane components when measuring lateral flexion with the CROM, the examiner should ensure as far as possible that the participant's head does not include rotation and/or flexion/extension. The indicator needle hanging freely in the lateral flexion angle meter can visually confirm this. The ETS was not affected by out-of-plane components and has the capability to measure all planes during ROM testing [416].

The results obtained with the CROM for rotation were undermined by the removal of the electromagnetic yoke in study 2. The electromagnetic yoke was removed due to interference with the ETS. During testing, to overcome the absence of the electromagnetic yoke, the participant's frontal plane was aligned with the electromagnetic north-south axis and considerable time was given to permit the earth's electromagnetic field to move the compass goniometer.

5.6.3 STUDY 3: INTER-EXAMINER AND INTRA-EXAMINER RELIABILITY

Intra and inter-examiner reliability were measured in **Study 3** using the ETS only. Intra-examiner reliability was high for both examiners for all measured planes. Inter-examiner reliability ranged from fair-to-high with poor lower ICC confidence intervals. The experience level of each examiner possibly influenced the inter-examiner reliability.

Nilsson [419] measured passive cervical ROM with an experienced and an inexperienced examiner and found low inter-examiner reliability possibly due to insufficient training of their inexperienced examiner. Nilsson et al. [418] conducted a follow up investigation with two experienced examiners and acceptable inter-examiner reliability was achieved. More acceptable inter-examiner reliability for the ETS may

have been achieved if comparisons were made between the results of two experienced examiners.

It was interesting to note that the inexperienced examiner achieved similar intra-examiner reliability values to those of the experienced examiner, with strong confidence in results (high lower ICC confidence intervals >0.84). Perhaps due to different experience levels and application methods the examiners measured passive ROM slightly differently (lower inter-examiner reliability) but in a highly consistent manner (high intra-examiner reliability).

Examiner 2 (AM) had better intra-examiner reliability with the ETS (Study 3) compared with the CROM (Study 1). This may be due to instrument application. When conducting ROM measurements with the ETS the examiner remained in the same position (standing behind the participant) for the entire test. However, with the CROM the examiner moved position to read the dials and to record results for each ROM measurement. The ETS measurement procedure was more efficient and systematic than the CROM and this may account for the higher intra-examiner reliability values. For similar reasons Examiner 1 (CC) possibly had higher ETS reliability values in Study 3 compared with Study 1. In Study 1, Examiner 1 had to alter position after each ROM measurement (to record the VE values). In Study 3 the examiner remained in the same position (standing behind the participant) during the entire test, thus streamlining the measurement procedure.

5.6.4 OTHER CONSIDERATIONS

The distance between the sensor and transmitter influenced the angular accuracy of the ETS. For the range in which the ROM measurements were conducted, the angular accuracy was better than 0.6 deg RMS error for the three measured planes. The accuracy results of the ETS are shown in App. F, Sec. F.3.2. This compares well with the CROM which has median accuracy range of 0 to 2 deg in three planes [434].

Jordan et al. [499] reported greater ROM for their first measurement compared with later measurements of active ROM. The results of the current investigation did not reflect this, no order effect was apparent. This was possibly due to different measurement protocols employed during testing and also Jordan et al. [499] measured active ROM. The authors [499] discussed possible reasons why *the participant* decided

to move more on the first measurement than subsequent ROM movements during active ROM measurements. Passive ROM limits a participant's involvement during measurement and therefore results reflect ROM based on *the examiner's* perception of 'end feel'.

The author of the current study describes this investigation as a 'pilot study' due to the non-blinded results obtained from the CROM and the improper inter-instrument study design completed in study 1. In study 1, different examiners with dissimilar experience levels completed measurements with the CROM and the ETS that undermined inter-instrument reliability comparisons. Also, examiners using the CROM measured and recorded their own results and therefore compromised the blindedness of results. The recording of results on paper by the examiner interrupted the measurement process, which may have affected CROM results. For future studies the author recommends a non-examiner read and record results from the CROM device and for inter-instrument reliability each examiner conduct tests with all ROM measurement devices.

As well, for future studies testing of the DC ETS against a similar system that relied on AC technology in the presence of metallic objects, could help ascertain if the DC ETS does perform more accurately and reliability in this situation. This would assist with technology selection if field measurements were to be conducted in the presence of metallic objects. This was not tested in the current experiment.

5.7 CONCLUSION

This preliminary investigation provided encouraging results. The DC ETS was an accurate instrument and provided efficient and objective quantitative measurement and recording of passive cervical ROM. Measuring cervical ROM with the ETS demonstrated high intra-examiner reliability for experienced and inexperienced operators in all measured planes, and fair-to-high inter-examiner reliability for ROM movements in rotation, lateral flexion and flexion/extension. It was probable that inter-examiner reliability would have improved if tests were conducted with examiners of similar experience levels. The ETS compared favourably with the commercially available CROM device.

This investigation mounted the ETS transmitter and sensor to measure cervical ROM in a similar manner to the CROM device for comparative purposes. Movement of the upper thoracic spine was probably included in ROM results obtained. The ETS mounting arrangement could easily be altered to measure cervical ROM only excluding potential contribution from the upper thoracic segments by using two sensors [414-416] or by positioning the transmitter at the T2 level [498] or torso [417]. These alternate mounting arrangements would possibly measure only cervical ROM and results may provide users with a more comprehensive analysis of cervical spine ROM.

CHAPTER 6

CERVICAL SPINE FUNCTION IN CHRONIC MUSCULOSKELETAL PAIN SYNDROMES

- **CHAPTER SUMMARY**

This chapter investigates the third goal of this thesis – the relationship between dysfunction of cervical spine structures and clinical features of chronic pain syndromes was explored. The chapter is split into two sections: the literature review (Sec. 6.1) and the research investigation (Sec. 6.2).

The literature review explores the manual therapy field and introduces the concept of *spinal dysfunction (note:* the reader may skip this section and proceed directly to the investigation Sec. 6.2 if there is a good understanding of manual therapies and spinal dysfunction).

Spinal dysfunction is believed to play a key role in the onset and maintenance of chronic musculoskeletal pain. Better understanding of the onset of non-specific musculoskeletal pain is an aim of this thesis, and hence spinal dysfunction is an important feature of this thesis.

Spinal dysfunction can purportedly be detected by palpation. Manual therapists use *spinal palpation for stiffness,* which manually tests the mechanical properties of a spinal joint to seek abnormalities in the perceived stiffness properties of a spinal joint. They equate abnormal spinal joint stiffness as indicative of spinal dysfunction. However, this procedure has poor reliability. Hence the validity of spinal stiffness palpation has not been established. Debate continues in the manual therapy literature regarding the clinical relevance of spinal palpation for stiffness.

Spinal palpation for tenderness has shown better reliability, but it has not been demonstrated that spinal tenderness is indicative of a treatable lesion that could be defined as spinal dysfunction. This is discussed below in Sec. 6.1.1.4.

Mechanised stiffness measurement devices have been developed to overcome the poor reliability of manual palpation. These devices apply force to the skin over the spinous process and measure the force and displacement properties of the spinal musculoskeletal system. These devices have demonstrated good reliability, but they are not applicable to the cervical spine (these devices are reviewed in Sec. 6.1.3). As well, these devices do not assess tenderness, which is a crucial measurement variable associated with chronic musculoskeletal pain. Therefore, a hand-held device (the Modified Tissue Compliance Meter (M-TCM)) was developed in this thesis (see App. F) to measure: 1. pain sensitivity (pressure pain threshold) and 2. mechanical stiffness in the posterolateral cervical spine. The M-TCM has high reliability and accuracy on inert surfaces (see App. F).

The research investigation (see Sec. 6.2) explored the presence of abnormal cervical spinal function in participants with regional and widespread chronic musculoskeletal pain with varying results. The M-TCM was applied to the posterolateral aspect of the cervical spinal in three groups of participants: fibromyalgia patients (FM), chronic neck pain participants (NP) and normal asymptomatic participants (NORM). It was hypothesised that pressure pain threshold (PPT) measurements and stiffness estimates of the cervical spine could indicate the presence or not of spinal dysfunction in the necks of the FM and the NP participants. Cervical range of motion (ROM) (Ch. 5) and self-reporting instruments (Ch. 4.3.5.4) were also tested in this investigation. The discriminate ability and reliability of assessment tools over short and medium terms were determined.

The results, discussion and conclusions of this investigation are presented in Sec. 6.5 to 6.7. In summary, the M-TCM stiffness results had *poor reliability* and *poor discriminate ability* between the participant groups. However, the PPT measurements and cervical ROM had *good to high reliability* and *discriminate ability*. The ROM and PPT results were significantly altered in the symptomatic versus healthy participant groups (although this was not a significant outcome) and supported the hypothesis that in the participants with chronic musculoskeletal pain there was some form of dysfunction of the cervical spine. It was concluded from this investigation, and the review of the literature, that abnormalities of spinal function and changes in modulation of the central nociceptive system, may associate with clinical features characteristic of chronic pain syndromes.

6.1 LITERATURE REVIEW – SPINAL ASSESSMENT METHODS

This section (the literature review) explores the manual therapy fields (both physiotherapy and chiropractic) and introduces the concept of *spinal dysfunction*. Spinal dysfunction is an important feature of this thesis. A definition of this entity is provided below. However, detection of spinal dysfunction is a challenging task, and currently the myriad of spinal imaging and assessment techniques provide little or no diagnostic assistance to those with neck spinal pain. Clinicians have developed stiffness measurement devices to detect abnormal stiffness in spinal region. However, these devices are not applicable to the cervical spine region. These issues are discussed in this literature review, between pages 212 to 222, and are incorporated into the research investigation that begins on page 224.

Note: the reader may skip this section and proceed directly to Sec. 6.2 if there is a good understanding of manual therapies and spinal dysfunction.

6.1.1 MANUAL SPINAL ASSESSMENT

6.1.1.1 PASSIVE SPINAL PALPATION FOR STIFFNESS

Manual palpation is a subjective qualitative assessment tool commonly used by manual therapists in the evaluation of the human spinal musculoskeletal system [506]. It is an essential aspect of symptom evaluation [507]. The hands are the primary tool used during palpation analysis for identification of putative spinal dysfunction [506]. Manual palpation has been described as the application of manual pressures through the surface of the body to determine the shape, size, consistency, position and inherent mobility of the tissues beneath [506].

Manual spinal palpation can purportedly give an indication of segmental stiffness and joint play [508]. Passive palpation tests include motions that are induced by the examiner [509] to test joint play, end feel and joint tenderness [506]. The term ‘passive accessory motion’ has been used in chiropractic [506] and manual therapy [398] literature and refers to the process of manual examination of the spine, whereby a passive joint test is conducted by displacing one component of the joint in relation to another to determine the quantity and quality of the resultant motion [510]. Passive

accessory motion, or passive spinal palpation for stiffness, involves displacement of articular structures through the application of force at a prescribed location, in a prescribed direction, and is used in the diagnosis of spinal dysfunction (discussed below), to determine a course of treatment and to assess the outcome of treatment [510]. In this thesis, unless specifically stated, *spinal palpation for stiffness* does not include palpation for provocation of pain (tenderness) and instead refers only to the purportedly perceived joint movement (displacement), end feel and resistance to motion.

It is unlikely that manual therapists rely only on segmental displacement during spinal palpation. Individual spinal segments have been shown to translate only a few millimetres in response to: active flexion and extension [511], applied anterior force *in-vitro* and *in-vivo* [512,513] and applied posterior anterior manipulative thrusts [514]. Displacements of this magnitude are unlikely to be detected by manual therapists [513,515]. Instead, manual therapists likely rely principally on the nature of the tissue resistance to the applied force; segmental displacement is not the primary cue [515]. In this context, spinal palpation for stiffness has been described as a basic *in-vivo* test of the elastic mechanical behaviour of the segmental tissues based on the segmental displacement (distance) and the tissue resistance (force) to displacement [515-517].

6.1.1.2 SPINAL DYSFUNCTION

There are many terms employed by manual therapists to describe the spinal problem that is purportedly detected by spinal palpation for stiffness. Some of these terms include subluxation [518], somatic dysfunction [519], joint complex dysfunction [366], musculoskeletal dysfunction [385], functional spinal lesion [365], spinal segmental dysfunction [94] and spinal joint dysfunction [516]. This list is not exhaustive; eighty individual preferred terms were reported in a mail survey of chiropractors in Australia [520] supposedly referring to the same putative spinal phenomenon. The lack of consistency with terminology within and between manual therapy disciplines has hindered uniformity, greater acceptance of manual therapy and the exchange of clinical skills and data [401]. *Spinal dysfunction* is a term that has been used previously [401,521,522] and indicates the area of the musculoskeletal system in which the pain syndrome of interest purportedly exists. Spinal dysfunction is synonymous with other manual therapy terms (see above) and will be adopted for use in this thesis.

Theoretically, abnormalities of the articular structures, shortening of joint capsules and adjacent ligaments or the presence of paravertebral muscle spasm are believed to cause the alterations that are detectable by palpation [102,103]. Vernon [94] proposed that spinal dysfunction is characterised by a disturbance in alignment and/or motion characteristics of the vertebral motion segment, most especially a loss of motion or hypomobility. Such disorders may involve single or multiple segments [523]. Spinal dysfunction has also been described as a lesion, or 'the manipulable lesion' [94].

Models of spinal dysfunction have as their basis the phenomenon of a barrier to joint motion [94]. As noted above, spinal palpation for stiffness involves the manual testing of the mechanical properties of a spinal joint and abnormalities are sought in the perceived stiffness properties of individual joints; the relationship between the perceived passive displacement of a joint and its resistance to displacement is tested [112].

It is unlikely that the neck muscles are a source of chronic neck pain. Limb muscles heal relatively quickly and presuming the same for the neck muscles, it is unlikely that neck muscles are a source of chronic neck pain [524]. Instead, injuries to tissues that heal slowly or heal less so than muscles are more likely contenders for chronic neck pain. These tissues include the synovial joints and the intervertebral discs [524]. Tears of the zygapophysial joint capsules, haemarthroses and fractures of the articular cartilage and subchondral bone have been demonstrated in whiplash injuries [525] and may account for chronic pain stemming from the cervical zygapophysial joints. Aetiological theories encompassing specific structures involved in spinal dysfunction have been reported by several authors [366,398,518,523,526,527], however no operational definition has been validated.

Clinical signs that have been used previously for diagnosis of symptomatic cervical zygapophysial joints with spinal palpation for stiffness included the *combined presence* of: 1. abnormal 'end feel' (an abnormal quality of resistance at the extreme range of motion), 2. abnormal tissue resistance to displacement and 3. spinal palpation for the provocation of pain or tenderness [112,516]. Jull et al. [112] offered putative explanations for the physical basis of these criteria. Abnormal end feel may be experienced when the joint is restricted by capsular contracture or the onset of unyielding muscle spasm. The physical characteristics of such a state would be different

from a normal joint. Abnormal tissue resistance to displacement means that a greater than normal force has to be applied to achieve the same degree of movement and could possibly occur in the presence of: muscular spasm (that braces the joint), an increase in joint viscosity (from the proliferation of fat within the joint), the development of intra-articular adhesions or the loss of synovial fluid and erosion of articular cartilage.

6.1.1.3 RELIABILITY OF SPINAL PALPATION FOR STIFFNESS

The traditional manual therapy model involves some basic tenets regarding spinal dysfunction [528]. These include: spinal dysfunction exists in the human spine; the presence of spinal dysfunction may cause disease; spinal dysfunction can be detected and removed by spinal adjustment; and removal results in reversal of the disease process [528]. However, *no validated definition of spinal dysfunction exists* – at present it is a hypothetical construct [528,529]. In the cervical and lumbar spine regions, little advance has been made in achieving a specific structural diagnosis in patients with chronic spinal pain. Clinicians do not know what, if any, structural factors or tissue pathology may cause the pain in neck and back pain patients [110,111]. This is despite use of sophisticated imaging techniques [110].

There appears to be consensus regarding the conceptual definitions of spinal dysfunction, but such theories provide no evidence of the actual existence of the putative phenomenon [530] or of its relevance to human health [523,530] and local or referred pain [519]. Furthermore, the validity of spinal palpation for stiffness has been questioned [509,531-533], because a measurement system with poor inter-examiner reliability is unlikely to demonstrate validity [531].

The inter-examiner reliability of spinal palpation for stiffness by manual therapists is poor [397,512,531,534-536] and intra-examiner reliability ranges from good to moderate [398,534,537,538]. Keating [531] reviewed inter-examiner reliability studies of spinal palpation for stiffness of the lumbar spine region and found marginal to no reliability, and that no strong claims for objectivity (inter-examiner reliability) were justified. Keating [531] concluded that this diagnostic technique failed to meet the requisite levels of inter-examiner reliability required for a diagnostic test. Matyas and Bach [512] explored the reliability of physical therapy spinal palpation for stiffness techniques and also found that the reliability was poor. They [512] and others [535,539-

541] suggested that the assessment role of this technique be seriously reconsidered. Spinal palpation for abnormal stiffness may simply be too difficult a task for manual therapists [512].

6.1.1.4 SPINAL PALPATION FOR TENDERNESS

Palpation for provocation and reproduction of pain, or *spinal palpation for tenderness*, of spinal musculoskeletal tissues is intended to compress or place mechanical load on a specific structure in order to provoke pain [400]. This spinal assessment tool has shown encouraging reliability results in the lumbar [395,512,535,542] and cervical [400,543,544] spine and some [512,513,541,545,546] believe that this assessment technique should be the preferred examination tool in the clinical setting.

Sandmark et al. [400] compared tenderness assessment results of five manual tests of the cervical spine with self-reported presence or not of chronic neck pain and other musculoskeletal neck complaints. Tenderness over the zygapophysial joints was the most appropriate screening tool to corroborate self-reported musculoskeletal dysfunctions of the neck [400]. Nilsson [544] derived a 'total tenderness score', which was the summation of scores derived from a 0-3 grading system based on palpation for pain of four bilateral muscle groups in the cervical region. This system of tenderness assessment was deemed to have acceptable intra and inter-examiner reliability [544]. Hubka and Phelan [543] assessed tenderness unilaterally in symptomatic participants with unilateral neck pain. They [543] reported good inter-examiner reliability and concluded that palpation for cervical pain was reliable and simple to use.

Spinal palpation for tenderness has demonstrated greater reliability than palpation for stiffness [512,535,541]. Comparison of the two assessment methods showed poor reliability for spinal palpation for stiffness and good to excellent reliability of palpation for tenderness [512,535]. The more reliable tenderness tests should form the basis for clinical decisions and diagnostic measurement of spinal dysfunction, rather than spinal palpation for stiffness [512,535].

Maher and Latimer [541] argued that spinal palpation for stiffness should be omitted altogether from the diagnostic process and instead therapists should rely on the more reliable tenderness assessment. They [541] suggested that treatment could be directed at the most painful level as it would be logical to direct treatment to the segmental level

that is most painful and physiologically capable of producing the patients symptoms. In addition, if stiffness and pain are related, as clinical theory states, then directing treatment at the most painful level would also direct treatment towards stiffness. If stiffness and pain are not related then treatment directed at the painful level is the more logical approach.

6.1.1.5 SPINAL PALPATION: TENDERNESS OR STIFFNESS?

One investigation, conducted by Jull et al. [112], has lent support for the diagnostic ability of cervical spinal palpation for stiffness. The ability of a manual therapist to diagnose symptomatic cervical zygapophysial joints was tested against diagnostic nerve and joint blocks (diagnostic nerve and joint blocks are discussed in Sec. 6.1.2). The therapist correctly identified all symptomatic cervical zygapophysial joints and demonstrated excellent sensitivity and specificity. This study [112] provided support for the use of spinal palpation for stiffness and tenderness for diagnosis of spinal dysfunction.

However, Triano [365] commented that because this study was conducted with a small number of selected symptomatic subjects, the reliability of spinal palpation for stiffness still remains undetermined. Only one examiner was tested, inter-examiner reliability was not established and results may not be generalisable beyond the therapist involved. Further, Matyas and Bach [512] suggested that because the patient sample had severe pain, provocation and reproduction of pain may have been the key factor in reliable identification of the injured level, rather than stiffness evaluation. This study by Jull et al. [112] has not been repeated and results cannot be generalised to other areas of the spine [506].

In response to calls to discard spinal palpation for stiffness and instead to rely solely on tenderness diagnostic tests, Jull et al. [516] measured an examiner's ability to differentiate painful and non painful cervical segments without verbal cues from the participant. The examiner based their decision entirely upon the perception of abnormal or normal tissue stiffness. The examiner had good agreement with the participant's nomination of the painful and painless segments. Jull et al. [516] concluded that tenderness was not the only cue in the diagnosis of spinal dysfunction; mechanical variables in segmental tissue stiffness related to symptomology can be detected and

manual examination should include *spinal palpation for tenderness and stiffness*. The authors [516] cautioned against relying solely on tenderness assessment as this may cause false-positive spinal dysfunction diagnoses.

These studies [112,516] and others [547] suggested that spinal palpation for stiffness evaluation should not be discarded as a diagnostic criterion when examining the human spine for spinal dysfunction. However, there remain many issues that are not yet resolved. Presently, clear guidelines for the diagnosis of putative spinal dysfunction do not exist. The absence of an operational definition is a hindrance to investigative research of the impact of this putative phenomenon on human health [548].

6.1.2 OTHER METHODS OF SPINAL ASSESSMENT

From the above discussion, it is clear that reliable manual techniques for detection of abnormal stiffness do not exist. Hence, other techniques have been developed for the putative diagnosis of spinal dysfunction. Unfortunately, no one technique stands out as a reliable and valid method for detection of abnormal spinal function, except perhaps for mechanised stiffness assessment (discussed below). In general though, the myriad of imaging techniques available to physicians provide little or no diagnostic assistance in most patients with spinal pain in the neck or low back [110,111]. In neck pain patients, clinicians do not know what, if any, structural factors or tissue pathology may cause the pain [110]. In most patients with chronic low back pain, there is also usually no identifiable structural or mechanical abnormality [111]. These other techniques are briefly discussed here, and are classified as invasive or non-invasive.

Invasive techniques include 'Ionising radiation'. Ionising radiation procedures cannot diagnose painful disorders of tissues such as the zygapophysial joints and intervertebral discs that are believed to be the source of chronic neck pain [524,525,549]. X-ray interpretations addressing relative vertebral positions have repeatedly failed to discriminate between patients with back pain complaints and those without [365]. 'Diagnostic blocks' are a diagnostic procedure of zygapophysial joint and intervertebral disc pain. Local anaesthetic blocks are applied to zygapophysial joints, or nerves that supply them, and if the pain is completely relieved it is inferred that the target zygapophysial joint was the source of pain. Diagnostic blocks require specialised

facilities and skills that are not generally available [550]. This investigative technique is unsuitable for widespread use for diagnostic purposes in a large population group [547].

Non-invasive procedures include: spinal palpation for stiffness and tenderness, ultra-sonic indentation testing, surface scanning electromyography (EMG), cervical range of motion (ROM) assessment, and mechanised stiffness measurement. 'Ultra-sonic indentation' involves measurement of spinal tissues with an ultra-sonic transducer during indentation testing. Indentation testing involves applying a blunt probe to the surface tissue of interest and measuring the resultant deformation of the external surface. Ultrasonic waves may be able to measure displacement of internal structures in a non-invasive manner [551] and provide biomechanical information of internal tissues at various loading conditions. Kawchuk and colleagues have pioneered the validity of this diagnostic procedure and have established: measurement error on a standardised surface [551], error based on measurement of bovine paravertebral tissue [552], accuracy and reliability of measurement of a spring-loaded platform and a porcine lumbar spine [553], and diagnostic performance data based on the presence or not of surgical intervention generated lumbar disc degeneration in pigs [554]. A hand-held ultra sonic indentation probe has also been developed [555]. Ultrasonic technology is a potentially useful technique for quantifying spinal FD properties [553], but this procedure has not yet been validated for the human spinal musculoskeletal system.

'Electromyography' (EMG) is used to measure muscle activity in humans [556]. Non-invasive surface scanning EMG provides for surface measurement only and therefore is limited to measurement of muscle activity close to the skin surface and cannot discriminate deep intersegmental muscle activity [523]. EMG signals can be contaminated by activity from other muscles through a phenomenon called cross-talk [365]. EMG is also very sensitive to postural changes and fatigues effects, and the lack of a standardised protocol that accounts for these factors makes it difficult to make clinical interpretations or comparisons from one test to another, or between examiners [365,542]. The inter-examiner reliability of lumbar paraspinal scanning EMG has been shown to be poor, undermining the validity of this diagnostic procedure [542]. 'Cervical range of motion' (ROM) assessment is a measurement of how far the head can be moved from one extreme to another. ROM measurements do not reveal what is actually happening inside the neck, although they do implicitly provide data on the global function of the neck [478] (see Ch. 5, Sec. 5.1 for further discussion).

'Mechanised spinal stiffness measurement' is an objective measurement procedure using automated stiffness measurement devices. This assessment technique has demonstrated good reliability for measurement of several areas of the spine. This technique is further discussed immediately below.

6.1.3 MECHANISED SPINAL STIFFNESS ASSESSMENT

6.1.3.1 SPINAL DYSFUNCTION AND MECHANICAL STIFFNESS

Manual therapists have hypothesised that increased spinal stiffness, as perceived with spinal palpation for stiffness, may be due to degeneration of articular structures, shortening of joint capsules and adjacent ligaments, or the presence of paravertebral muscle spasm [102,103,113]. As noted above, these pathological conditions may represent mechanisms of spinal dysfunction. Abnormal spinal stiffness is also thought to be associated with pain and that restoration of normal stiffness with manipulation will produce an improvement in health [102,515,535,541,546].

The primary goal of manual therapies is the restoration of mobility within soft tissues and joints, and relieving pain [398]. Manual therapy methods may influence spinal mobility in soft tissues and joints via three closely related mechanisms: mechanical alteration of tissues purportedly involves restoration of mobility within soft tissues and joints; neurophysiologic effects may influence pain modulation and therefore influence mobility through neuromuscular mechanisms; psychological influences involve the relief of anxiety, uncertainty and pain that in turn may influence the neuromuscular system in terms of muscle tension or relaxation [398]. Common to these mechanisms associated with manual therapy methods is the possible alteration of muscle tension and stiffness. This hypothesis includes a possible spinal reflex mechanism, whereby tissue damage can initiate nociceptive impulses which may cause a somatomotor reflex and a resultant increase in tension or spasm of skeletal muscles [61] (see Figure 6-1). However, the poor reliability of spinal palpation for stiffness has meant that the relationship between spinal stiffness and abnormal spinal function is not well understood [102,115,546].

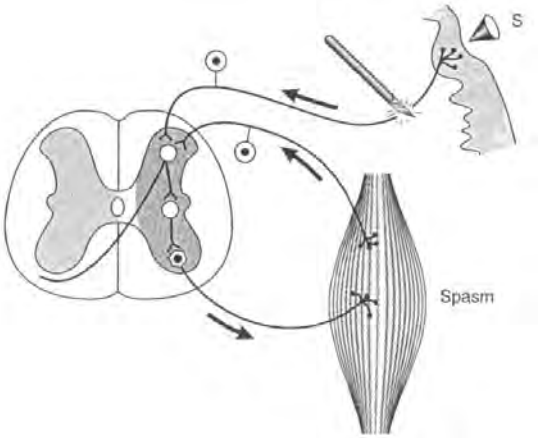


Figure 6-1 – Increased muscle stiffness as a result of reflex neuromuscular mechanisms from Fields and Cousins.

(From [71,222])

6.1.3.2 STIFFNESS MEASUREMENT DEVICES

The poor inter-examiner reliability of spinal palpation for stiffness has lead to the development of objective quantitative techniques for *in vivo* musculoskeletal assessment of the spinal region [109]. Mechanised stiffness measurement devices were developed to mimic manual assessment techniques [535]. These devices apply a force via a blunt indentation probe and record concurrently the applied force and resulting skin deformation [102,118,119]. The mechanised force application devices are fixed to rigid support frames. Measurements taken with these instruments are normally displayed as a force-displacement (FD) curve and the slope of the curve (the first derivative) characterises the tissue stiffness (or mechanical resistance [557]) of the measurement [118,558-560]. It is possible that the mechanical stiffness, derived from the slope of the FD curve, relates in some way to a manual therapists perception of stiffness during manual palpation [510,515,517,561]. *Mechanised stiffness measurement devices do not objectively assess pain sensitivity* during stiffness assessment.

Spinal stiffness assessment with these instruments has been completed in the lumbar [116,558,560,562,563], thoracic [546,559,564] and sacral [558,562] spine regions. Spinal stiffness measurements have not been completed in the cervical spine region. These devices have demonstrated good accuracy and reliability from measurement of foam surfaces [114,118] and aluminium beams with known mechanical properties [102,115]. These devices have demonstrated good reliability for spinal stiffness measurement in asymptomatic [115,116,564] and symptomatic [102] participants.

Empirical evidence exists supporting the use of stiffness assessment for the identification of spinal abnormalities. Lee et al. [115] developed a low back spinal stiffness assessment instrument and demonstrated that muscle activity could affect stiffness levels in the low back [565]. This outcome has been confirmed [560]. Latimer et al. [566] reported an association between low back pain and lumbar posteroanterior stiffness. Symptomatic participants with low back pain were measured initially, when symptomatic, and again afterwards when their condition had considerably improved. *The stiffness coefficient, derived from the slope of the FD curve, decreased by approximately 8% between assessments*. This decrease was *statistically significant*. Asymptomatic participants were also assessed and there was no significant change in low back stiffness between stiffness measurement times.

Further information regarding sources of variation in spinal stiffness data, and how to derive stiffness estimates from force-displacement data is discussed in App. G, Sec. G.1.1 and G.1.2.

6.1.4 SPINAL ASSESSMENT SUMMARY

Assessment and diagnosis of spinal dysfunction with manual spinal palpation for stiffness is an *unreliable technique*. The poor reliability of this technique has undermined its clinical and research applicability and makes its use for diagnostic purposes unclear. Spinal palpation for tenderness, or the reproduction of pain, has demonstrated better reliability than palpation for stiffness and has good inter and intra examiner reliability. Some clinicians believe that tenderness tests should form the basis for clinical decisions and diagnostic assessment of spinal dysfunction, although there is still debate about this issue. In addition, tenderness assessment of various regions of the musculoskeletal system with pressure algometry has demonstrated good reliability (see Ch. 4, Sec. 4.3.5.1 for review).

Other techniques for the detection of spinal dysfunction have been discussed and presently spinal stiffness measurement with mechanised instrumentation appears to be the most developed. Results appear encouraging regarding detection of spinal stiffness abnormalities with these devices. However, there are numerous sources of variability and clear guidelines do not exist for the detection of altered spinal stiffness that may indicate the presence or not of spinal dysfunction. In addition, current stiffness

measurement devices do not incorporate pain sensitivity assessment with stiffness measurements and therefore, *do not assess the function of the pain system*. Tenderness assessment has demonstrated good reliability, and therefore, it would be advantageous to include pain sensitivity assessment with stiffness measurements.

Mechanised spinal measurement devices are fixed to rigid mounting frames and presently there does not exist an instrument suitable for application in the cervical spine region. Spinal musculoskeletal stiffness measurements have not been conducted in the cervical spine. *Presently, a stiffness measurement device that incorporates pain sensitivity assessment and would be applicable to the cervical spine does not exist*. Hence, one was developed for this thesis (see App. F).

Ultrasonic indentation shows great promise and with further development and validation on the human musculoskeletal system may provide an objective and valid measure for detection of spinal dysfunction. However, the specialised equipment associated with this method limits applicability.

6.2 INTRODUCTION – SPINAL DYSFUNCTION IN REGIONAL PAIN SYNDROME AND FIBROMYALGIA

6.2.1 FM, RPS AND SPINAL DYSFUNCTION

It is likely that dysfunction in spinal structures (spinal dysfunction) is a factor associated with the pathogenesis of RPS and FM [17,20,21,32,93-100], particularly in the cervical and lumbar spine. The axial skeleton and shoulder and pelvic girdles are the most common areas of pain, and it is very unusual for FM patients not to have cervical or low back pain [176]. The cervical and lumbar spinal regions are commonly reported as one of the most problematic areas associated with FM [33,101,106,567]. FM patients report pain in the thoracic (72.3%), lumbar (78.8%) and cervical (85.3%) spinal regions [101]. In an investigation of RPS and FM by Inanici et al. [21], the most common regions of pain reported were the neck/trapezius (51% of RPS and 85% of FM patients) and upper extremity (47% of RPS and 91% of FM patients). These figures were very similar to those reported by Granges and Littlejohn [20], with symptom complaints located in the neck (43% of RPS and 74% of FM patients), thoracic (35% of RPS and 77% of FM patients), arm (32% of RPS and 55% of FM patients) and low back (60% of RPS and 57% of FM patients). These figures point to the *spinal regions an being of importance in FM and RPS*. Some investigations completed recently are reported here.

Buskila et al. [78] stated that although equivocal, some evidence suggests that biomechanical disturbances of the cervical spine may play a role in the pathogenesis of FM. Buskila et al. [78] investigated the rate of FM occurrence in patients who suffered a single event cervical spine injury. They [78] reported that 21.6% of patients subsequently developed FM in an average of 3.2 months after the initial cervical injury. Compared with a control group with major leg injuries, people with cervical spine injuries were thirteen times more likely to develop FM. The patients with neck injuries also had more tenderness and more sensitive tender points in the upper torso than the patients with leg injuries. A neck injury may trigger the development of RPS (in the cervical and chest areas) that may evolve into a diffuse musculoskeletal pain disorder [78]. These results [78] suggested that some areas of the musculoskeletal system, particularly the neck, were *more susceptible* than others to initiating aetiologic factors relating to the onset of FM.

Lapossy et al. [98] investigated retrospectively chronic low back pain patients and found that 25% went on to develop FM. They concluded that dysfunction in the lumbar spine appeared to contribute to the onset of FM.

More recently, Giesecke et al. [111] showed that patients with chronic low back pain and FM experienced significantly more pain and showed more extensive patterns of brain activity when pressure was applied, than healthy controls. The patient groups also had more tenderness at a neutral site than the controls. Patients showed more extensive, common patterns of neuronal activation in pain-related cortical areas, than the controls for equal levels of applied pressure (five pain-related cortical regions showed neuronal activity in the patient groups, compared with one in controls). The increased regional cerebral blood flow from application of pressure corroborated the fact that patients with chronic back pain and FM were more sensitive to pressure stimuli than were controls. Giesecke et al. [111] concluded that the findings were consistent with the occurrence of augmented central pain processing in patients with chronic low back pain and FM.

Muller et al. [93] investigated clinical spinal instabilities and deformities in FM patients. They [93] measured spinal contours, mobility and vertebral angles and reported that functional disturbances of the spine were more frequent in FM and low back pain patients compared with healthy controls. They [93] concluded that *the spine played a large role in the development of FM*. Chronic local pain may develop via repeated mechanical irritation of small vertebral joints or ligaments and activation of nociceptors in these regions, as well as from reflex muscle spasm together with postural problems. *The pain may then spread via central mechanisms*. Psychopathological variations most likely also played a role [93]. This hypothesis was based on an observed, hastened generalisation of pain in patients who had a stronger psychosocial stress, depression or anxiety burden [93].

Spinal dysfunction is a common occurrence in the community [20,96] and, in association with aberrant central pain mechanisms could characterise the clinical features of RPS and FM [17,20,94]. Abnormal function in and between vertebral units and subsequent activation of nociceptors in the spinal region alone would not characterise the features of RPS; the diffuse nature of the pain in RPS and FM mitigates against this [256]. Instead, for RPS, central pain-processing changes may occur,

providing amplification of nociceptive stimuli and access to the pain system of non-nociceptive input from dysfunctional spinal structures [20,96,104-107].

Granges and Littlejohn [20,108] investigated spinal dysfunction in FM and RPS patients with manual therapy methods; they reported that no patient could be found in their investigations without spinal dysfunction. The number of spinal dysfunctions correlated with the total number of tender points, pressure pain thresholds, and clinical signs and symptoms in RPS and FM patients. The presence of cervical and thoracic tender points best predicted the presence of clinical signs and symptoms. However, as detection of spinal dysfunction using manual therapy techniques has not been validated, these results do not provide definitive evidence of an association between dysfunction of spinal mechanisms and RPS and FM.

In simplistic terms, dysfunction of one or more of the structures in the deep paraspinal region may constitute 'spinal dysfunction' [20]. However, there is confusion regarding the concept and validity of the phenomenon of spinal dysfunction [529]. Hence, more work is needed to better understand this entity and its association with RPS and FM (spinal dysfunction is discussed in further detail in Ch. 6, Sec. 6.1.1).

In summary, it appears likely that spinal dysfunction plays a role in the onset of initial complaints and RPS, and continues to be an important factor when symptoms have become generalised. While the exact mechanisms are unknown, it has been proposed that a strong nociceptive stimulus from axial somatic structures is effective at initiating centrally mediated pain phenomena, such as referred pain, and primary and secondary hyperalgesia [20,568]. An afferent barrage from dysfunction in the structures of the neck could be a factor involved in the pathogenesis of altered central pain processing. Increased excitability of the nociceptive neurons in the central nervous system could then be maintained by ongoing nociceptive stimuli from a nociceptive source in the spinal region. It has been hypothesised that augmented central pain processing could develop and, in combination with dysfunction of spinal structures, associate with the clinical features of RPS [20,94,108].

However, this relationship has not been extensively investigated, in part due to difficulties in validly defining the putative spinal entity spinal dysfunction. The relationship between spinal dysfunction and chronic neck pain patients (some of whom

would represent RPS patients, but not all) and FM patients is investigated in this chapter.

6.2.2 MUSCULOSKELETAL STIFFNESS ASSESSMENT

Presently, a validated *in vivo* technique for detection of spinal dysfunction does not exist. As discussed above, there is little scientific evidence to support the validity of spinal palpation for stiffness or even the existence of the putative phenomenon, spinal dysfunction [530]. The inter-examiner reliability of this assessment technique is poor and the clinical role of spinal palpation for stiffness has been questioned [535,539,540]

Because judgements of spinal stiffness made using manual tests are unreliable, mechanised stiffness measurement devices were developed to mimic manual assessment techniques that assess *in vivo* musculoskeletal stiffness of the spinal region [109]. These devices have good reliability for spinal stiffness measurement in asymptomatic [115,116,564] and symptomatic [102] participants. Reliability has been examined by measuring displacement data [116] and stiffness estimates [115] on asymptomatic participants over a two day period, in asymptomatic participants over a two minute period [564] and in symptomatic participants with low back pain in a five minute period [102]. However, spinal stiffness assessment of FM patients has not been conducted with mechanised stiffness measurement devices.

Current mechanised stiffness measurement devices are fixed to rigid mounting frames and would experience practical difficulties for measurement of the cervical spine. It is unlikely that these devices could be applied at angles that are not aligned with a participant's sagittal plane. As noted above, there does not exist a mechanised stiffness measurement device that would be applicable to the posterolateral aspect of the cervical spine, and no stiffness measurements of the cervical spine have been conducted. Hence *a spinal stiffness instrument applicable to the cervical spine was developed in this thesis*. This device is discussed in Sec. 6.2.4 and App. F.

6.2.3 TENDERNESS ASSESSMENT

A principal classification feature of FM and RPS is a lowered pressure pain threshold (PPT) or tenderness. Tenderness, assessed either by pressure algometry or manual palpation, is associated with pain and pain behaviour in patients with FM

[186,240,287,470,471,473,474] and RPS [33]. Increased pain sensitivity is indicative of the generalised pain experience in patients with FM [471] and is a measure of general distress [474].

Pressure algometry involves application of a gross mechanical pressure for the assessment of tenderness, which is expressed quantitatively by the PPT value. Pressure algometry has demonstrated good inter and intra-examiner reliability for assessment of PPT in various regions of the musculoskeletal system, and in asymptomatic and symptomatic participants (see Ch. 4, Sec.4.3.5.1).

Palpation for provocation and reproduction of pain (tenderness assessment) by manual therapists has also demonstrated good reliability [512,543,544]. As noted above in Sec. 6.1.1, some authors [512,535] believe that pain tests should form the basis for clinical decisions and diagnostic measurement of spinal dysfunction, rather than spinal palpation for stiffness.

The association of tenderness and symptoms in chronic musculoskeletal pain, and the good reliability of pressure algometry and manual palpation for tenderness, support inclusion of pain evaluation in a measurement system that purports to assess the association of spinal dysfunction and clinical features of chronic pain syndromes.

Presently, the mechanised stiffness measurement devices *do not include measurement of pain sensitivity during stiffness measurements*. Instead other methods have been used to assess pain in participants: the McGill pain questionnaire [102,566], visual analogue scale [566], excluding participants if they report pain on application of force [113] or simply requesting participants to report pain during stiffness measurement [558]. Hence, *the spinal stiffness instrument developed in this thesis was designed to also assess tenderness*. This device is discussed in the next section (Sec. 6.2.4) and App. F.

6.2.4 MODIFIED TISSUE COMPLIANCE METER (M-TCM)

The modified tissue compliance meter (M-TCM) was *developed in this thesis* to measure *concurrently musculoskeletal tissue stiffness and pain sensitivity* in the *cervical spine*. As discussed above (Sec. 6.1.3.1), abnormal spinal musculoskeletal stiffness is believed to be indicative of dysfunction in the spinal region. It was hoped that this device would indicate the presence or not of abnormal musculoskeletal stiffness in the

cervical region. As well, this device was designed to measure pain sensitivity, which is a critical aspect of chronic musculoskeletal pain. As will be discussed below, this device was used in this chapter to measure cervical musculoskeletal stiffness and PPT in chronic pain patients and healthy persons.

The M-TCM is a hand held device is based on the original tissue compliance meter developed by Fischer [569]. Modifications include the replacement of the original analogue transducers with electromechanical transducers and the inclusion of an electromagnetic tracking system (ETS) for alignment guidance. The M-TCM had the same application tip, exactly as that used in the Algometer instrument described in Ch. 4, Sec.4.3.5.1, and was applied at the same force application rate, and therefore *also measures PPT*.

The M-TCM has demonstrated good to high intra and inter-examiner reliability when tested on homogenous foam samples and a flat control surface, and high accuracy on foam surfaces. The M-TCM foam and control surface reliability and accuracy results are presented and discussed in Sec. 6.4.2.1 and App. F.

6.2.5 CERVICAL RANGE OF MOTION

In Ch. 5 it was discussed that cervical range-of-motion (ROM) measurement is utilised in clinical practice as an assessment tool for the identification of disorders of the cervical spine [475]. For example, a decreased cervical ROM may be indicative of disorder of the cervical spine [414,435]. It is believed that this measurement provides an objective measure of the status or function of the cervical spine [476,481]. In this chapter, it is postulated that chronic pain patients have dysfunction of the cervical spine – hence cervical ROM was measured to assess the status of the cervical spine.

Cervical ROM has been shown to be significantly reduced in symptomatic patients with chronic musculoskeletal pain, when compared with asymptomatic participants. Mannerkorpi et al. [570] demonstrated that FM patients have significantly reduced rotation ROM, compared with age-matched healthy controls. Patients with chronic neck pain, including whiplash-associated disorders, have also demonstrated a reduced cervical ROM compared with healthy controls [416,476,479,480,483]. These previous studies support the measurement of cervical ROM in patients with chronic pain (see Ch. 5, Sec. 5.1 for further discussion).

6.2.6 THE ZYGAPOPHYSIAL JOINTS AND CERVICAL PAIN

In this section, it is discussed that the zygapophysial joints are the most common source of pain in chronic neck pain. These cervical joints are commonly assessed by manual therapists during examination, including manual pain assessments. PPT assessments over the cervical zygapophysial joints have also been conducted. For the investigation reported in this chapter, the zygapophysial were the region of the cervical spine assessed with the M-TCM (see Sec. 6.4.5.2).

Neck pain can arise from any structure in the cervical spine that receives a nerve supply [571]. These include the cervical zygapophysial joints, the neck muscles, the atlanto-occipital and atlantoaxial joints and their ligaments, the cervical dura matter and the cervical intervertebral discs and their ligaments [571]. It is unlikely that the cervical muscles are a source of chronic neck pain [572]. Injuries to tissues that heal slowly or heal less so than muscles, are more likely contenders for chronic neck pain. These tissues include the synovial joints and the intervertebral discs [524].

The zygapophysial joints are a common source of pain in chronic pain syndromes of the cervical spine [572]. Early investigations by Bogduk and colleagues suggested that the zygapophysial joints were a source of chronic neck pain [402,524,550,573,574]. This was confirmed in a double-blind study of diagnostic blocks of the cervical zygapophysial joints of symptomatic participants with chronic neck pain [525]. Barnsley et al. [525] identified painful joints in 54% of cases indicating that, in their investigation, cervical *zygapophysial joint pain was the most common source of neck pain*.

The zygapophysial joints and the surrounding soft tissues are normally assessed during an examination procedure by manual therapists. They apply spinal palpation for stiffness to test the mechanical properties of the joint [507]. However, as discussed above in Sec. 6.1.1, the poor reliability of this method has undermined the diagnostic ability of this assessment technique.

In contrast, *manual palpation for provocation of pain over the zygapophysial joints has demonstrated good reliability* in symptomatic participants [543] and the assessed tenderness appears to corroborate with self-reports of pain in the neck [400]. Sandmark and Nisell [400] compared the results of five different manual tenderness assessment

tests of the cervical spine with self-reported presence or not of chronic neck pain and other musculoskeletal neck complaints. Tenderness assessment over the zygapophysial joints was the most appropriate screening tool to corroborate self-reported musculoskeletal dysfunction of the neck [400]. This test had high specificity and sensitivity for the presence or not of chronic cervical pain [400].

Pressure algometry has also been applied over the cervical zygapophysial joints. Sterling et al. [386] applied an algometer over zygapophysial joints in the upper and lower cervical spine in whiplash patients and asymptomatic participants. The cervical zygapophysial joint PPTs were significantly lower in the patient group.

6.3 OBJECTIVE

The objective of this chapter was to investigate the supposition that in fibromyalgia patients and participants with chronic regional neck pain syndrome there was dysfunction of the cervical spine. It was hypothesised that abnormalities of cervical spinal function may be an important pathophysiological factor in the chronic non-specific pain syndromes.

Another aim of this investigation was to assess the reliability and discriminate ability of clinical tests and the modified tissue compliance meter's (M-TCM) ability to measure musculoskeletal stiffness and pain sensitivity.

6.4 MATERIALS AND METHODS

6.4.1 EXPERIMENT SUMMARY

This research explored the presence or not of abnormal cervical spinal function in patients with chronic neck and widespread pain. The Modified Tissue Compliance Meter (M-TCM) (described below) was applied to ten different locations in the posterolateral aspect of the cervical spinal of each participant. Three participant groups were assessed: fibromyalgia, chronic neck pain participants and normal asymptomatic participants. Participants were required to lie prone on a soft mattress placed over a desk, and the M-TCM was then applied to the posterior region of the neck.

The M-TCM measured concurrently the musculoskeletal stiffness of the cervical spine region and the pressure pain threshold (PPT), over the skin at the zygapophysial joints. It was hypothesised that the M-TCM instrument would detect abnormal musculoskeletal stiffness and pain sensitivity in the cervical spine region of the symptomatic participants, compared with the healthy participants. The cervical stiffness and PPT results were analysed for differences between the three participant groups using a multifactor repeated measures Analysis of Variance (ANOVA). The discriminate ability of these measurements was also assessed.

All participants were assessed three times: initially, ten minutes later and finally two hours after the first assessment. These time delayed measurements were conducted to assess the reliability of the M-TCM stiffness and PPT results. The Intraclass Correlation Coefficient (ICC) was used to evaluate reliability.

Cervical range of motion (ROM) and self-reporting instruments were also measured.

Ethics approval was given for this research prior to commencement from the Swinburne University of Technology, Human Research Ethics Committee. App. H shows the ethics approval provided from this committee.

6.4.2 EQUIPMENT AND MEASURED VARIABLES

6.4.2.1 MODIFIED TISSUE COMPLIANCE METER (M-TCM)

The modified tissue compliance meter (M-TCM) was developed in this thesis (see App. F and Figure 6-2). This instrument was applied in this chapter to measure and record force-displacement (FD) data at prescribed locations of the cervical spine.

Briefly, the M-TCM consists of a shaft with a rubber tip that was pressed into the skin, displacing the skin surface. Skin displacement was measured by a disc-shaped collar (the slide collar) that surrounded the shaft and remained at the original skin surface level. A linear variable differential transducer (LVDT) measured the displacement of the slide collar in relation to the application tip. A load cell at the top of the shaft measured the applied force.

For each measurement, the load cell and LVDT output was displayed as a force-displacement (FD) curve (see Figure 6-3). The M-TCM measured the displacement of

the assessed surface relative to the indentation rubber tip. This removed several sources of variability associated with measuring absolute tip displacement (see Sec. 6.1.3). The M-TCM has demonstrated good to high intra and inter-examiner reliability and good accuracy from application to foam surfaces, wooden blocks and a control surface (see App. F for full results).

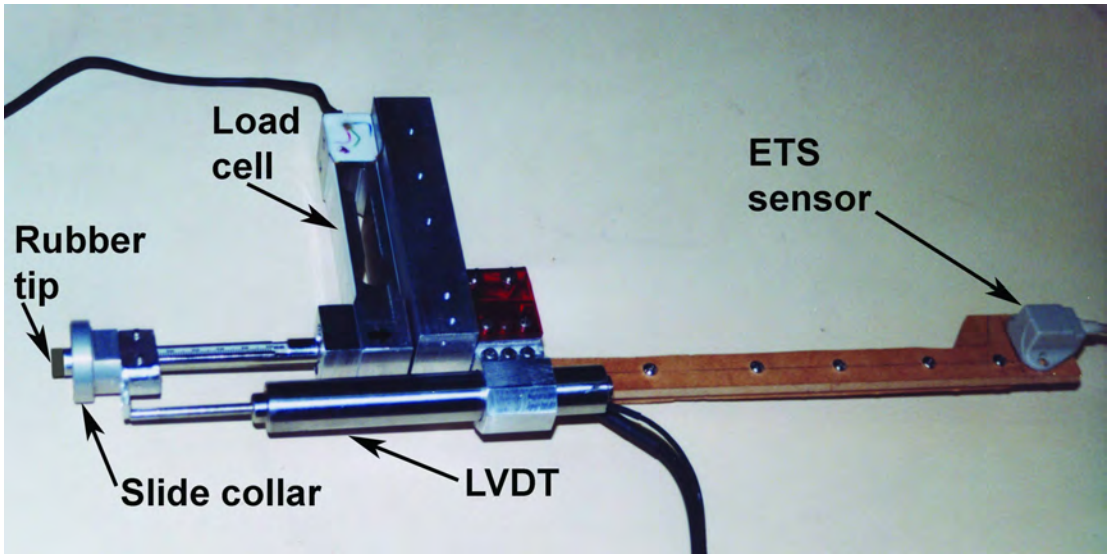


Figure 6-2 – The modified tissue compliance meter (M-TCM) without a cover over the load cell

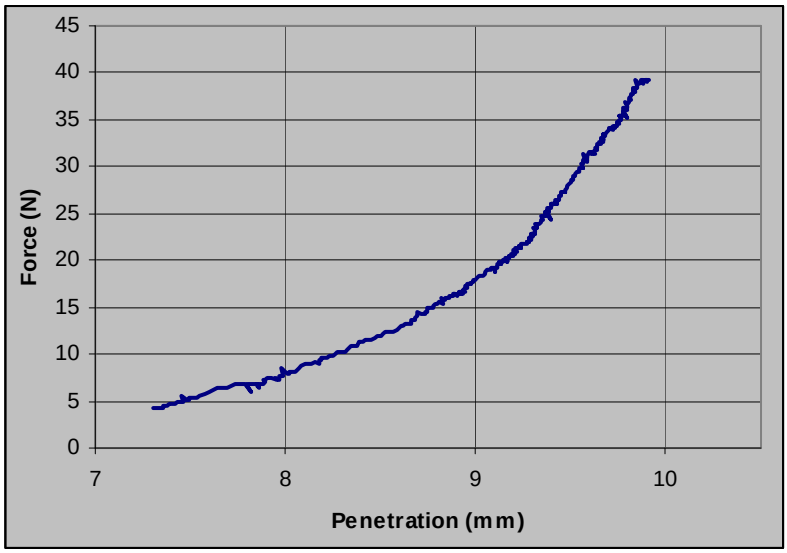


Figure 6-3 – Example of the output from the M-TCM instrument – the force-displacement curve.

The M-TCM utilised an Electromagnetic Tracking System[15] (ETS) to assist the examiner guide the M-TCM instrument to a perpendicular orientation to a measured

[15] Ascension Technology Corp: 'Flock-of-Birds', P.O. Box 527, Burlington, VT, USA

surface. The method of using the ETS sensor to achieve a perpendicular orientation of the M-TCM is described in Sec. 6.4.5.3 and Sec. 6.4.5.4.

The ETS was an accurate instrument with high angular and translational accuracy (see App. F, Sec. F.3.2 and App. A, Sec. A.1.1).

6.4.2.2 THE MEASUREMENT DESK

The ETS transmitter was fixed to a wooden beam located above a desk. Participants were required to lie prone on a soft mattress placed over a desk – see Figure 6-4. Two foam cylinders running parallel with the participant were placed at the head of the desk. The participant placed their head in between the foam cylinders. This position restricted head and neck movement and encouraged flexion of the cervical spine. This permitted easy access to the posterior lateral aspect of the cervical spine.

Figure 6-4 – Participant lying prone on the measurement desk ready to be assessed with the M-TCM

6.4.2.3 PASSIVE CERVICAL RANGE OF MOTION (ROM)

The ETS was also used to measure passive cervical ROM. Measurement of passive cervical ROM with the ETS has demonstrated high intra-examiner and fair to high inter-examiner reliability and compares well with other ROM measurement devices (see Ch. 5 and [575]). The ETS sensor was mounted so that the X axis was directed posteriorly,

the Y axis laterally left and the Z axis in a caudal direction. The transmitter axes were also aligned in this manner.

Measurements were recorded at extremes of motion in each movement plane (sagittal, frontal, transverse). Conjunct motions were also recorded. Conjunct movements are motions in planes other than the primary movement plane and were recorded when the extreme position in a primary movement plane was attained. Whole plane ROMs were measured from one extreme to another in a movement plane. This technology and its application to the measurement of passive cervical ROM is further discussed in Ch. 5.

6.4.2.4 SELF-REPORTING INSTRUMENTS

Participants completed a series of health assessment questionnaires before commencement of testing (see Ch. 4, Sec. 4.3.5.4 for review). Participants indicated their age, areas of the body that they had suffered frequent pain in over the past three months, areas of the body in which they had suffered frequent pain in the past (described below), a past history of injury to the spine and the number of hours per week that participants undertook significant manual activities, maintained static postures and exercised.

Participants also indicated on visual analogue scales (VAS) [407] the average headache and neck pain felt during the week before testing. Participants completed the Neck Disability Index (NDI) [421], Profile of Mood States (POMS) [422], Spielburger State-Trait Anxiety Inventory State-Anxiety scale (STAI-S) [423] questionnaires and for FM participants the Fibromyalgia Impact Questionnaire (FIQ) [576]. The VAS, POMS, STAI-S, and NDI are discussed in Ch. 4 Sec. 4.3.5.4. The FIQ questionnaire is discussed below.

The POMS measured six identifiable mood or affective states:

- Tension-Anxiety (TA)
- Depression-Dejection (DD)
- Anger-Hostility (AH)
- Vigour-Activity (VA)
- Fatigue-Inertia (FI) and
- Confusion-Bewilderment (CB)

For areas of the body that participants had suffered frequent pain over the past three months, six areas were available for selection:

	Left Side	Middle	Right Side
Neck			
Front of Chest			
Upper-back			
Low-back			
Arm / Shoulder			
Leg / Buttock			

Table 6-1 – Regions that participants could indicate they had suffered pain in for more than three months

In total, there were eighteen areas to indicate frequent pain over the past three months. A '*total region count*' was derived by adding the number of regions indicated as painful. Participants completed the questionnaires on average in less than 15mins.

6.4.2.4.1 Fibromyalgia Impact Questionnaire (FIQ)

The Fibromyalgia Impact Questionnaire (FIQ) is a brief 10-item self-administered questionnaire that assesses the current health status of women with the FM syndrome. Initial construction of the FIQ was based conceptually on the premise that the instrument should contain physical, psychological, social and global well-being components. The FIQ has demonstrated good test-retest reliability, and construct and content validity, and acceptable reliability when compared with similar scales on another well-established rheumatology questionnaire [576]. The sensitivity to change has been validated [577]. The FIQ has been used to show similar global quality of life scores in FM and rheumatoid arthritis patients, with FM having a slightly higher score [578]. Furthermore, the FIQ is the only scale that addresses function in FM. However, it mainly focuses on instrumental and other activities of daily living, rather than work capacity [244].

For these reasons, the FIQ was selected for to use to assess the health status of FM patients assessed in this experiment. The FIQ is the only tool available that assesses function in FM.

6.4.3 PARTICIPANTS

Sixty-two female participants were measured in total. Three classification categories were included:

Participant Classification	Code	Number	Age
Fibromyalgia patients	FM	21	45.5 (SD 10.5)
Chronic neck pain sufferers	NP	18	40.0 (SD 10.1)
Normal (asymptomatic) participants	NORM	23	37.0 (SD 13.9)

Table 6-2 – Classification of participants and number in each group.

(Note: participants were not age matched).

FM participants were recruited by mail invitation from private rheumatology practices in Victoria, Australia. NP participants were recruited by invitation email to staff at Swinburne University of Technology and also by referral from local chiropractic clinics. NP participants were classified as chronic if their condition had existed for a period of three months or more. Over half of the NP participants indicated that they had sustained a major spinal injury in the past, generally from a fall or motor vehicle accident. Most NP participants indicated they were receiving regular treatment for the neck pain and some also indicated they suffered from headache pain.

The NP participants were not considered to be patients suffering from a regional pain syndrome, although it was highly likely that some participants were so. A thorough clinical examination was not conducted on these participants and therefore specific clinical diagnosis could not be discounted. Instead, these participants were included because they reported chronic and significant neck pain, and therefore were likely candidates to have putative spinal dysfunction.

Participants were classified as NORM if they presented without neck and headache pain and did not have a history of neck or headache pain. Criteria for exclusion included participants with internal metal objects or pacemakers.

6.4.4 EXAMINER

- The *author* conducted all M-TCM measurements and ROM measurements.

6.4.5 METHOD

6.4.5.1 PROCEDURE OF MEASUREMENT WITH THE M-TCM

Participants lay in a prone position on the measurement desk. The M-TCM was applied to *five bilateral measurement locations* (ten in total) on the posterolateral aspect of the neck – see Figure 6-5.

Figure 6-5 – Participant being measured with the M-TCM in the posterior cervical spine, on the left side

This process was repeated *three times: initially* (time 1), again *10 minutes later* (time 2) and *2 hours* (time 3) after the first measurements were conducted. Thirty M-TCM measurements were conducted in total on each participant, resulting in a total of 1860 M-TCM measurements on all participants.

A *maximum applied force of 50N* was applied unless the participant indicated that the measurement was beginning to become painful, when the measurement would stop immediately. Participants were instructed to indicate verbally as soon as the applied pressure became painful. This *limited each measurement to the participant's pressure pain threshold* (PPT) at a particular location, unless the PPT value was greater than 50N, when the measurement would stop regardless of PPT. A maximum value of 50N was selected as this value is approximately half that used in manual therapy [579] and was unlikely to cause injury or significant discomfort to participants. For each measurement with the M-TCM, the maximum applied force was recorded as the PPT. Measurements that reached the maximum applied force of 50N were recorded as such.

PPT measurements at each site were only measured once per session. Current research practice is to test three times consecutively and take the average of the three results an

the value. This was not applied due to the large number of sites tested within each participant, three times over, and the inconvenience to the participant. This was particularly relevant to the FM patients, who experienced some discomfort lying prone for extended periods.

6.4.5.2 LOCATING THE CERVICAL MEASUREMENT SITES

The ten cervical measurement locations were located and marked with non-permanent marker as described in Sec. 4.3.5.1.2.1.

As discussed above, the lumber spinal stiffness testing devices apply pressure over the spinous processes, and test the ability of the entire vertebra to resist the applied force. This is similar to clinical practice for lower back manual stiffness assessments. In the cervical spine however, practitioners do not test the spinous process of vertebra, but instead test the ability of the zygapophysial joints to resist motion in response to applied manual pressure. As well, the zygapophysial joints have been identified previously as the most common source of neck pain in chronic neck pain populations [524,525,574]. The method of clinical assessment, nerve innovation and studies that have previously assessed PPT in the cervical spine over the zygapophysial joints were reviewed above in Sec. 6.2.6.

It was therefore logical to test the cervical structures previously identified as the most likely candidate for causing pain in chronic neck pain patients. As well, in this study, the M-TCM was applied over the zygapophysial joints to mimic manual methodologies used in clinical practice when clinicians used manual palpation to assess for spinal dysfunction. The cervical locations of assessment were outlined previously in Sec. 4.3.5.1.2.1.

6.4.5.3 FINDING A PERPENDICULAR M-TCM ORIENTATION

The ETS sensor was used to measure and record a profile of the cervical spine prior to any M-TCM measurements. The profile of the neck was used to assist the examiner attain a perpendicular orientation of the M-TCM to the neck surface at each measurement location. A plastic holder was used to house the ETS sensor to assist with this task. The plastic ‘neck profiler’ consisted of a small base (approximately 40mm x 45mm) and a square piece of plastic placed along the midline of the base in a vertical

orientation. The base was slightly curved. The ETS sensor was attached to the vertical plastic piece.

A profile of a participant's neck was accomplished by slowly moving the neck profiler, with the ETS sensor attached, from the inferior to superior measurement locations. The data recorded from the ETS sensor combined with the known offsets and angles from the ETS sensor to the base of the neck profiler permitted derivation of a perpendicular orientation of the skin surface under the neck profiler. This was stored in a data file and used to assist the examiner attain a perpendicular orientation during M-TCM measurements.

Others have used similar techniques. Allison et al. [580] used a 'T' square to align their stiffness measurement device perpendicular to measurement locations.

Figure 6-6 – The neck profiler (without the ETS sensor attached).

For M-TCM measurements completed at 10 minutes and 2 hours, the neck was positioned in the same orientation as at the initial assessment. The participant placed their neck in the headpiece and the examiner placed the sensor of the ETS firmly over the marked spinous process of the C7 joint. A comparison was then made with measurements taken at the initial measurement time. The angles of the ETS sensor had to be within 2 deg. This was displayed visually to the examiner as moving bar graphs that changed colour to green when at the required orientation. The examiner requested the participant to alter position if necessary. This was repeated with the ETS sensor over the spinous process of the C2 vertebra. This ensured that inferiorly (C7) and superiorly (C2) the cervical spine had an orientation of within 2 deg between measurement times.

6.4.5.4 COMPUTER INTERFACE FOR THE M-TCM

A custom Microsoft Visual Basic v6.0 program used the data from the neck profiler to assist the examiner attain a perpendicular orientation of the M-TCM to the neck surface

prior at each measurement. The Visual Basic program used the neck profiler data and the actual ETS sensor location to ascertain the distance and direction required for a perpendicular orientation. The distance of the M-TCM from a perpendicular orientation was graphically displayed to the examiner.

A target with cross-hairs at the centre represented 'perpendicular' and an easily visible circular 'marker' represented the current orientation of the M-TCM with respect to the target – the closer the marker was to the centre of the target, the closer the M-TCM was to perpendicular. In addition, a bar chart indicating the rate of change of force was displayed to assist the examiner maintain a continuous application rate during M-TCM measurements. The chart changed colour from green if the rate was lower or higher than the recommended application rate of 9.81N/sec. This application rate is the same used with the Algometer instrument [374]. The examiner interface is shown in Figure 6-7 and discussed in more detail in App. F.

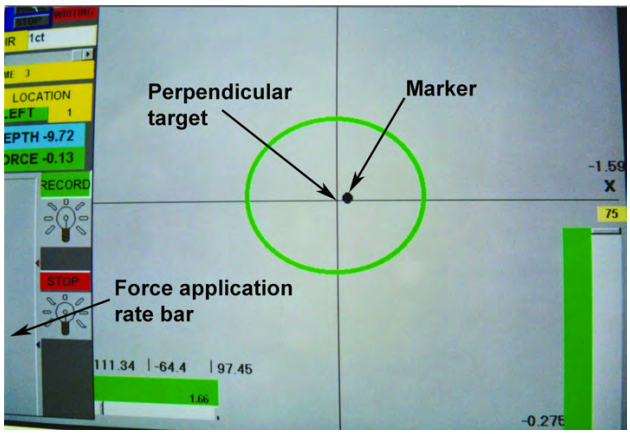


Figure 6-7 – The M-TCM computer interface

6.4.5.5 PASSIVE ROM MEASUREMENTS WITH THE ETS

The thesis author conducted whole plane passive cervical range of motion (ROM) measurements just prior to M-TCM measurements. The author has demonstrated acceptable inter and intra-reliability for cervical ROM measurements with an ETS (see Ch. 5 and [575]). Participants were measured in a seated position on an upright wooden chair. The ETS sensor was attached to a custom headpiece that was placed on each participant for ROM measurements. Passive cervical ROM was measured in the transverse (rotation), frontal (lateral flexion) and sagittal (flexion/extension) planes, from one extreme to the other (whole plane motion).

Two measurements were recorded in each plane of motion for each participant. Conjunct motions were also recorded. Conjunct movements were motions in planes other than the primary movement plane. The full procedure employed is outlined in Ch. 5. Unlike the M-TCM measurement procedure, ROM was not measured at 10 minutes and 2-hour intervals. It was only measured at the initial assessment time.

6.4.6 DATA ANALYSIS

6.4.6.1 CERVICAL STIFFNESS DATA ANALYSIS

The Force-Displacement (FD) data was examined to characterise the spinal responses at different cervical locations and to explore the possible contribution of independent variables to the measured responses.

6.4.6.1.1 FD linear, exponential and polynomial model analysis

Results from the M-TCM were displayed as a FD curve. The computer program Mathematica[16] v3.0 was used to fit the FD curves with three curve fitting models: linear, exponential and 5th order polynomial. Each curve was fit with an exponential model ($Y = a + b.e^{c.x}$) where *a, b* and *c* represented the constants of the model; and a 5th order polynomial model ($Y = a + b.x + c.x^2 + d.x^3 + e.x^4 + f.x^5$) where *a-f* represented the constants of this model. Fitting the FD curves with an exponential and polynomial model made data analysis considerably simpler as each FD curve was reduced to the constants of the models. For each curve, the first derivative of the exponential and polynomial models was calculated using custom written software in Microsoft Visual Basic v6.0.

The slopes of each curve *up to the PPT value* were derived for values of 12.5N, 25N, 37.5N and 50N – see Figure 6-8. If the PPT stopped a measurement reaching 50N, the stiffness value for 50N was not calculated. These force categories correspond to 25%, 50% 75% and 100% of the maximum applied force. The derived slope values *characterised the stiffness* of each FD curve at the four force values and this data was

[16] Wolfram Research Inc., 100 Trade Center Drive, Champaign, IL 61820, USA

used with all statistical analysis. The PPT value for each measurement was the upper limit of the FD curve.

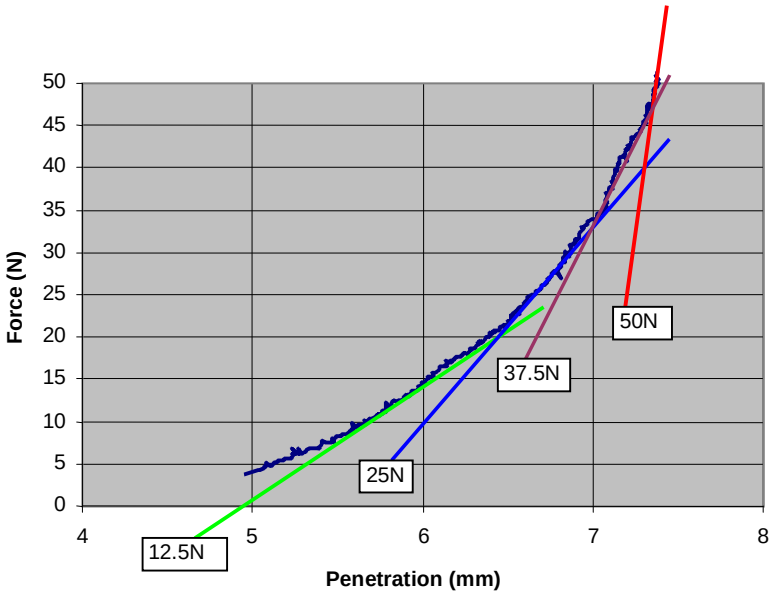


Figure 6-8 – Example of the force-displacement curve with the slope (stiffness) at 12.5N, 25N, 37.5N and 50N shown. These stiffness values (the slopes) were used in statistical analysis.

FD curves that did not reach a maximum force value of 12.5N (25% of maximum) were not included in the data analysis. FD data below this value may characterise superficial tissues only and were of little benefit for analysis. In addition, a force of 12.5N is not greatly above the start force value and therefore would provide a limited amount of data for analysis.

Exponential and polynomial models fitted to FD curves that did not achieve a correlation coefficient (r^2) of greater than 0.97 were not included in the data analysis. Exponential and polynomial models with r^2 values below this value did not appear to fit the data sufficiently well. A small percentage of FD curves were removed from analysis due to irregular shape. Irregular shaped FD curves included backward sloping and unexplained spikes in the data. This was likely due to the measurers hand shaking during recording and affecting the measurement (see App. G, Sec. G.2.5 for results).

6.4.6.1.2 Cervical stiffness reliability

The Intraclass Correlation Coefficient ICC(2,1) [433] was used to assess the inter-measurement reliability of the M-TCM for times 1, 2 and 3 results at each location and for each participant class. ICC values between 0.90 to 0.99 were interpreted as

indicative of high reliability; 0.8 to 0.89 as good reliability; 0.70 to 0.79 as fair reliability and below 0.69 as moderate to poor reliability [434,435].

6.4.6.1.3 Cervical stiffness analysis of Variance

Three multifactor repeated measures Analysis of Variance (ANOVA) were calculated at the force categories 12.5N, 25N, and 37.5N. There was insufficient data for analysis at 50N. Each ANOVA was a mixed design with one between-subjects factor of participant classification (FM, NP and NORM) and two repeated within-subjects factors of time (measurement time 1, 2 and 3) and measurement location (L1–R5). Stiffness values derived from the exponential model were the dependent variable. Newman-Keuls post-hoc analysis method was conducted on significant outcomes. Significant outcomes are described as * $p<0.05$, + $p<0.01$.

Some ANOVAs did not have equal group sizes and for calculations a least-squares solution was used [581]. Unequal group sizes occurred mostly due to the PPT value stopping a FD curve reaching the maximum applied force of 50N. This restricted predominantly the number of FM participants stiffness results in the higher force ranges of 37.5 and 50N. Therefore, the unequal group sizes were as a result of the particular treatment (application of force due to measurement with the M-TCM) and the least-squares method was employed [581].

6.4.6.1.4 Trend analysis of cervical stiffness

Systematic variation in stiffness between levels in the cervical region of the spine was assessed by an analysis of trend [582]. Polynomials up to a degree of $q - 1$ were used for the analysis of trend where q is the number of points in the profile [582]. For this analysis q equals five, which is the total number of measurement locations on one side of the cervical spine. A mixed design ANOVA was calculated with one between factor (participant classifications) and one within factor (measurement locations on one side). The ANOVA within-subjects sum of squares was partitioned to establish if a pattern in systematic variation in stiffness between cervical levels could be characterised by a linear, quadratic, cubic or quartic trend. Group sizes for the ANOVA between factor (participant classification) were not always the same. Therefore, the larger of the groups had subjects randomly removed until all group sizes were the same.

Each side (left and right) of the cervical spine was assessed separately. Location L1 to L5 and R1 to R5 stiffness values were analysed separately for the force values of 12.5N and 25N and for each measurement time (times 1, 2 and 3); a total of 12 trend analyses. Trend analysis was not completed for force values 37.5N and 50N, as there was insufficient data. For inclusion in a trend analysis a participant must have had stiffness values at all measurement locations on a side of the cervical spine for the given measurement force. Significance was set at the 0.01 level.

6.4.6.1.5 Left vs Right stiffness analysis

A paired *t*-test compared segmental level stiffness values between the left and right sides. Each side was compared at the same segmental level for each participant classification, force category and time.

6.4.6.1.6 Estimation of stiffness and displacement data

As discussed above in Sec. 6.4.6.1.1, an exponential model was applied to each stiffness measurement or FD curves. This model permitted extrapolation to estimate stiffness and displacement values for omitted data, because it is a stable model when extended past the last measurement data. The polynomial model is unstable outside the data measurement range and is therefore not suitable for extrapolation.

Omitted data occurred often due to the participant stopping the measurement due to reaching the PPT tolerance value. This resulted in many FD curves not reaching the maximum applied force of 50N, thereby limiting the ability to investigate differences between the participant groups at the higher forces.

To investigate extrapolating the exponential model to estimate omitted data, a series of extrapolations were conducted. The following force ranges were extrapolated:

- 12.5N to 25N, 12.5N to 37.5N, 12.5N to 50N
- 25 to 37.5N, 25 to 50N
- 37.5N to 50N

For each curve whose maximum applied force was greater than the larger force value of the ranges given above, their data was truncated at the lower force value of the ranges above. The remaining data was fit with an exponential model and the model was used to

estimate the stiffness and displacement values for the higher force value of the force range. The extrapolated data was then compared with actual data that had been truncated.

6.4.6.1.7 Force application rate

The average rate of change of applied force was analysed by measuring the length of time between each 2.45N increase in force. This was completed for each measurement location.

6.4.6.1.8 Angle of application of the M-TCM

The difference between the M-TCM initial estimate of a perpendicular orientation determined by the unaided eye and the orientation advised by data recorded from the 'neck profiler', purportedly at an actual perpendicular orientation, was determined. The average amount of movement of the M-TCM between the start and end of a measurement was also determined for each measurement location. The difference in orientation between each measurement time was also calculated.

6.4.6.2 CERVICAL PRESSURE PAIN THRESHOLD (PPT) ANALYSIS

PPT values were derived from the upper limit of all FD curves. A total PPT score was derived for each participant from the addition of the PPT scores at each measurement site.

On occasions, the PPT was not reached before the maximum applied force of 50N. This occurred predominantly in the NORM participant group due to their higher mechanical pain threshold. For these measurements, the PPT value was recorded as 50N.

Similar to the analysis of stiffness results described above, several statistical measures were employed to analyse PPT measurements. The ICC(2,1) was used to assess the reliability of PPT measurements for times 1 (initial), 2 (ten minutes later) and 3 (two hours after the initial measurement). An ANOVA examined for significant differences for between and within variables.

A trend analysis was completed for PPT measurements on each side of the cervical spine. PPT measurements of the left and right side of the cervical spine were compared.

The percentage change in PPT in the symptomatic participant groups (FM and NP) compared with the asymptomatic participant group (NORM) was determined.

A discriminate analysis was also undertaken to determine whether participants could be categorised based on their PPT scores from all measurement locations. Another discriminate analysis was conducted between asymptomatic (NORM) and symptomatic (FM and NP) participants. This was to determine if participants could be categorized based on whether they symptomatic or not, and to determine sensitivity and specificity.

6.4.6.3 CERVICAL RANGE-OF-MOTION (ROM) ANALYSIS

Averages for each ROM plane was calculated. Total ROM was derived from summation of planes of motion. Other statistical analyses were applied similar to the PPT analyses.

6.4.6.4 SELF-REPORTING INSTRUMENTS

Averages for each questionnaire score were calculated. Total region score was derived from summation of regions indicated as painful during the past three months (region score). One-way ANOVAs were conducted to test for significant differences between participant classification for each independent variable. Post-hoc analysis was conducted with Newman-Keuls method.

6.4.6.5 CORRELATION ANALYSIS

6.4.6.5.1 Correlation analysis

The association between PPT and stiffness values was assessed by correlation analysis. Pearson product moment correlation coefficients were determined to examine the inter-relationship within the dependant variables of PPT, stiffness scores, ROM and the self-reporting variables. Correlations of 0 to 0.25, 0.25 to 0.5, 0.5 to 0.75, 0.75 to 1.0 indicated little or no, low to fair, moderate to good, and good to excellent relationships, respectively [433].

The association between total PPT (derived from the addition of a participant's PPT scores) from time 1 measurements and total ROM (derived from the addition of a participant's ROM values in each measurement plane) was also assessed by correlation analysis.

6.5 RESULTS

6.5.1 CERVICAL MUSCULOSKELETAL STIFFNESS RESULTS

6.5.1.1 STIFFNESS ESTIMATES FROM FORCE-DISPLACEMENT (FD) CURVES

6.5.1.1.1 Location

Eighteen hundred and sixty measurements (1860) were completed in total with the modified tissue compliance meter (M-TCM). In Table 6-3 the number of FD curves, average stiffness values and SDs for the four force values and each category (FM, NP, NORM) are given. Figure 6-9 shows that the stiffness values were greater at the higher force values.

There was considerable variability within and between the participant groups. As is evident in Figure 6-9, there were *no patterns of difference between the participant groups*. This indicated that the *M-TCM could not detect differences in musculoskeletal stiffness* between the participant groups.

	Fibromyalgia			Neck Pain			Normal			Average		
Force	Avg	SD	No	Avg	SD	No	Avg	SD	No	Avg	SD	No
12.5	6.67	2.3	517	6.86	2.79	507	6.68	2.44	650	6.73	2.52	1674
25	11.3	4	284	10.9	5.06	280	10.4	4.24	458	10.81	4.42	1022
37.5	15.8	6.3	98	16.1	9.17	104	13.3	5.42	156	14.79	7.06	358
50	19.2	9.5	13	22.4	15	36	17.3	8.65	69	19.08	11.20	118
Total			912			927			1333			3172

Table 6-3 – Average musculoskeletal stiffness in the cervical spine for each force category. Number (No), average (mean) and standard deviation (SD) are reported for participants with fibromyalgia (FM), neck pain (NP), and normal (NORM).

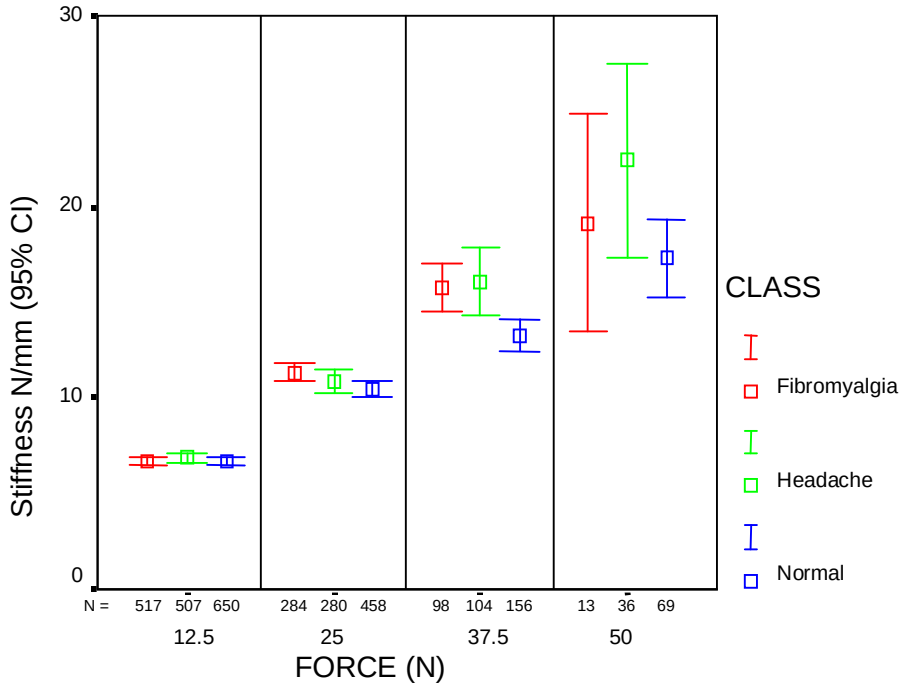


Figure 6-9 – Average and 95% CI stiffness values for each force and participant classification

As well, there were no systematic differences in musculoskeletal stiffness at each individual site between the participant groups. There was large variability within and between measurement locations. Between the measurement sites, the cervical stiffness was considerable higher in the upper cervical spine compared with the lower cervical measurement locations. This is evident in Figure 6-10 to Figure 6-13, and in App. G in Table G-1

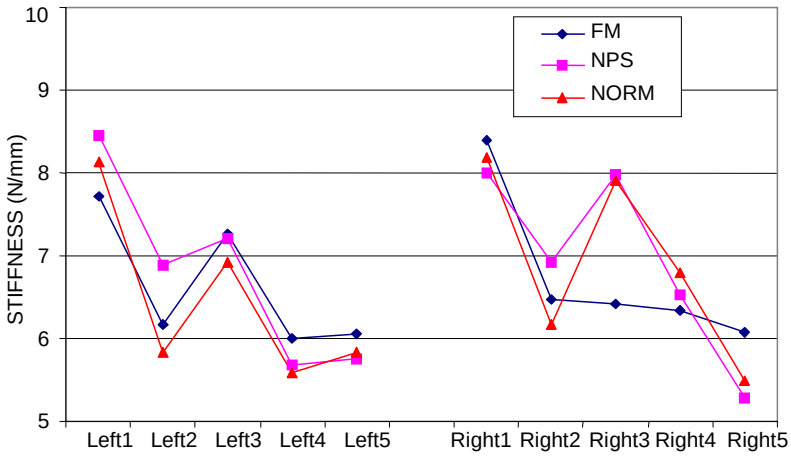


Figure 6-10 – Average stiffness at the ten measurement locations at the force value of 12.5N

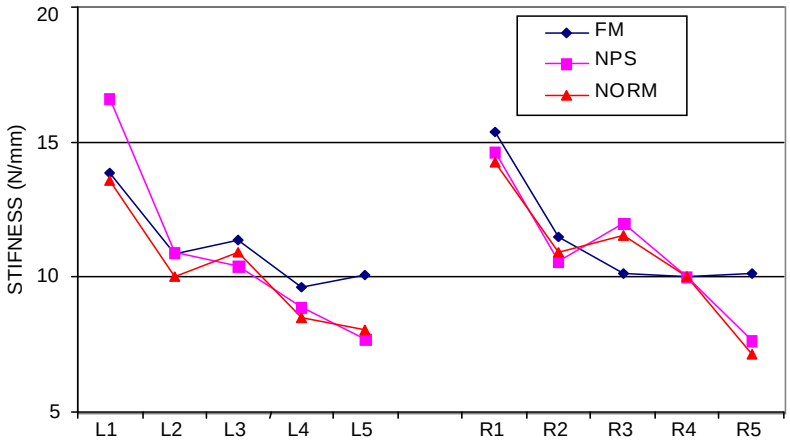


Figure 6-11 – Average stiffness at the ten measurement locations at the force value of 25N

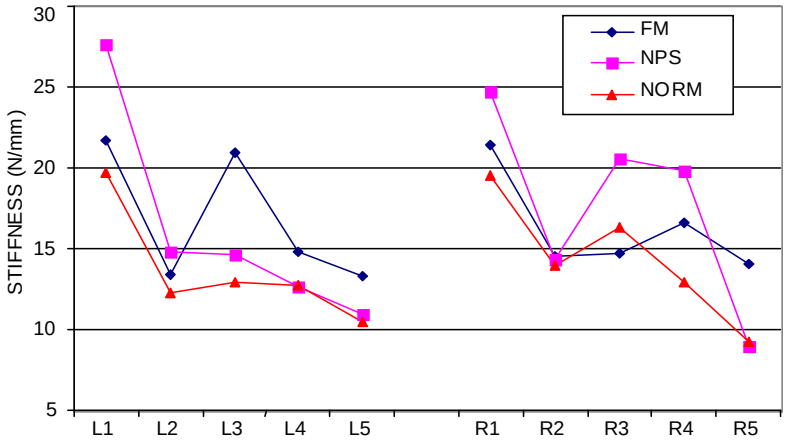


Figure 6-12 – Average stiffness at the ten measurement locations at the force value of 37.5N

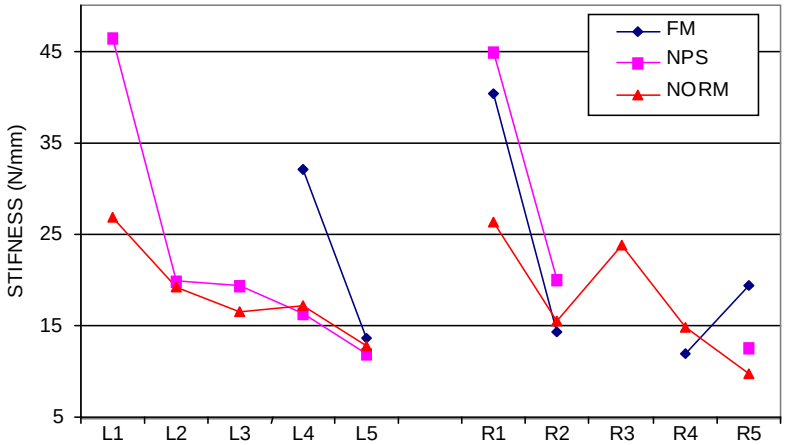


Figure 6-13 – Average stiffness at the ten measurement locations at the force value of 50N. Gaps in lines indicate insufficient data.

6.5.1.1.2 Time: start, ten minutes, two hours

The average stiffness values for the four force values for each time measurement (start, 10 mins, and 2 hours) are given in Table 6-4 and Figure 6-14. Figure 6-14 clearly shows that there was considerable variability in musculoskeletal stiffness between the

three measurement times. This showed that musculoskeletal stiffness was *not consistent over time, undermining the reliability* of this measurement variable.

	Time1 – start			Time2 – 10 minutes			Time3 – 2 hours		
Force	Avg	SD	No	Avg	SD	No	Avg	SD	No
12.5	6.77	2.65	554	6.89	2.49	566	6.54	2.41	554
25	10.92	4.39	346	10.92	4.51	359	10.56	4.36	317
37.5	15.77	7.29	138	14.13	6.98	123	14.25	6.73	97
50	20.45	11.77	47	17.07	10.27	40	19.59	11.45	31

Table 6-4 – Stiffness values (average, SD and number of measurements) for the start, ten minutes and two hour measurement times

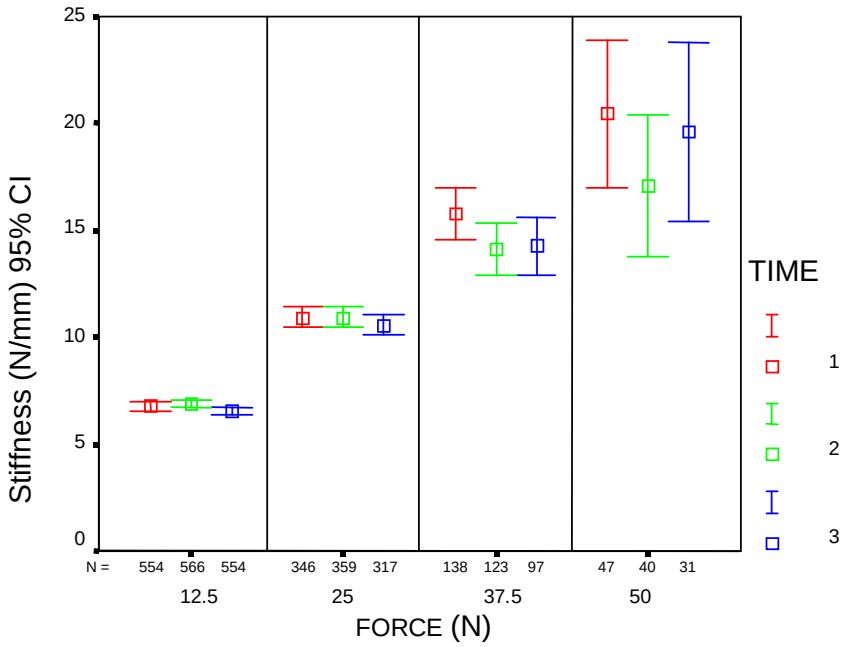


Figure 6-14 – Average and SD stiffness values of each time measurement for each force category

6.5.1.2 CERVICAL STIFFNESS ANALYSIS OF VARIANCE

There was *no significant difference* in stiffness values between the participant groups (Table 6-5). This outcome indicated that M-TCM cervical musculoskeletal stiffness data could *not discriminate* between the three participant groups.

However, there was a significant outcome for the *time of measurement*. There were significant differences in cervical stiffness between measurement times, indicating that there was variability in the stiffness data over time. This outcome confirmed the poor reliability of the M-TCM stiffness results (see Table 6-6 below) – the M-TCM *stiffness data was not reliable*.

Force	Factor	F value
12.5N	time	$F_{(2,118)} = 4.16$*
	location	$F_{(9,512)} = 16.13$+
25N	location	$F_{(9,350)} = 26.74^{+}$
37.5N	time	$F_{(2,45)} = 9.72^{+}$
	location	$F_{(9,113)} = 12.87^{+}$

Table 6-5 – Significant outcomes from the ANOVA analysis for cervical musculoskeletal stiffness results. Only significant outcomes are shown. * $p<0.05$, + $p<0.01$.

There were significant outcomes for location, indicating that the musculoskeletal stiffness was significantly different between the locations. The post-hoc analysis reported in App. G in Table G-5 confirmed the trend shown above in Figure 6-10 to Figure 6-13, where the upper cervical spine was significantly more stiff than the lower locations. The trend analysis reported in App. G in Table G-6 showed that the cervical spine had a *linear trend* in musculoskeletal stiffness, with higher stiffness in the upper cervical spine and lower stiffness in the lower cervical spine.

6.5.1.3 CERVICAL STIFFNESS RELIABILITY

The *M-TCM stiffness results had poor reliability* between the three measurement times (start, ten minutes and 2 hours after initial measurement). The ICC(2,1) for each force category and participant classification is reported in Table 6-6. Most values were below 0.69, or poor reliability.

	Normal		Neck pain		Fibromyalgia		All data	
Force (N)	ICC (95% CI)	No	ICC (95% CI)	No	ICC (95% CI)	No	ICC (95% CI)	No
12.5	.62(.54 -.68)	196	.51(.42 -.60)	150	.49(.39 -.58)	145	.55(.50 -.60)	491
25	.57(.47 -.67)	103	.74(.64 -.82)	67	.62(.49 -.73)	69	.64(.58 -.70)	239
37.5	.50(.29 -.69)	32	.87(.72 -.95)	13	.66(.42 -.84)	19	.70(.59 -.79)	64
50	.42(.10 -.74)	13	.82(.45 -.97)	6		0	.59(.34 -.80)	19

Table 6-6 – Intraclass Correlation Coefficient (ICC) and 95% confidence interval (CI) reliability between each measurement time for the cervical stiffness data

6.5.1.4 PENETRATION OF THE M-TCM TIP

The average amount of M-TCM tip penetration between each force category and the total amount is shown in Figure 6-15 (and in App. G, Table G-2). This figure shows that the amount of tip penetration was *not large* (average penetration was between 2.5mm and 4.2mm). Therefore, the stiffness results most likely *characterised superficial tissues, rather than the deeper tissues*, particularly at the lower force categories.

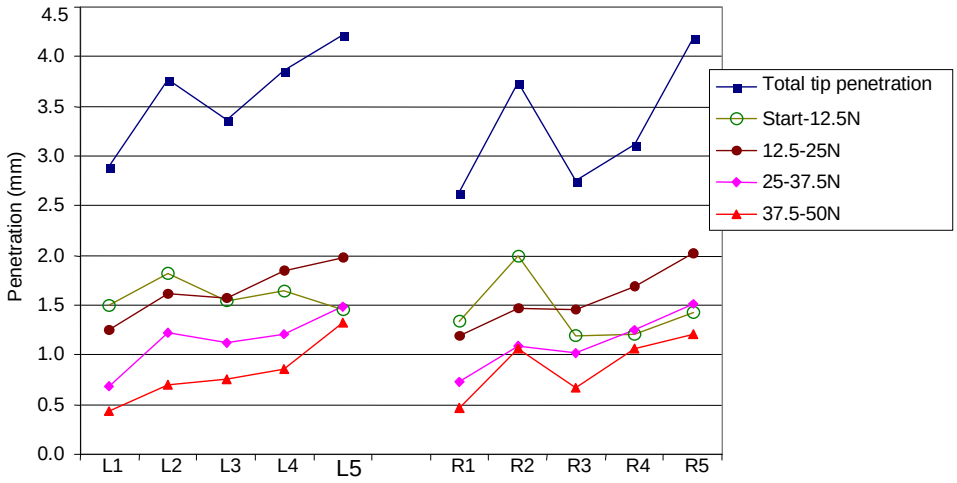


Figure 6-15 – Average penetration of the M-TCM tip between each force category at the ten measurement locations.

6.5.2 CERVICAL PRESSURE PAIN THRESHOLD (PPT) RESULTS

6.5.2.1 CERVICAL PPT ANALYSIS OF VARIANCE

The PPT values in the NORM participants were considerably higher than the NP and FM participants, in all cervical measurement locations and for all measurement times. However, the outcome *was not significant between the three participant groups*. The outcome was very close to significance (Table 6-7) and as noted below (Table 6-11) the true PPT values for some measurements in the NORM participants, would have been higher than that recorded. Therefore, it was *likely* that there was a *significant difference in PPT* between the participant groups. This outcome was consistent with previous reports that shown that participants with chronic musculoskeletal pain display significantly increased pain sensitivity (see Ch. 2, Sec. 2.4.5.2).

Figure 6-16 showed that the lower *cervical measurement locations were significantly less tender* than the other measurement locations. The lower cervical spine was less sensitive to mechanical pressure than the middle and upper cervical spine. The trend analysis of the PPT results indicated that there was a quadratic trend between the measurement locations (see App. G at Table G-16).

The post-hoc analysis of significant outcomes is reported in App. G in Table G-14 and Table G-15.

FACTOR	F value
class	$F_{(2,59)} = 2.97$ ns $p=0.057$
time	$F_{(2,118)} = 12.27^{+}$
location	$F_{(9,531)} = 12.86^{+}$
class x location	$F_{(18,531)} = 2.21^{+}$
time x location	$F_{(18,1062)} = 2.62^{+}$

Table 6-7 – Significant outcomes from the ANOVA analysis for PPT and participant classification, measurement location and time (independent variables). * $p<0.05$, + $p<0.01$.

6.5.2.2 DISCRIMINATE ANALYSIS OF CERVICAL PPT

The discriminate analysis of all PPT data resulted in *83.9% of participants correctly categorised*. The PPT data was also analysed with discriminate analysis based on an asymptomatic (NORM) and symptomatic (FM and NP) participant classification. This discriminate analysis resulted in 91.9% of participants correctly categorised as symptomatic or asymptomatic (sensitivity 92.3%, specificity 91.3%). Discriminate analysis of only the NORM and FM PPT data correctly categorised 95.5% of participants (sensitivity 90.5%, specificity 100%).

6.5.2.3 SUMMARY OF PPT RESULTS

6.5.2.3.1 Location

There were 1860 pressure pain threshold (PPT) measurements completed with the M-TCM in the posterior area of the cervical spine. The PPT values were derived from the upper limit of each force-displacement (FD) curve. The breakdown of PPT scores in Newtons (N) for each location and participant classification is given in Table 6-8.

There were *clear differences in pain sensitivity* between the participants at all locations. Not surprisingly the FM participants displayed the lowest PPT values (average of 25.06N) , followed by the participants with neck pain (average 28.52N) and then the normal participants with the highest PPT values (average of 31.80N).

Figure 6-16 shows this difference in pain sensitivity at each cervical measurement location. Note the clear difference between the participant groups.

	Left1			Left2			Left3			Left4			Left5		
	Avg	SD	No	Avg	SD	No	Avg	SD	No	Avg	SD	No	Avg	SD	No
FM	23.82	9.5	63	24.28	10.6	63	22.77	8.8	63	25.04	11.8	63	27.45	12.0	63
NP	30.84	12.0	54	30.58	11.6	54	28.20	10.6	54	29.26	11.2	54	31.76	11.7	54
NORM	31.28	10.0	69	31.29	9.6	69	30.99	8.4	69	30.13	8.8	69	35.54	10.8	69
Avg	28.63	11.0	186	28.71	11.0	186	27.40	9.8	186	28.15	10.8	186	31.70	11.9	186

	Right1			Right2			Right3			Right4			Right5			Average		
	Avg	SD	No	Avg	SD	No	Avg	SD	No	Avg	SD	No	Avg	SD	No	Avg	SD	No
FM	24.73	11.0	63	25.47	12.0	63	23.65	9.4	63	24.01	10.9	63	29.34	13.0	63	25.06	11.0	630
NP	27.57	10.2	54	26.89	9.1	54	25.64	7.9	54	25.05	8.8	54	29.44	10.9	54	28.52	10.6	540
NORM	31.07	10.3	69	31.27	9.4	69	29.52	7.8	69	30.99	8.8	69	35.94	11.1	69	31.80	9.7	690
Avg	27.91	10.8	186	28.03	10.5	186	26.41	8.7	186	26.90	10.0	186	31.82	12.1	186	28.57	10.8	**1860**

Table 6-8 – Pressure pain threshold (PPT) average (avg), number (No) and standard deviation (SD) at each measurement location and for each participant classification. Measurement times 1, 2 and 3 results combined

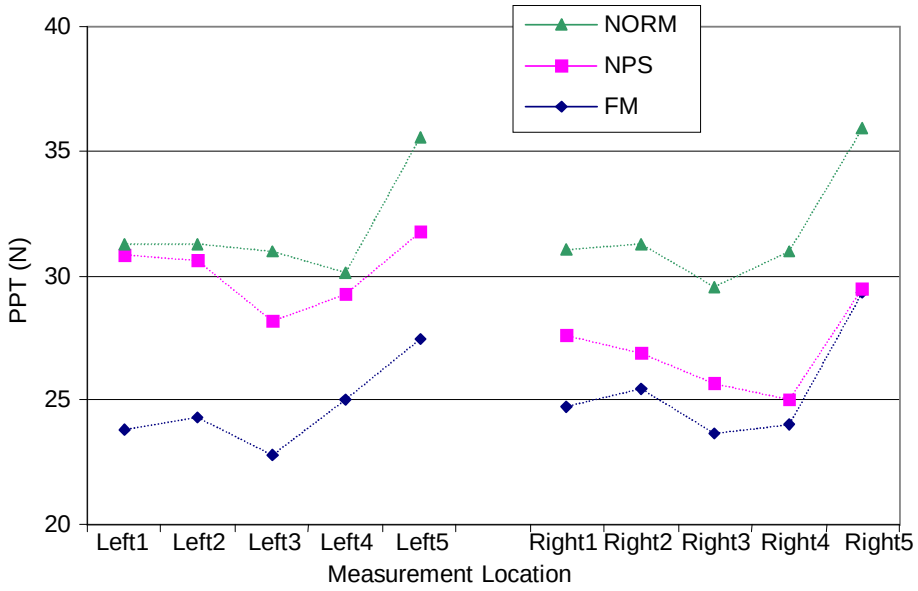


Figure 6-16 – Average PPT value for each location and for fibromyalgia (FM), neck pain (NP) and normal (NORM) participants.

6.5.2.3.2 Time: start, ten minutes, two hours

The average values of PPT for each measurement time (start, 10 minutes, and two hours) are given in Table 6-9 and shown in Figure 6-17. There was variability between the measurement times, but it was not large. The NORM participants displayed the greatest variability, while the FM participants were very consistent over time.

	Time 1-start			Time 2-ten minutes			Time 3-two hours			Average		
	Avg	SD	No	Avg	SD	No	Avg	SD	No	Avg	SD	No
Fibromyalgia	25.01	10.96	210	25.52	10.83	210	24.64	11.51	210	25.06	11.09	630
Neck pain	29.82	11.22	180	28.73	11.06	180	27.02	9.49	180	28.52	10.66	540
Normal	32.56	10.05	230	32.35	9.68	230	30.50	9.42	230	31.80	9.75	690
Average	29.21	11.16	620	28.98	10.86	620	27.51	10.48	620	28.57	10.86	1860

Table 6-9 – PPT mean, SD and number for each measurement time

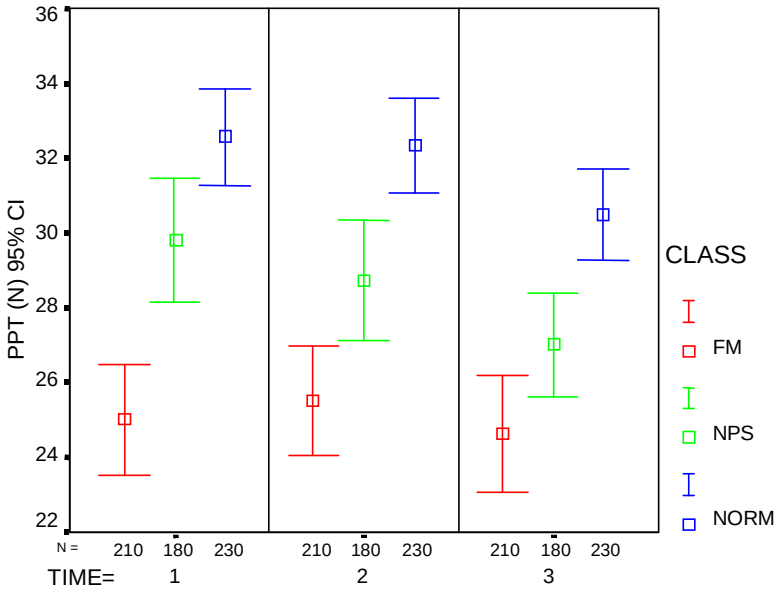


Figure 6-17 – PPT mean, SD and number for each measurement time

6.5.2.3.3 Total cervical PPT results

The difference in PPT between the participant groups was also clearly observed in the total PPT values (derived from the addition of PPT scores of measurement locations L1-R5) as shown in Table 6-10. The normal group total PPT was 318.03N, or 27% higher than the FM group of 250.56N. Figure 6-18 shows that there was a consistent difference in total PPT between the participant groups.

	total PPT Values											
	Time 1-start			Time 2-ten minutes			Time 3-two hours			Average		
	Avg	SD	No	Avg	SD	No	Avg	SD	No	Avg	SD	No
Fibromyalgia	250.12	97.86	21	255.15	99.42	21	246.40	104.56	21	250.56	99.08	63
Neck pain	298.19	99.16	18	287.31	100.40	18	270.18	86.35	18	285.23	94.42	54
Normal	325.61	88.00	23	323.45	85.21	23	305.03	79.24	23	318.03	83.50	69
AVERAGE	292.08	98.56	62	289.83	97.53	62	275.06	92.50	62	285.65	96.01	186

Table 6-10 – Average and SD of the total PPT values

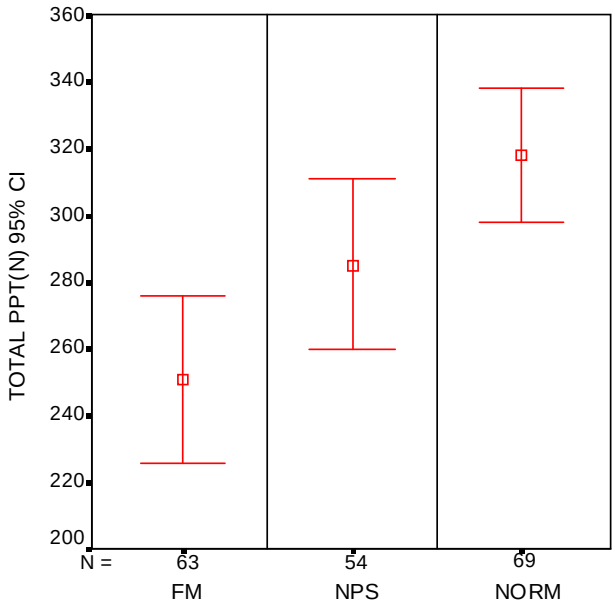


Figure 6-18 – Average (95% CI) of total PPT for each participant classification

6.5.2.4 MEASUREMENTS GREATER THAN THE MAXIMUM APPLIED FORCE

Eighty-one measurements were greater than the upper limit of 50N. They were recorded as 50N, although the actual PPT value was greater than 50N. Table 6-11 shows a breakdown of these participants. Figure 6-19 demonstrates that in the NORM group there were considerably more PPT measurements that ceased at the maximum applied force of 50N; almost double the number than the NP participants and more than five times as many as the FM participants. This outcome indicated that the true PPT data for the NORM participants would have been higher than the other participant groups, if not for the stopping value of 50N.

	L1	L2	L3	L4	L5	R1	R2	R3	R4	R5	TOTAL
Fibromyalgia				1	1		1		2	4	9
Neck pain	5	2	2	1	6	2	1			3	22
Normal	5	5	2	2	12	6	3	2	3	10	50
TOTAL	10	7	4	4	19	8	5	2	5	17	81

Table 6-11 – Number of participants that had a PPT value greater than the maximum applied force of 50N

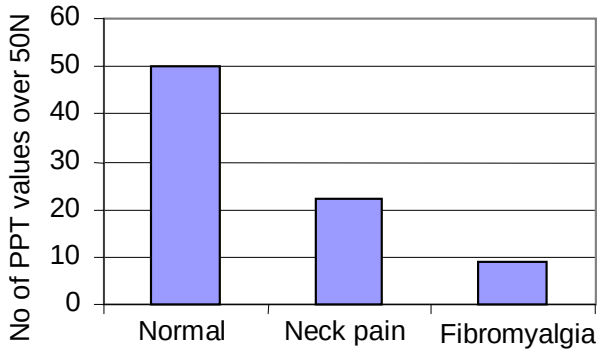


Figure 6-19 – Number of participants in each participant group that had a PPT value greater than the maximum applied force of 50N

6.5.2.5 CERVICAL PPT RELIABILITY

The reliability for the PPT measurements *was good* between the three measurement times. Table 6-12 shows that the ICC(2,1) was high for each participant group and for all PPT data. The total PPT reliability was high (0.94). This outcome indicated that pain sensitivity measurements in the cervical spine with the M-TCM *were reliable* over a medium length of time (2 hrs).

TIME	ICC(2,1) and 95% CI	No
Fibromyalgia	.88(.86 - .91)	210
Neck pain	.83(.78 - .87)	180
Normal	.80(.75 - .84)	230
All data	.85(.83-.87)	620
total PPT	.94(.91-.97)	62

Table 6-12 – Reliability (ICC) of PPT for each participant class

6.5.2.6 PERCENTAGE CHANGE IN CERVICAL PPT

The average percentage change in PPT at each measurement location in the symptomatic participant groups (FM and NP) compared with the asymptomatic participant group (NORM) is shown in Table 6-13. On average, the FM and NP participants had *21% and 10% lower PPT scores than the NORM participants*, respectively.

Figure 6-20 shows that in the *FM participants, the decrease in PPT was consistent when compared with the NORM participants,* at all cervical measurement locations. The percentage decrease of the FM results compared to the NORM results were calculated for each location (e.g. for location Left1, the average PPT value for FM participants was 23.82 and for NORM was 31.28, a decrease of -23.84%).

However, the decrease in PPT at each location in the *NP participants was considerably varied,* compared to the NORM results (Figure 6-20). At some sites in the NP participants (e.g. the upper left cervical spine at level 1 (sites Left1 and Right1)) there was virtually no change in PPT compared with the NORM participants. While in other sites the change was considerable (e.g. the lower cervical spine at level 5 (sites Left5 and Right5)).

The relatively uniform change in pain sensitivity at all measurement locations in the cervical spine in the FM participants was consistent with a more generalised change in PPT due to central pain mechanisms. Yet the non-uniform change in pain sensitivity in the NP participants may have been due to peripheral and/or central pain mechanisms. This is discussed further in Sec. 6.6.2.

	L1	L2	L3	L4	L5	R1	R2	R3	R4	R5	Average
Normal	0	0	0	0	0	0	0	0	0	0	NA
Fibromyalgia	-24%	-22%	-27%	-17%	-23%	-20%	-19%	-20%	-23%	-18%	-21%
Neck pain	-1%	-2%	-9%	-3%	-11%	-11%	-14%	-13%	-19%	-18%	-10%

Table 6-13 – Average percentage change in PPT in the fibromyalgia (FM) and neck pain (NP) participants compared with the normal (NORM) participants

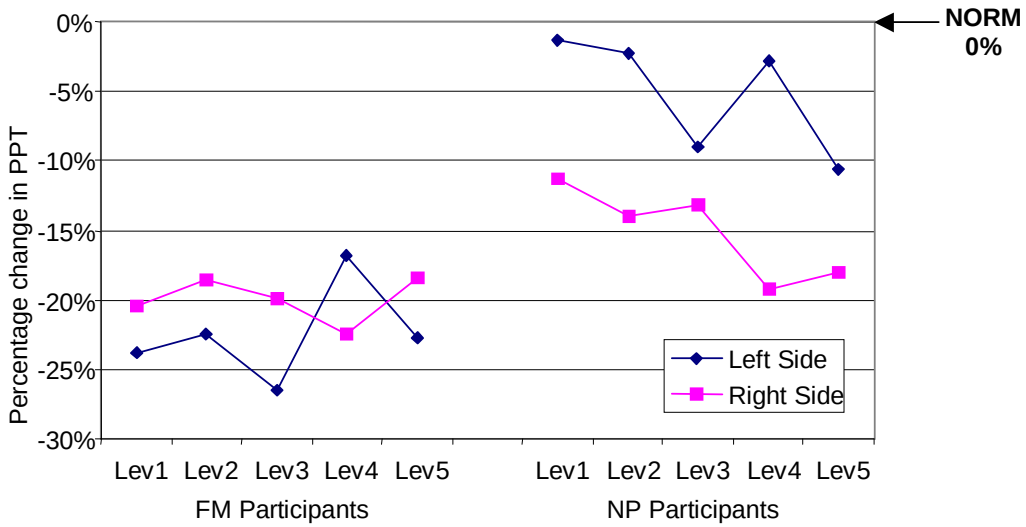


Figure 6-20 – Average percentage change of PPT in the FM and NP groups, compared with the NORM group, at each measurement level of the cervical spine on the left and right sides

As well, the left vs right analysis of the PPT results (reported in App. G in Table G-17) showed that the NP participants had significantly different pain sensitivity between sides. This difference was not observed in the FM or NORM participants.

6.5.3 CERVICAL RANGE-OF-MOTION (ROM) RESULTS

6.5.3.1 SUMMARY OF ROM RESULTS

A summary of whole plane ROM results for the three measured planes and for total ROM is shown in Table 6-14. The two consecutive ROM assessments, conducted only at the first measurement time, were combined due to similar results. One NORM participant was not measured due to human error.

There were *clear differences in cervical ROM between the participant groups*. There was almost a 90 deg difference in the total ROM (derived from the addition of the ROM in the three movement planes) between the NORM (389.8 deg) and FM (304.6 deg) participants.

	Lateral Flexion		Flexion/Extension		Rotation		total ROM		
Class	Avg	SD	Avg	SD	Avg	SD	Avg	SD	No
Fibromyalgia	71.0	15.2	101.9	24.0	131.7	23.3	304.6	58.2	21
Neck pain	81.8	13.2	121.0	14.4	151.2	17.3	354.1	37.4	18
Normal	91.4	15.9	132.7	14.8	165.7	24.2	389.8	50.0	22
Average	81.6	17.1	118.6	22.4	149.7	26.2	349.9	61.2	61

Table 6-14 – Cervical range of motion (ROM) and total ROM results for each participant classification

It is evident from Figure 6-21 that there was a consistent difference in ROM in each plane between the participant groups. The ROM was higher in the NORM participants, followed by the NP participants and finally the FM participants, in which there was considerably lower ROM in all planes. Figure 6-22 confirmed this trend of altered ROM between the participant groups in the total ROM.

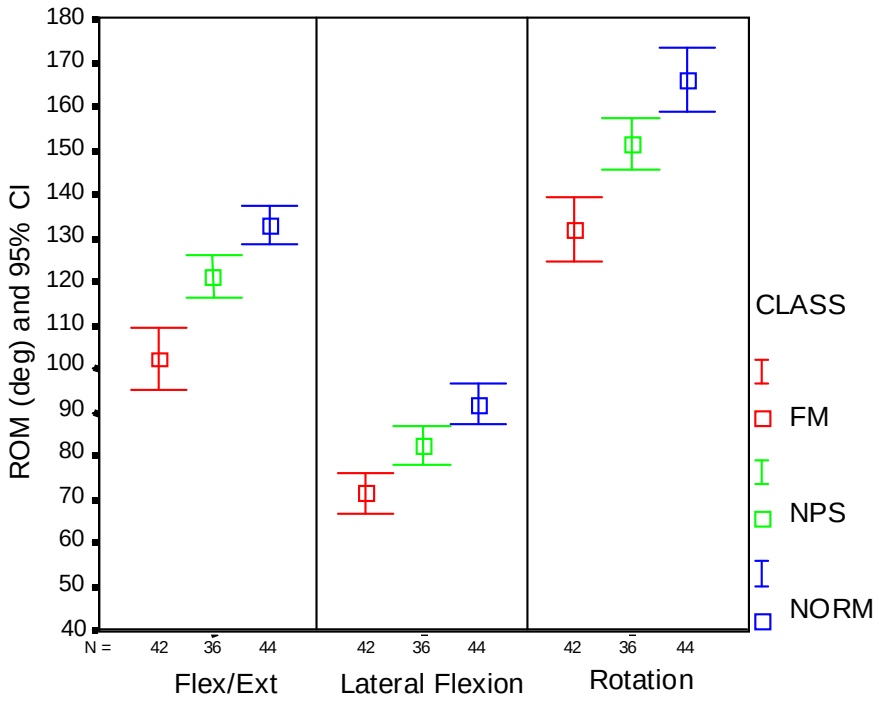


Figure 6-21 – ROM values for each measured plane. First and second measurements were averaged

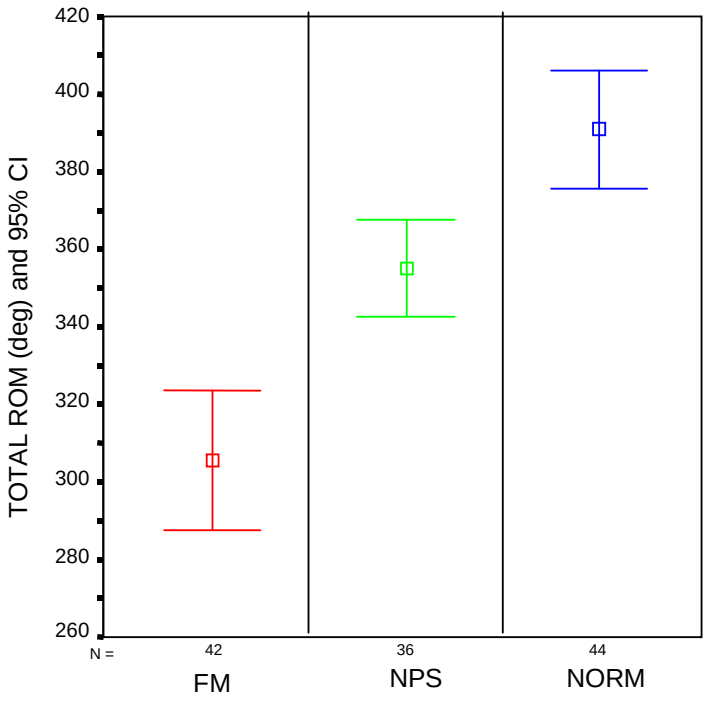


Figure 6-22 – total ROM values. First and second measurements were averaged

As well, the ROM data indicated that in all movement planes there was *not unequal bi-lateral motions* in the any of the participant groups. Instead, the NP and FM participants demonstrated a *gross deficit in ROM in all movement planes* compared with the NORM participants, and it was consistent bi-laterally. The conjunct motion ROM (motions in planes other than the primary movement plane) is reported in App. G in Table G-18.

6.5.3.2 CERVICAL ROM ANALYSIS OF VARIANCE

There *was a significant difference* in the ROM data between the three participant groups. This was demonstrated in *all measurement planes* (see Table 6-15).

ROM	F Value
All ROM data	$F_{(2,58)} = 14.94+$
Plane of motion	$F_{(2,116)} = 615.8+$
Lat flex	$F_{(2,58)} = 11.57+$
F/E	$F_{(2,58)} = 14.18+$
Rot	$F_{(2,58)} = 10.71+$

Table 6-15 – Significant outcomes from the ANOVA analysis for ROM and participant classification. * $p<0.05$, + $p<0.01$.

The Newman-Keuls post-hoc analysis in Table 6-16 showed that in all planes and for all ROM data (or total ROM), there was a significant difference in ROM between all combinations of participants groups. This outcome *supported the ability of cervical ROM measurements to significantly differentiate between the participant groups*.

	Fibromyalgia	Neck pain	Normal
Fibromyalgia	--	Lateral flexion* Flexion/Extension+ Rotation* All ROM data (total ROM)+	Lateral flexion + Flexion/Extension + Rotation + All ROM data (total ROM) +
Neck pain		--	Lateral flexion * Flexion/Extension * Rotation * All ROM data (total ROM) *
Normal			--

Table 6-16 – Post-hoc analysis ROM values for significant difference between participant classification for first ROM measurements. * $p<0.05$, + $p<0.01$.

6.5.3.3 PERCENTAGE CHANGE IN ROM

The average percentage change in ROM of each movement plane was -22% and -9% lower in the FM participants and NP participants, compared with the NORM participants, respectively (Table 6-17). The FM participants and NP participants demonstrated consistently lower ROM values in all of the measured planes. This outcome indicated that the *symptomatic participants had a gross deficit in ROM in all movement planes*, and that it was relatively consistent bi-laterally.

	Fibromyalgia	Neck Pain
Right Rot	-19%	-8%
Left Rot	-22%	-10%
Right LF	-23%	-12%
Left LF	-22%	-9%
Flexion	-28%	-11%
Extension	-18%	-6%
Average	-22%	-9%

Table 6-17 – Average percentage change in ROM in the FM and NP groups compared with the NORM group

6.5.3.4 DISCRIMINATE ANALYSIS OF CERVICAL ROM

Discriminate analysis of whole plane ROM values in the three movement planes resulted in 52.5% of participants correctly categorised. The whole plane ROM data was also analysed based on asymptomatic (NORM) and symptomatic (FM and NP) participant classification. The discriminate analysis resulted in 77.0% of participants correctly categorised as symptomatic or asymptomatic (sensitivity 71.4%, specificity 80.0%). When primary ROM motions (from neutral to an extreme in a movement plane) were analysed by discriminate analysis, 68.9% of participants were correctly categorised. A similar discriminate analysis based only on if participants were asymptomatic or symptomatic correctly categorised 83.6% (sensitivity 81.0%, specificity 85.0%).

The primary ROM data and all conjunct ROM values (movements in planes other than the primary movement plane) were analysed by discriminate analysis; 100% of participants were correctly categorised.

The high discriminate analysis results supported the use of cervical ROM in the assessment of patients with chronic musculoskeletal pain in the cervical spine.

6.5.4 SELF- REPORTING INSTRUMENT RESULTS

A summary of the questionnaire variables is shown in Table 6-18. There were significant differences between the participant groups in the neck disability index (NDI), total region count and the self-reported musculoskeletal pain in the neck and head results (the areas of pain that participants could select is explained in Sec. 6.4.2.4).

Specifically, the FM participants had a *significantly higher number of regions of pain* than the NP and NORM participants. The total region count (see Sec. 6.4.2.4 for explanation) was further analysed below in Table 6-20.

In addition, a much larger proportion of the FM and NP participants (about half in each group) reported a *previous spinal injury*, compared with the very low number of NORM participants. The *musculoskeletal pain reported in the head and neck* (the neck VAS and the head VAS) by the FM and NORM participants was significantly higher than the NORM participants.

The NDI results indicated that in the *NORM participants there was mild disability, but in the FM and NP participants the neck disability was moderate to severe* [421]. The FM participants reported almost complete neck disability and their disability was even higher than the NP participants. Compared with the neck and head VAS scores, the NDI on a 0-100% scale was higher than the VAS scores, as the NDI is rated on a scale of 0-50, rather than 0-100 which the VAS is scaled on. The VAS and NDI were significantly correlated (App. G, Sec. G.5).

The STAI-S was similar between the three participants groups, and was in accordance with working population values [423]. The POMS values were similar between the three participant groups, although in the depression-dejection scale, the NORM participants had significantly lower values than the FM participants. The scores were similar to female adult normative samples [422].

	Fibromyalgia		Neck Pain		Normal		Average	
	Average	SD	Average	SD	Average	SD	Average	SD
Age	45.57	10.49	41.72	11.60	38.17	14.56	41.71	12.64
Total Region Count +[1]	9.38	4.24	6.22	3.26	1.43	2.13	5.52	4.70
Static Postures	4.64	9.27	5.25	2.20	5.63	2.81	5.19	5.70
Manual postures	3.95	7.41	2.17	6.42	1.22	3.23	2.42	5.89
Total Exercise	4.59	3.64	5.14	4.70	4.24	2.49	4.62	3.59
Major Spinal Injury #	47.7%		55.5%		13.0%		37.1%	
Headache VAS +[2]	42.86	33.92	25.56	27.24	15.74	19.69	27.77	29.29
Neck VAS +[3]	44.71	29.40	35.17	15.91	11.70	18.39	29.69	26.16
NDI +[4]	33.48	16.76	25.33	14.86	5.91	6.48	20.89	17.71
POMS_TA	12.19	6.93	10.67	6.59	8.04	4.71	10.21	6.25
POMS_DD *[5]	11.67	10.60	8.33	9.22	5.09	4.70	8.26	8.73
POMS_AH	8.05	6.67	8.56	8.31	6.00	4.76	7.44	6.58
POMS_VA	13.00	5.46	15.00	6.03	16.96	7.33	15.05	6.49
POMS_FI	12.14	7.10	13.33	5.70	10.43	6.86	11.85	6.63
POMS_CB	8.57	4.97	6.11	4.96	6.04	3.48	6.92	4.55
POMS_TMDS	39.62	32.67	32.00	34.04	18.65	19.54	29.63	29.87
STAI-S	35.86	7.86	36.94	10.08	31.13	6.83	34.42	8.49
FIQ	48.29	17.56						

Table 6-18 – Summary table of questionnaire variables including psychological questionnaires.

(# = percentage of participants in classification group who reported a previous major spinal injury. Note: see Sec. 6.4.2.4 for explanation of self-reporting instruments and terms used in Table 6-18)

1- ($F_{(2,59)}$ = 32.55, p< 0.01), 2- ($F_{(2,59)}$ = 5.48, p< 0.01), 3- ($F_{(2,59)}$ = 12.93, p< 0.01), 4- ($F_{(2,59)}$ = 25.33, p< 0.01), 5- ($F_{(2,59)}$ = 3.36, p< 0.05).

The post-hoc analysis of the significant outcomes is shown in Table 6-19. This table confirmed that the each participant group, there were significant differences between them based on the questionnaire results. As well, Table 6-19 shows that the 'total region count' and the 'headache VAS' were the only variables that were significantly different between each participant group.

	Normal	Neck pain	Fibromyalgia
Normal	--	Total Region count+ Neck VAS+ NDI+	Total Region count+ Headache VAS+ Neck VAS+ NDI+ POMS_DD*
Neck pain		--	Total Region count+ Headache VAS*
Fibromyalgia			--

Table 6-19 – Summary of post-hoc analysis of questionnaire variables for participant classification. * p<0.05, + p<0.01

Because the 'total region count' significantly distinguished the three participant groups, further analysis of this variable was undertaken. In Table 6-20, a breakdown of the total region count scores is shown. Each region was split into left, middle and right (a score of 0 to 3 per region) giving participants a total of eighteen areas to indicate frequent pain over the past three months. In the *neck region, the FM and NP participants had much higher scores* than the NORM participants. In the other musculoskeletal regions, the *FM participants consistently reported higher values* than both the NORM and NP participants.

The FM participants nominated the neck as the region with the most pain. This was consistent with previous reports of the neck as the most common area of pain in FM (see Sec. 6.2.1). This research and previous reports highlight *the importance of this region in chronic musculoskeletal pain*.

Class	Neck#	Chest#	Upper Back#	Arm/ Shoulder#	Lower Back#	Legs/ Buttocks#	Average total Region Count (out of a total of 18)
Fibromyalgia	1.95	0.90	1.43	1.86	1.43	1.81	9.38
Neck pain	1.83	0.28	1.17	0.94	1.39	0.61	6.22
Normal	0.30	0.00	0.26	0.30	0.48	0.09	1.43

Table 6-20 – Average number of self-reported painful regions in the regions of the musculoskeletal system (# - the score range for each cell was 0 to 3)

6.5.4.1 DISCRIMINATE ANALYSIS OF NDI AND TOTAL REGION COUNT

Discriminate analysis of the *total region count* data resulted in 67.7% of participants correctly categorised. Analysis of the total region count based on an asymptomatic (NORM) and symptomatic (FM and NP) participant classification showed 85.5% of participants correctly categorised as symptomatic or asymptomatic (sensitivity 79.5%, specificity 95.7%).

Discriminate analysis of the *neck disability index (NDI)* scores resulted in 66.1% of participants correctly categorised. Analysis of the NDI scores based on an asymptomatic (NORM) and symptomatic (FM and NP) participant classification showed 82.3% of participants correctly categorised as symptomatic or asymptomatic (sensitivity 76.9%, specificity 91.3%).

6.5.5 CORRELATION ANALYSIS

The correlation analysis are reported in App. G, Sec. G.5.

6.6 DISCUSSION

This investigation examined the supposition that in fibromyalgia (FM) patients and participants with chronic neck pain (NP) there was dysfunction of the cervical spine. Results from various electromechanical and clinical assessment tests indicated that in the NP and FM participants there was dysfunction of the cervical spine and hypersensitivity of the nociceptive system. Abnormalities of spinal function and aberrant pain modulation mechanisms in the symptomatic participants, possibly including central pain mechanisms, appeared to be associated with features characteristic of chronic musculoskeletal pain syndromes. These factors are most likely an important factor in the aetiology of chronic non-specific musculoskeletal pain.

It was hypothesised that the M-TCM instrument would detect abnormal musculoskeletal stiffness in the cervical spine region of the symptomatic participants, compared with participants without chronic neck complaints. Unfortunately, the *stiffness results* were *unreliable and had poor discriminate ability*; the M-TCM stiffness results did not display consistent differences between the three participant groups. Therefore, the M-

TCM was not useful for the assessment of abnormal stiffness in the cervical spine. The M-TCM stiffness results are discussed further in Sec 6.6.1.

The *pressure pain threshold* (PPT) results from the cervical spine were *reliable and demonstrated high discriminate ability* between symptomatic and asymptomatic participants. Not surprisingly, *the PPT results were lower to higher in the FM, NP and NORM participants*, respectively. However, this result was not significant. The increased pain sensitivity observed in the symptomatic participants indicated that in cervical spine there was a *hyperalgesic response* to the applied mechanical pressure. The hyperalgesic response indicated involvement of a *sensitised nociceptive system*, either at a primary and/or secondary level. The generalised decrease in cervical PPT, observed in the FM participants, may have indicated that the neck was characterised by secondary hyperalgesia, indicating involvement of central pain mechanisms. The PPT results, and the potential involvement of peripheral and central pain factors, are further discussed in Sec. 6.6.2. It is also discussed (in Sec. 6.6.3) that the concept of spinal dysfunction may require further expansion to include examination of the mechanism of pain in patients with chronic neck pain.

The *passive cervical ROM results* were *significantly reduced* in the FM and NP participants, compared with the NORM participants. The whole plane ROM results displayed good discriminate ability, and perfect discriminate ability when conjunct motions were included in the discriminate analysis. The ROM results supported the hypothesis that in the symptomatic participants there was abnormal function of the cervical spine. This is further discussed in Sec. 6.6.4.

6.6.1 CERVICAL MUSCULOSKELETAL STIFFNESS

6.6.1.1 STIFFNESS DISCRIMINATE ABILITY

Consistent variation in stiffness estimates were not displayed between participant groups; the M-TCM stiffness assessments had poor discriminate ability. The multi-factor ANOVA did not demonstrate a significant difference for the between-subjects factor of participant classification. At the higher force category of 37.5N the average difference between participant categories was larger than the lower force categories, but did not achieve statistical significance. At the lowest cervical measurement locations on

the right (location R5) and left (location L5), the FM participants displayed significantly higher stiffness than the NORM or NP group at force categories 25 and 37.5N. These measurement locations also demonstrated higher PPT values than other measurement locations, enabling analysis of a greater proportion of FD curves at the higher force categories of 37.5N (approximately more than double the number available to other measurement locations). The low forces used to measure the cervical musculoskeletal stiffness most likely contributed to the poor discriminate ability of the M-TCM. This is discussed in the next section.

The within-subject factor of location was significant for each force category, indicating that stiffness estimates varied significantly between measurement locations. The upper cervical spine displayed higher stiffness than the lower cervical spine. Post-hoc analysis revealed that for each force category the upper cervical measurements locations had significantly higher stiffness estimates than other measurement locations (see App. G in Table G-5). The analysis of trends [582] revealed that there was a significant linear trend of decreasing stiffness from the upper measurement locations to the lower locations, on each side of the cervical spine (see in App. G in Table G-6). The linear trend observed in the cervical spine has also been reported in the lumbar spine [558].

The lower stiffness estimates and higher amount of penetration of the M-TCM tip in the lower cervical spine measurement locations suggested that this region of the cervical spine is more compliant than the upper cervical spine. Post hoc analysis and a significant linear trend of decreasing stiffness in an inferior direction confirmed that the upper cervical spine had more stiffness and was less compliant (less amount of penetration of the M-TCM tip) than the lower cervical spine. Briefly, measurement locations of the upper cervical spine were probably made lateral to the right upper border of the trapezius and semispinalis capitus. Measurement locations in the lower cervical spine would likely have included contributions from the trapezius and the splenius capitis that lies deep to the trapezius. The lower stiffness and higher penetration observed at the inferior measurement locations may be accounted for by the greater proportion and thickness of muscular tissue compared with the upper cervical spine measurement locations. However, information regarding which anatomical structures contributed most significantly to stiffness values is purely speculative [566].

6.6.1.2 STIFFNESS RELIABILITY

The reliability of the stiffness results between the measurement times of initial, ten minutes and two hours was poor. Stiffness estimates derived at forces 12.5, 25 and 50N had poor reliability. At 37.5N there was fair reliability. The number of measurements included in each force category lowered dramatically with each higher force category due to PPT limiting the number of FD curves at higher forces. The reliability appeared to be better at higher force values, but PPT limited the number of FD curves available for analysis at the higher force values.

The reliability of the M-TCM was low in comparison with that shown with other mechanised stiffness measurement devices. Latimer et al. [102] tested symptomatic participants in the lumbar region over a five minute period and demonstrated high reliability. For asymptomatic participants, ICC values of 0.99, 0.95 [116] and 0.88 [115] have been reported in the lumbar region and 0.81 and 0.87 for the thoracic and sternum regions respectively [564]. In these other studies, the force ranges were considerable different to that used in this study: a lower limit of 30N to an upper force limit of up to 150N. As will be discussed, this large force application difference may have contributed to the lower reliability values of the M-TCM.

It is not known whether the poor reliability of the M-TCM was due to instrument design and application protocol or if stiffness assessment of the cervical spine over the zygapophysial joints demonstrates more variability than stiffness assessment of the spinous processes in the thoracic and lumbar spine. The application protocol of this investigation involved considerably lower forces than those applied by mechanised stiffness measurement devices in the lumbar and thoracic spine. It is probable that the lower applied forces was a factor in the low reliability of the M-TCM stiffness results.

The initial section of FD curves from measurements of spinous processes in the lumbar and thoracic spine, with mechanised stiffness measurement devices, has been described as the ‘toe-in’ region [113,559,562,564,583] (see Sec. 6.1.3). The ‘toe-in’ region is a non-linear region of the FD curve and occurs below a force of 20-30N (above 30N the FD curve becomes more linear). The ‘toe-in’ region of a spinal FD curve has been attributed to compression of the skin and superficial tissues lying over the lumbar and thoracic spinous processes and that nearly all of the soft tissue compression is likely to

occur at relatively low levels of force [562,565]. For this reason, the 'toe-in' region is commonly discarded. Lee and Svensson [562] reported that at a force of 10N a non-linear displacement of 1.5-2mm was observed, which they attributed to compression of the skin.

In this investigation, most FD data was in the 'toe-in' region. The M-TCM tip penetration from the start of a measurement up to 12.5N is shown in App. G in Table G-2. The penetration ranges of 1.2-2mm were approximately the same figures reported by Lee and Svensson [562] to quantify skin compression at lower application forces. The thickness of superficial tissues over the spinous process of the lumbar and thoracic spines is less than the region measured in this investigation, the postero-lateral region of the cervical spine. Therefore, the FD curves of this investigation more likely characterised the superficial tissues than the deeper tissues; particularly in the FM participants due to the lower forces applied to this mechanically hypersensitive group.

If higher force values had been applied with the M-TCM better reliability values would most likely be attained. However, it is difficult to envisage how higher forces could be applied to the cervical spine due to the limitation of a participants pressure pain threshold. It was important to restrict the upper limit of the FD curve to the PPT value for health and safety concerns of the participants. To do otherwise would involve application of a force to a specified value. This may involve application of force greater than PPT, which would invoke a painful response. Ethically this was not acceptable, especially for FM participants who experience increased pain sensitivity. Furthermore, it was possible a somatic reflex response may have been invoked from application of force perceived as noxious to the participant, potentially altering muscular stiffness and stiffness measurements, introducing variability to results.

6.6.1.3 EXPONENTIAL MODELLING OF THE FORCE-DISPLACEMENT CURVES

Each M-TCM Force-Displacement (FD) curve was modelled with a linear, polynomial and exponential mathematical function. The FD curves were clearly not linear and therefore this mathematical model was not pursued. The exponential and polynomial approximations modelled the FD data with high r^2 values. There were minor differences in stiffness estimates between the two models. This difference was slightly higher at higher force categories. Polynomial models are not stable outside the range of data they

are modelling and on occasions will display 'endpoint error' [584], which is characterised by error at the terminal ends of the FD curves [510,560]. End-point error was observed with the polynomial model in some FD curves and was depicted as the curve deviating greatly away from the raw FD data towards the terminal ends of the curve. This error was not observed with the exponential model and explained the stiffness estimate differences between the exponential and polynomial models. Therefore, stiffness estimates derived from the *exponential model* were used in statistical analysis.

An advantage of the exponential model is that it is stable outside the FD data range. PPT restricted the upper ends of many FD curves to a value below the maximum applied force of 50N. This greatly reduced the number of FD curves available for analysis at the higher force categories of 37.5 and 50N. For this reason, the ability of the exponential model to extrapolate beyond the upper terminal end of FD curves was explored. It was hoped that for the FD curves with an upper force value below 50N, the exponential model might predict the data between the actual terminal end and 50N. Unfortunately, extrapolation of the exponential model was not a reasonable proposition, because, as shown in App. G in Table G-10, the absolute difference in displacement between the actual and the extrapolated data showed large differences. Extrapolation of FD curves for the purpose of stiffness estimation with an exponential model demonstrated large error and unfortunately did not solve the problem of M-TCM stiffness measurements limited by a participant's PPT.

A common feature of most FD curves was transient behaviour at the very start and end of the curve. Presumably, this was due to the high variations in acceleration of the applied force, increasing and decreasing at the start and end of each measurement, respectively. This transient behaviour was expressed as an obvious deviation from the general shape of the FD curve. This had an undesirable effect on the exponential and polynomial models. These models tried to accommodate all data and therefore deviated slightly from the FD curve. To avoid this problem most FD curves had a small percentage of the start and end 'chopped' to remove the transient start and end behaviour. Each FD curve was inspected and decisions for removal of data were completed visually (see App. G, Table G-8).

6.6.2 PRESSURE PAIN THRESHOLDS

There were large differences in the pain pressure threshold (PPT) results between the participant groups. The multifactor repeated measures ANOVA did not achieve statistical significance for the between-subjects factor of participant classification (p<0.057 Table 6-7), although the outcome did suggest a strong trend. However, from Table 6-11 some FM (n=9), NP (n=22) participants and many NORM (n=50) participants had a PPT value higher than the maximum applied force of 50N. For these measurements, the true PPT would have been greater than the maximum applied force of 50N, although they were recorded and subsequently analysed as 50N. The large disparity between the number of PPT measurements greater than 50N in the NORM participant group, compared with the pain participant groups, suggested that if the true PPT value had been attained there would have been a significant difference between the participant groups.

The PPT discriminate analysis correctly categorised 83.9% of participants based on classification. A discriminate analysis of whether participants were symptomatic (NORM) or not (FM or NP) correctly categorised the two groups in 91.9% of cases, with high sensitivity and specificity. Discriminate analysis between the FM and NORM PPTs correctly categorised 95.5% of participants. The PPT measurements were consistent across the three measurement times. This was expressed as good reliability (ICC>0.8) for the PPT results and for total PPT the reliability was high (ICC>0.9). The good discriminate ability and good reliability supports cervical pressure algometry for the assessment and classification of asymptomatic and symptomatic participants.

These outcomes were consistent with previous studies of PPT in asymptomatic and symptomatic participants. Patients suffering from chronic whiplash associated disorders [52,267,386] and FM [33,286,287] have demonstrated significantly lower PPT values in the cervical region, and other musculoskeletal areas, when compared with healthy participants and other symptomatic participants without neck pain. The good inter-measurement reliability observed in this investigation is in accordance with the good reliability of pressure algometry reported by others (see Ch. 4, Sec. 4.3.5.1).

The PPT results were significantly different within and between measurement locations. There was a significantly different response between participant groups within each

measurement location. At almost all locations and for each measurements time, PPT scores were higher to lower in the NORM, NP and FM participant groups, respectively (see Figure 6-16). The total PPT scores also consistently displayed higher to lower values for NORM, NP and FM participants respectively, at each measurement time.

The PPT between measurement locations also significantly differed. The lower cervical spine bilaterally displayed higher PPT values compared with the upper cervical spine measurement locations in all participant groups. Post-hoc analysis of measurement location (see App. G at Table G-15) revealed that the lower cervical locations of L5 and R5 were significantly higher than all other measurement locations. Analysis of trends revealed that there appeared to be a quadratic trend between the upper and lower measurement locations, on each side of the cervical spine (see App. G in Table G-16). This outcome was in agreement with other studies that have shown that the examined region of the musculoskeletal system can influence pain sensitivity [177,291,385,386].

The PPT results of this investigation have implications for manual therapists who apply spinal palpation for the provocation and reproduction of pain. The results of this investigation indicate that tenderness in asymptomatic participants varies between different locations in the neck. Determination of a 'normal' tenderness value may be a challenging task for manual therapists, as different measurement locations have significantly different 'normal' pressure pain thresholds.

6.6.2.1 PERIPHERAL AND CENTRAL PAIN FACTORS

The FM and NP participants demonstrated a hyperalgesic response to the mechanical stimulation at all cervical measurement locations. In the FM participants the pain sensitivity was consistently increased at all measurement locations; on average the PPT was 21% lower than the NORM values (see Table 6-13). The NP participants also displayed a hyperalgesic response to mechanical stimulation, but not as consistently as the FM participants. As a percentage of the NORM PPT scores, the NP PPTs demonstrated varied responses: an average 10% decrease, but with large variability (range 1-19%). In addition, the left side of the NP participants had significantly higher PPT scores than the right (see Figure 6-20).

The consistent hyperalgesic results of the FM participants suggested a generalised state of hypersensitivity existed in the neck region of these participants. As reviewed in Ch.

2, this outcome agreed with previous reports of a generalised state of hypersensitivity in FM participants [33,52,177,383]. What was unclear was if the state of hypersensitivity was due to primary or secondary mechanisms, depending on whether the tenderness originated in tissue which had been damaged (peripheral) or in normal tissue that was neuroanatomically related to the area of damage (central) [385], or a combination of both.

Psychophysical studies of FM patients have suggested that painful areas of these patients can be defined as regions of secondary hyperalgesia [54,56]. Secondary hyperalgesia is characterised by an increased pain response to mechanical stimuli and occurs in undamaged tissue that is neurally related to a site of injury or inflammation [56]. Secondary hyperalgesia is believed to be due to sensitisation of the central pathways, primarily at the dorsal horn neurons [386]. Previous studies (see Ch. 2, Sec. 2.4) have indicated that aberrant central pain mechanisms most likely contribute to the pain manifestations seen in FM patients.

Because the pain seen in FM patients may be due to secondary hyperalgesia (implying central mechanisms) and that in this investigation there was a consistent increase in cervical pain sensitivity (compared with NORM participants), it was possible that sensitisation of central pain pathways was in part responsible for the generalised cervical tenderness, in the FM participants. However, it cannot be discounted that primary hyperalgesia due to peripheral sensitisation was not also a contributory factor. Injury or spinal dysfunction of multiple structures of the cervical spine could sensitise nociceptors of the cervical spine musculoskeletal system and may account for the tenderness observed in this region. Furthermore, it was possible that ongoing nociceptive input from spinal dysfunction may also contribute to changes in the pain sensitivity at the central level. Ongoing nociceptive afferent input may be a necessary factor for the maintenance of central sensitisation [215,226].

The NP participants did not display a consistent increase in pain sensitivity at the measurement locations in the cervical spine. Their PPT scores were not consistently decreased compared with the NORM participants. Furthermore, there was a significant difference in PPTs between the left and right sides of the neck (see in App. G in Figure G-1). This outcome was dissimilar to the FM participants who displayed a generalised tenderness in the cervical region. It was possible that a primary nociceptive source,

which may be characteristic of spinal dysfunction, may have accounted for the tenderness observed in some measurement locations. The localised, and not generalised, increased pain sensitivity at some cervical locations, suggested that peripheral sensitisation may have been primarily responsible for the localised tenderness, rather than only central mechanisms. However, it is difficult to establish with pressure algometry whether tenderness is a result of primary (peripheral) or secondary (central) mechanisms [55,385-387].

The hypothesis that in patients with chronic idiopathic neck pain, peripheral nociceptor sensitisation is the primary mechanism for the pain, rather than central mechanisms, is consistent with research completed by Scott et al. [585]. Scott et al. [585] applied various sensory tests to examine the pain processing mechanisms underlying the persistent symptoms in chronic idiopathic neck pain patients, and patients with chronic whiplash associated disorders. In the neck pain group, the mechanical hyperalgesia over the cervical spine was thought to be due to ongoing peripheral nociception. Sites distant to the neck were not altered to sensory tests. However in the patients with whiplash disorders, abnormal sensory changes were observed in the cervical spine and also distant sites, suggesting the involvement of central pain mechanisms.

Therefore, in both patient groups, it was plausible that peripheral mechanisms or a combination of both peripheral and central mechanisms could have accounted for the increased tenderness. Central sensitisation normally involves a few intervertebral segments and is unlikely to cross the midline in most parts of the spinal cord [75,198]. Perhaps the consistently increased pain sensitivity on the right side of the neck in the NP participants involved central and peripheral sensitisation of a few vertebral segments. Whereas, on the left side of the neck peripheral mechanisms may have accounted for the few measurement sites that displayed high tenderness? As noted above, the possible contribution of primary hyperalgesia from a nociceptive source within the cervical spine cannot be ruled out as a contributory factor to ongoing neck pain [386] in the FM and NP participants.

6.6.3 PRESSURE PAIN THRESHOLDS AND SPINAL DYSFUNCTION

The increased pain sensitivity observed in the FM and NP participant groups and the poor stiffness results in all participant groups, suggested that the concept of spinal

dysfunction primarily as a model only involving abnormal intersegmental motion [94], requires further elucidation. There is general consensus [530] of the concept of spinal dysfunction that encompasses dysfunction of articular structures, joint capsules, adjacent ligaments and/or paravertebral muscle spasm (see Sec. 6.1.1), which contribute to the phenomenon of a barrier to joint motion. However, missing from some models of spinal dysfunction is examination of the *mechanism of the pain*.

Sheather-Reid and Cohen [55] identified that in patients with chronic neck pain, a distinction between the origin and the mechanism of pain is required. It is possible that a nociceptive source (possibly in the zygapophysial joints or related structures) may be responsible for the pain or, instead, afferent information from a site may be processed abnormally. In patients with persistent neck pain, either nociceptive or neuropathic mechanisms are possible. They [55] suggested that for patients with no obvious cervical pathology, an alteration in nociceptive processing is probably the mechanism for the ongoing pain.

The hyperalgesia seen in the FM and NP participants was characterised by a lowered threshold to mechanical stimulation. A lowered PPT, or hyperalgesia, is considered to reflect sensitisation of afferent pathways, either peripherally or centrally [55]. The generalised and non-generalised decreased PPT seen in the FM and NP participants respectively, suggested involvement of both peripheral and central mechanisms in the FM patients..

If the cervical regions of some of the chronic neck pain sufferers (NP) and FM patients were characteristic of secondary hyperalgesia then changes in the pain-processing function of the central nervous system contributed to the clinical outcomes in these participants. This implies that the concept of spinal dysfunction may not always exist only as a nociceptive source of the spinal musculoskeletal system. It is possible that central pain manifestations may characterise clinical features of spinal dysfunction. Perhaps the concept of spinal dysfunction requires further expansion to incorporate possible altered central pain processing mechanisms.

6.6.4 CERVICAL RANGE OF MOTION

The passive cervical range of motion (ROM) results of this investigation demonstrated a significant difference in ROM between the three participant groups. The ROM results

were consistently higher to lower in the NORM, NP and FM participants, respectively, in all measurement planes (lateral flexion, flexion/extension, rotation) and total ROM (derived from the addition of whole plane ROM values in each measurement plane). All measurement planes and total ROM displayed statistically significant differences between the participant groups.

There was almost a 90 deg difference between the NORM and FM participant groups for total ROM. In each movement plane the difference in ROM between the NORM and the NP and FM participants was 12 deg and 28 deg respectively. These large differences were greater than that suggested as necessary to overcome natural variation in cervical ROM [478], supporting the premise that the FM patients did have significantly reduced ROM due to some form of spinal dysfunction.

The significant difference in ROM between the participant groups demonstrated the discriminate ability of this measurement method. The discriminate analysis of whole plane motion in the three movement planes correctly categorised 52.5% of participants based on classification. A discriminate analysis of whether participants were symptomatic (NORM) or not (FM or NP) correctly categorised the two groups in 77.0% of cases. This value increased to 100% correct participant categorisation into the three groups based on all primary ROM measurements (from neutral to an extreme in a movement plane) and conjunct ROM motions (movements in planes other than the primary movement plane).

The cervical ROM data and discriminate analysis of this investigation supported previous assertions that participants with neck pain [416,476,479,483] and FM [570] display reduced cervical ROM. Dall'Alba et al. [416] showed that active cervical ROM was significantly reduced in patients with whiplash injuries compared with healthy participants. Discriminate analysis of primary ROM motions correctly categorised 79.5% of participants, and 90.3% of participants when conjunct ROM was included in the analysis. Osterbauer et al. [476] also reported reduced active ROM in participants with whiplash injuries with high discriminate values. In forest machine operators, Hagen et al. [320] showed reduced ROM in workers who reported neck pain. Logistic regression analysis correctly categorised 90% of workers for the presence or absence of neck pain based on cervical ROM and pain experienced during ROM measurements. These previously reported discriminate values are similar to the current investigation.

The results of the current investigation, and those from previous reports, strengthen the case for using ROM as an indicator of physical impairment [416].

There was no interaction effect between the independent variables of participant classification and measurement plane. The percentage decrease of primary ROM between the symptomatic and asymptomatic participants revealed a consistent decrease in ROM for each motion (see Table 6-17). The FM participants had a larger percentage decrease (mean 22%) than the NP participants (mean 9%). This decrease was consistent for each primary motion, indicating that there were not significantly altered motions in either group. Conjunct motions in the symptomatic and asymptomatic participants were similar; the symptomatic participants simply had decreased ROM in most primary ROM motions, rather than dysfunctional or bilateral differences in cervical ROM. This outcome agreed with Dall'Alba et al. [416], who stated that in patients with neck pain, abnormalities from normal movement planes have not been demonstrated.

It was unclear whether the reduced ROM observed in the FM and NP participants was caused by primary mechanisms (such as mechanical changes, tissue damage or putative spinal dysfunction), pain inhibition from primary and/or secondary pain mechanisms or other factors. However, it appears likely that pain inhibition was a factor for the reduced ROM in the participants with neck pain. Pain factors, including self-reports of pain and pressure pain thresholds, were associated with cervical ROM measurements. Correlation analysis between self-reported neck and headache pain, the neck disability index (NDI) and cervical ROM revealed moderate and significant (p<0.01) correlations (see App. G at Table G-19). As well, there was a moderate (0.39) and significant correlation between total ROM and total PPT (cervical tenderness). These correlation outcomes suggested that pain factors were associated with reduced cervical ROM in the pain groups.

Altered pain processing mechanisms, either peripheral and/or central, may have contributed to the reduced cervical ROM in patients with neck disorders. Peripheral pain mechanisms may contribute to hyperresponsiveness of nociceptors in muscular and joint tissues. In an inflamed joint or muscle there is an increase in nociceptor resting activity [197] and even minimal movements can be painful by activation of sensitised nociceptors [196,205,206]. Central mechanisms may also be a factor in patients with neck pain that express reduced cervical ROM. Sensitisation of dorsal horn neurons may

result in a long-term increase in excitability and alter how afferent stimuli is processed in the central nervous system. Kramis et al. [58] hypothesised that deep somatic non-nociceptive afferents that normally serve proprioceptive functions, may gain access to the pain system via central mechanisms; innocuous movements or postures may thus be painful. The results of this investigation and previous reports of decreased ROM in patients with chronic neck pain lend support to the hypothesis that hypersensitivity of the nociceptive system, either through peripheral and/or central mechanisms, plays a role in the reduction of cervical ROM in patients with neck pain. However, whether a reduction in cervical ROM is caused by mechanical changes in the tissues or spinal dysfunction, pain inhibition or other factors remains unclear [320,416].

Conjunct motion can only be assessed by three-dimensional measurement systems that concurrently measure cervical ROM in the three movement planes. There are several systems that can accomplish this including optoelectronic [491], sophisticated electrogoniometer linkage system [500] and electromagnetic tracking [575], the latter of which was used in this investigation. The inclusion of conjunct ROM in the discriminate analysis increased the percentage of participants correctly categorised from 68.9% to 100%. *This supports the use of three-dimensional cervical ROM systems (such as that used in this investigation) and the inclusion of conjunct motion in a cervical ROM analysis system*. It is recommended that a measurement system that can capture ROM in three dimensions be used in future cervical ROM investigations.

6.6.5 SELF REPORTING INSTRUMENTS

The FM participants reported more extensive body region discomfort, psychological distress and pain (see Table 6-18). The FM participants had significantly greater headache pain than the NORM and NP participants and greater neck pain than NORM participants. Self-reports of neck disability and pain differed significantly between the asymptomatic and symptomatic participants; the NORM participants reported significantly lower neck pain and lower neck disability index (NDI) scores than the symptomatic (FM and NP) participants. The NDI and neck visual analogue scale (VAS) scores were higher in the FM compared with the NP participants, but the differences were not significant. The FM participants reported severe neck disability, and the NP participants reported moderate to severe disability [421]. The FM participants reported an FIQ score of 48, which was close to the average of 50 [577].

The total region count (derived from the addition of the number of regions indicated as painful) differed significantly between all participant groups. A break down of the total region count (Table 6-20) revealed that in all musculoskeletal regions, the FM participants reported more discomfort. This was most evident in the lower limbs, arm/shoulder and chest regions. However, in the neck the NP and FM participants reported similar frequency of pain.

Discriminate analysis demonstrated that this measurement variable could very well discriminate between the different participant groups. The total region score correctly discriminated between symptomatic and asymptomatic participants in 85.5% of cases. This outcome was in agreement with previous reports of regional pain scores in FM patients [586]. Discriminate analysis of the NDI scores demonstrated similar scores as the total region count, although not as high.

The pain variables (including total region count, the VAS scores and the NDI) were significantly altered in the FM group compared to the NORM group in the post-hoc analysis. This is consistent with the pain symptoms that are prevalent in FM.

The Profile of Mood States (POMS) and State-Trait Anxiety Inventory (STAI-S) questionnaires have been identified as instruments that may measure psychologic distress in FM patients [425]. These instruments are described in Ch. 4, Sec. 4.3.5.4. The POMS depression-dejection mood factor scale was significantly different between the FM and NORM participants. This mood scale was not significantly different between the NP and NORM participants. This scale represents a mood of depression accompanied by a sense of personal inadequacy [422]. Previous studies have reported depression in FM patients. FM patients have demonstrated higher depression than patients with rheumatoid arthritis [176], other rheumatic disorders [240], normal controls [241] and patients with regional pain syndrome [21]. Of interest, in the current study, there was a lack of psychological features in the FM patients, which was in contrast to previous studies. The FM patients recruited for the study were from an older previous study, so perhaps with the variation in symptoms that is prevalent in FM, some participants may have improved over time, and presented with reduced psychological features.

The results of the NP participants were consistent with previous studies. Inanici et al. [21] reported a non-significant difference in depression between normal controls and patients with regional pain syndrome. This is consistent with results of this investigation. The other POMS mood factors were not significantly different between the participant groups.

The STAI-S and the POMS tension-anxiety (TA) mood factor scale were not significantly different between the three participant groups. The STAI-S Anxiety scale consists of twenty questions that evaluates how respondents feel 'right now, at this moment' [423]p6. The essential qualities evaluated by the STAI-S scale are feelings of apprehension, tension, nervousness and worry [423]. The POMS TA scale is descriptive of heightened musculoskeletal tension, including reports of somatic tension and observable psychomotor manifestations [422]. Previous studies have shown a significantly higher level of anxiety in FM patients compared with rheumatoid arthritis patients [176] and normal controls [241]. However, Inanici et al. [21] investigated clinical features and psychologic factors in FM, regional soft tissue pain patients and normal controls and did not report significant differences in anxiety scores. The authors [21] reported STAI-S scores that were similar to this investigation for the three participant groups. In addition, Clark et al. [248] did not demonstrate a significant difference for the STAI-S between FM patients and a general medical outpatient population, consistent with this investigation.

There were significant correlations between the self-reporting instrument results and the clinical measures of ROM and PPT. These are reported in App. G, Sec. G.5. The NDI and neck VAS scores demonstrated moderate but significant correlation with the ROM and PPT results. The NDI had good correlation with the neck VAS. This was consistent with previous research [421].

6.6.6 STUDY LIMITATIONS AND FUTURE RESEARCH

As discussed above, experimental methodology and design may have contributed to some of the non-significant outcomes of this research. Better preparation of research tools may have avoided some of the limitations of the research.

Pilot studies performed on asymptomatic subjects may have highlighted some of the limitations of the M-TCM stiffness assessments, particularly for limited data at higher

forces due to pain thresholds. Further development of experiment methodology on a sample of NP subjects could also have assisted with highlighting protocol limitations. Future studies should conduct pilot studies.

The low force application, particularly in the upper spinal measurement locations could have been predicted with a small pilot study. The PPT limiting force application and not allowing the collection of FD data at higher forces significantly restricted the applicability of the M-TCM device.

As well, the anatomical differences between the upper and lower cervical spine should in future be considered for musculoskeletal stiffness assessments of this region. In the upper cervical spine, smaller muscle groups result in less displacement for a given force, compared to the lower cervical spine region, over the zygapophysial joints. Hence, the lower cervical spine will generally be more "compliant", or less stiff, than the upper cervical spine. For future studies the anatomical structures and muscle groups, and resultant displacements required for given forces should be given careful consideration.

The dimensions, controlled speed of application of the M-TCM, and continuous real-time feedback about orientation and application speed make the M-TCM a suitable pressure algometer. However, some preliminary testing comparing the two functions of the device (stiffness assessment, and PPT) independently would have provided more assurance that the device was suitable for the purpose of pressure algometry. Future studies that use a devices such as the M-TCM should conduct tests to provide assurance that the PPT measurements are not influenced by the combination of stiffness and PPT measurements.

The analysis of the FD curves at multiple force values did not add value to musculoskeletal cervical stiffness outcomes. This data may have been overanalysed given no differences between the groups was revealed, and the limitations of testing in the symptomatic groups with the FD measures being linked to the limiting factor of the PPT. Extrapolation of data was not useful and did not add to the interpretation of results. For future studies, a different approach to applying statistical analysis of the FD curves from the cervical region would be required.

As discussed in Ch. 4, the PPT measurements at each site were only measured once per session. This is not in alignment with current research practice where each site is assessed three times consecutively the average of the three results is derived as the PPT value. Three measurements per site may have provided more accurate data, as there may be variation in any one application. This was not applied due to the large number of sites tested within each participant, three times over, and the inconvenience to the participants. In addition, for this study, some FM patients reported that lying prone for extended periods for testing caused some discomfort. Hence, for some patients only one PPT measurement was possible. For future studies it is recommended that sites are assessed three times consecutively per measurement time and the average calculated, if this is possible with the participant groups.

Also discussed in Ch. 4, the author undertook all measurements due to time constraints and understanding of the operation of the equipment. Future studies would benefit from having blinded examiners to remove the possibility of participant status bias within the results.

The current study did not include assessment sites remote from the cervical spine. Hence, it was not possible to make conclusions about a possible generalised decrease in pain thresholds in the region of pain, and remote from it. If remote sites are also reduced this can indicate the presence of secondary hyperalgesia, which implies central mechanisms are involved. This analysis was not possible with the current research design. Future studies should include remote sites for pain sensitivity assessment.

6.7 CONCLUSION

A basic tenet of manual therapy states that altered spinal stiffness, as perceived with spinal palpation for stiffness, indicates presence of spinal dysfunction (see Sec. 6.1.1). It was hypothesised that the stiffness estimates of the cervical spine derived from the FD curves of the M-TCM, would detect abnormal stiffness in the symptomatic participants. However, this hypothesis was not tested because the M-TCM stiffness results were unreliable and had poor discriminate ability; the M-TCM stiffness results did not display systematic differences between the three participant groups. Therefore, the M-TCM is currently not useful for the assessment of stiffness in the cervical spine.

The pressure algometry measurements of the cervical spine were reliable and demonstrated large differences in pain sensitivity between the symptomatic and asymptomatic participants. However, the differences were not significant. The generalised hyperalgesic response observed in the FM participants, compared with the NORM participants, suggested there was a generalised change in pain sensitivity in the cervical spine. The NP participants also displayed a hyperalgesic response to mechanical pressure compared with the NORM participants, but not as severely or consistently as the FM participants.

The hyperalgesic response indicated involvement of a sensitised nociceptive system, either at a primary and/or secondary level. The generalised increase in pain sensitivity in the cervical spine of the FM participants supported the hypothesis that this region was characteristic of secondary hyperalgesia, indicating involvement of secondary mechanisms. This proposition was consistent with previous reports of centrally mediated altered nociception in FM participants (see Sec. 2.4.5.2). The NP participants did not display a consistent hyperalgesic response, suggesting that the increased pain sensitivity was more a localised phenomenon. The putative primary source may have been the basis of spinal dysfunction. This outcome was consistent with previous reports [585].

Other clinical tests also showed significant differences between the symptomatic participants and asymptomatic participants. There was significantly reduced cervical range of motion (ROM) in the symptomatic participants. This outcome supported the premise that in these participants there existed some form of spinal dysfunction.

The goal of this research was to investigate the supposition that in fibromyalgia patients and participants with chronic neck pain there was dysfunction of the cervical spine. The results of this investigation provided evidence of abnormal function of the cervical spine in the FM and NP participants. This supported the hypothesis that spinal dysfunction plays an important role in the aetiology of chronic musculoskeletal pain. However, the poor cervical stiffness results of this investigation indicated that the evidence was not conclusive. Further studies are required to elucidate the association of dysfunction of the cervical spine and regional and generalised pain syndromes.

CHAPTER 7

CONCLUSIONS

This thesis investigated issues that span several disciplines and has made links between them to assist in understanding the pathogenesis of chronic non-specific musculoskeletal pain syndromes.

Particular focus has been placed on regional pain syndrome (RPS) and fibromyalgia (FM). These disorders have significant impact on the quality of life of sufferers, hence knowledge regarding the aetiology of FM and RPS would be beneficial.

7.1 LITERATURE REVIEW

The review of the literature (Ch. 2) concluded that there is evidence to support the hypothesis that chronic non-specific musculoskeletal pain syndromes are caused by dysfunctional pain modulation. A combination of peripheral factors (peripheral sensitisation due to strong and persistent musculoskeletal pain) and possibly central factors are believed to be the key to the pathogenesis of RPS and FM (although central factors are less clear in RPS). Augmentation of afferent pain stimulus in the dorsal horn neurons manifests as hyperalgesia, referred hyperalgesia, referred pain and allodynia (Ch. 2). These phenomena play a critical role in expression of chronic musculoskeletal pain, hence hypersensitivity of the central pain pathways must be considered as an aetiological factor in RPS and FM. Ch. 2 explored the literature of different research fields regarding musculoskeletal disorders and their classification, and pathophysiological pain mechanisms and external factors that may contribute to the genesis of RPS and FM.

From the ergonomics literature, it seems that the field has not accepted the putative neurobiological hypothesis for the basis of RPS and FM. The relationship between ergonomic risk factors and the function of the pain system is not clear. In addition, the rheumatology and pain physiology fields have not notably investigated the contribution of ergonomic risk factors to the onset of RPS and FM. Consequently, it is not clear how

workplace ergonomic exposures could act as aetiological factors in chronic musculoskeletal pain.

The rheumatology and pain fields have also not extensively investigated the putative association between ergonomic risk factors and features of RPS and FM. Workplace ergonomic exposures that may act as aetiological factors in chronic musculoskeletal pain syndromes remain unclear. Specific guidelines regarding ergonomic workplace factors and hypersensitivity of the peripheral and/or central pain system, which may manifest as tenderness, allodynia and referred tenderness and pain, are presently at their very early stages. Studies are required to elucidate some of these issues and to promote links between the research fields of pain physiology and rheumatology, and the fields of ergonomics and occupational health and safety.

7.2 MEASUREMENT OF CERVICAL SPINE FUNCTION AND PAIN SENSITIVITY

Initially eletromechanical measurement devices were developed in this thesis to assess the function of the cervical spine. These included the new cervical range of motion (ROM) measurement device (Ch. 5) and the cervical musculoskeletal tissue stiffness measurement device, the modified tissue compliance meter (M-TCM) [see App. F]. The M-TCM also assessed pressure pain sensitivity (PPT).

The ROM and M-TCM devices had high inter and intra-examiner reliability and accuracy when tested on participants and foam surfaces.

These devices were valuable developments because they assisted in testing the relationship between cervical spinal dysfunction and chronic musculoskeletal pain, and in the investigation of ergonomic risk factors and changes in pain sensitivity.

7.3 FWAP-LINK: A NEW POSTURE AND ACTION MEASUREMENT SYSTEM

In Ch. 3, the FWAP-Link system was developed. The development of FWAP-Link was the first goal of this thesis (see page 65). This system was an instrument based posture and action measurement system that used an electromagnetic tracking system to

measure movement in three dimensions. The posture data could be analysed to investigate the occurrence and duration of static postures and the repetitiveness of actions required by a task.

The FWAP-Link system represented a significant step forward in using modern technology for ergonomic evaluation, particularly posture analysis based on a Predetermined Motion Time Standard. It was a novel development because it was the first system to use animation and custom analysis software to link posture data to a Predetermined Motion Time Standard.

7.4 THE ASSOCIATION OF ERGONOMIC RISK FACTORS AND MUSCULOSKELETAL PAIN

Constrained and awkward working body postures are one of the most important factors associated with the pathogenesis of musculoskeletal disorders [81-86]. Investigation of this risk factor of musculoskeletal pain was the second goal of this thesis, and was researched in Ch. 4 (see page 90).

The posture experiment examined the association between specific ergonomic risk factors of non-neutral and static working posture, combined with repetitive work actions, and clinical variables characteristic of RPS and FM.

The main findings of this research were:

- The medium term (four-hours) exposure to the significant ergonomic risk factors influenced the sensitivity of the pain system. There was a significant change in pain sensitivity and discomfort between the start and end of the computer based tasks. These changes were due to a change in the function of the pain system at a peripheral level and may have also reflected central changes as well, although this was not clear.
- The work actions of the neck were a significant factor for pain sensitivity and discomfort. The pain sensitivity and discomfort were significantly increased after the task with a static cervical spine posture, as compared with the task with more dynamic neck actions. Importantly, the pain sensitivity at some sites remote from the cervical spine was significantly different between the two tasks,

indicating that the changes were generalised. This outcome implied a possible change in pain processing function of the central nervous system. These results highlighted the importance of the cervical spine region in initiating pain sensitivity changes. This may have included functional changes within the dorsal horn cells of the central pain system, but this was speculative (see page 176 for full discussion).

- The increased excitability of the pain system, as a result of the poor ergonomic characteristics of the task, may have represented a risk factor for development of RPS. Long-term exposure to poor ergonomic variables that increase pain sensitivity could eventually induce permanent aberrant function of the nociceptive system. Central neuronal plastic alterations that become permanent, represent the pathological component of an ensuing chronic pain syndrome. Therefore, the postures and actions described in this experiment should not be undertaken as part of daily work because they increase pain sensitivity and are a risk factor of RPS.

These outcomes showed that medium-term exposure to poor and static working postures can increase pain sensitivity and self-reported discomfort in healthy female adults. The posture research also demonstrated that the work action characteristics of a task can significantly influence pain sensitivity: the work action characteristics of the neck were varied and this change significantly influenced the amount of pain sensitivity and self-reported pain. It was concluded that the postures and actions of the neck can influence how the pain system modulates pain (i.e. pain sensitivity).

It was also concluded that the posture and action characteristics of the neck should be measured in workplace ergonomic investigations. Firstly, because this research has shown that this region can influence pain sensitivity in this region and some other sites (e.g., the neck and at some distal musculoskeletal sites). Secondly, previous research over the past decade has supported the hypothesis that spinal factors are an important factor associated with the onset of chronic musculoskeletal pain.

7.5 SPINAL DYSFUNCTION IN RPS AND FM

Ch. 6 investigated the last goal of this thesis, that being the relationship between dysfunction of cervical spine structures and the clinical features of chronic

musculoskeletal pain. Cervical spine function was assessed in FM, patients with chronic neck pain and asymptomatic participants with the M-TCM, cervical PPT and other clinical measures.

The key findings of Ch. 6 were as follows:

- The manual therapies literature does not provide a validated definition of spinal dysfunction. The reliability of manual therapy techniques for the assessment of spinal musculoskeletal stiffness is poor. The reliability of manual assessment for spinal tenderness is good.
- The PPT results from assessments in the cervical spine had good reliability. Symptomatic participants had greater pain sensitivity, compared with asymptomatic participants. The hyperalgesic response to the applied mechanical pressure indicated involvement of a sensitised nociceptive system, either at a primary and/or secondary level. The hyperalgesic response was generalised in the neck region and it was concluded that this region was characteristic of secondary hyperalgesia in the FM patients. This implied perturbed central pain mechanisms, which is a proposition consistent with previous reports (see page 51 for previous reports list) of centrally mediated altered nociception in chronic pain patients.
- The reliability of the M-TCM for cervical musculoskeletal stiffness assessment was poor. Therefore, conclusions could not be made regarding the hypothesised greater cervical musculoskeletal stiffness in the symptomatic participants, compared with the asymptomatic participants. More research is needed to better understand the relationship between cervical musculoskeletal stiffness, spinal dysfunction and chronic musculoskeletal pain.
- Cervical ROM was significantly reduced in the symptomatic participants, indicating that in these participants there was abnormal function of the cervical spine.

These outcomes provided some evidence that in the symptomatic participants there was dysfunction of the cervical spine and hypersensitivity of the nociceptive system. It was concluded that abnormalities of spinal function and aberrant pain modulation mechanisms in the symptomatic participants most likely associated with the clinical characteristics non-specific pain syndromes.

This research was valuable because it was the first to assess PPT at so many locations (ten in total) in the cervical region. This provided a good understanding of the pain thresholds of the neck, and some insight into the cervical spinal dysfunction and chronic musculoskeletal pain in this region.

7.6 FURTHER RESEARCH

The posture experiment (Ch. 4) outcomes added to the limited understanding of the relationship between specific ergonomic risk factors (static and poor posture, and repetitive actions) and change in pain sensitivity. The ergonomics community should consider pathophysiological pain mechanisms when examining risk factors for chronic musculoskeletal pain. More research is warranted to better understand this relationship and for the development of better ergonomic guidelines regarding non-specific musculoskeletal disorders.

As well, the results of the spinal function investigation (Ch. 6), combined with previous research reports, highlight the importance of spinal dysfunction in the onset of chronic non-specific musculoskeletal pain. Further studies are required to elucidate the association of dysfunction of the cervical spine and regional and generalised pain syndromes.

CHAPTER 8

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APPENDIX A

FWAP-LINK TECHNICAL INFORMATION (CHAP 4)

A.1 ELECTROMAGNETIC TRACKING

Electromagnetic tracking was selected to complete posture measurement for the FWAP-Link system based on advantages associated with its operation and the specific requirements of the research application for which FWAP-Link was developed. A Fastrak Electromagnetic Tracking System[xvii] (ETS) consisted of a *master* and *slave electronics card* that operated up to four *sensors* per card (see Figure A-1). The master card also operated the ETS *transmitter*. The transmitter generated a magnetic field that was detected by each sensor. The signal from the sensor was processed by the electronics card and the three-dimensional position (X,Y,Z) and orientation (azimuth, elevation, roll) of the sensor *relative* to the transmitter was determined [336]. The orientation of the sensors was output as a Cardan angle rotation sequence of Zy′x′′ or azimuth, elevation, and roll [587]. These three angle values were converted to a technical reference system rotation matrix using Equation A-10 given below. A custom computer program was developed to enable communication between the Fastrak ETS and a personal computer. This program was developed by the author using Microsoft Visual Basic v6.0.

Measurement rates for the Fastrak ETS were extremely fast (up to 120 measurements per second), with high accuracy, reliability and resolution, and low latency. The Fastrak ETS could multi-plex four input signals, but each addition sensor halved the update rate. The ETS could permeate non-metallic items and direct line-of-sight between the transmitter and sensors was not required. If during posture measurements, a participant placed a body part (e.g., arm or torso) between the transmitter and sensor, the results

[xvii] Polhemus Incorporated, 40 Hercules Drive, Colchester, VT, USA

were not affected. The Fastrak ETS was limited to an operational range of approximately 1m and metallic items nearby may affect measurements.

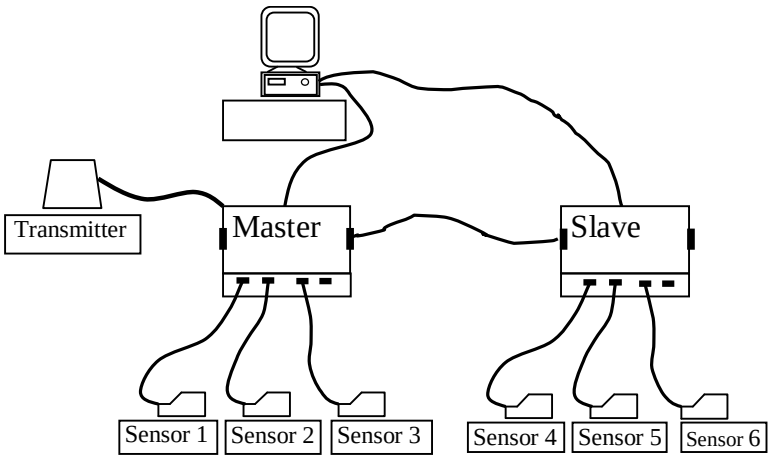


Figure A-1 – Polhemus 'Fastrak' electromagnetic tracking system with six sensors

A.1.1 ACCURACY OF THE FASTRAK ELECTROMAGNETIC TRACKING SYSTEM

The accuracy of the Fastrak ETS was tested in the location where posture research described in Ch. 4 was undertaken. This was to ensure that any unknown electromagnetic fields or metals (for example, power cables in the walls or concrete reinforcement in floor) that interfered with the ETS would be detected. Two sensors were fixed in a similar orientation to a flat plank of wood. The sensors were approximately 200mm apart. The plank of wood was then moved from close proximity to the ETS transmitter to a position that was further apart. The distance between the two sensors was determined from the output of the Fastrak ETS. This was compared with the actual distance between the two sensors, which was measured with a digital linear vernier (accuracy 0.03mm). The root mean square (RMS) error was determined as the difference between the ETS estimate of the distance between the two sensors and the actual distance. The Fastrak ETS was put into 'stream mode' during testing. The method of measuring distance between two points in space has been utilised previously for the purpose of assessing electromagnetic tracking systems [337,588].

Two experiments were undertaken to assess the positional accuracy of the Fastrak. To determine the accuracy of the instrumentation, the plank of wood, with the two attached ETS sensors, was moved away from the transmitter at both a 'fast' and 'slow' rate. The speeds emulated the actions of human participants when undertaking fast-moving

actions (e.g., moving the arm) or slow-moving actions (e.g., a static posture). The accuracy of the ETS for the plank moving quickly at a 'fast' rate was approximately 64mm/sec (see Figure A-2). The accuracy of the ETS for 'slow' movements was approximately 16mm/sec (see Figure A-3). The positional accuracy of the Fastrak ETS was within the manufacturer's positional specifications [587].

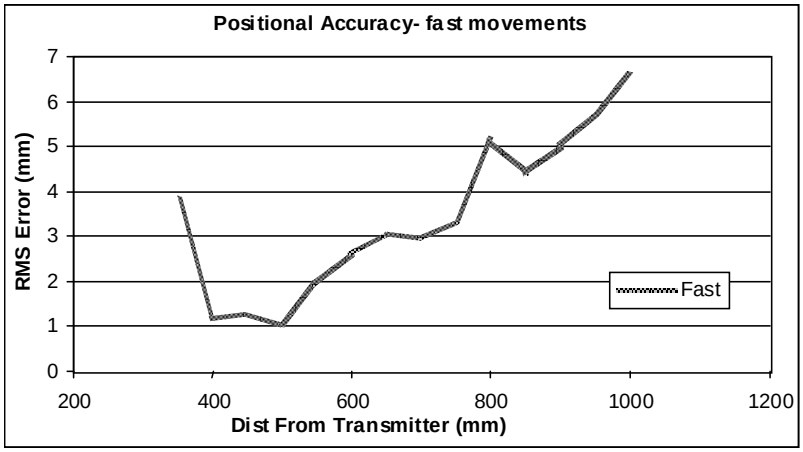


Figure A-2 – Positional accuracy of the Fastrak ETS when sensors were moving away from the transmitter at a fast rate

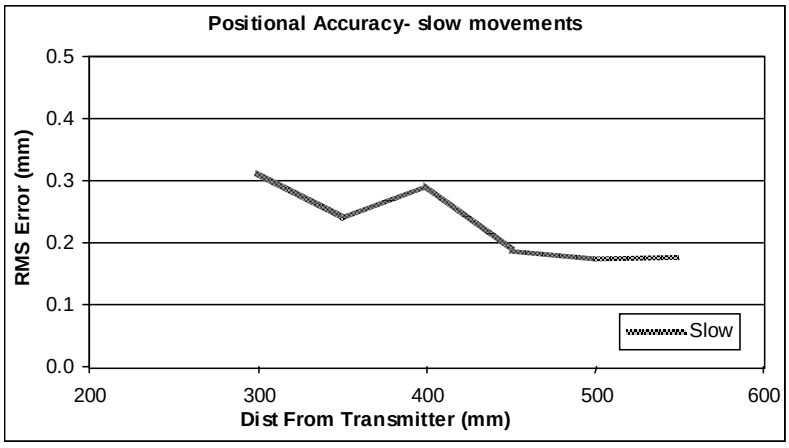


Figure A-3 – Positional accuracy of the Fastrak ETS when sensors were moving away from the transmitter at a quasi-static rate

A similar procedure was used to evaluate the orientation accuracy of the Fastrak ETS for elevation, roll and azimuth. A series of five wooden blocks were fabricated at angles of 15 to 75deg in increments of 15deg. The wooden blocks were placed on a single large horizontal wooden board. A sensor was then placed on each block to measure the angles of the blocks. A sixth sensor was placed on a level surface on the wooden board to provide a reference horizontal value. The difference in angles between the sensors on the wooden blocks and the sensor at approximately horizontal was determined, for sensor-to-transmitter distances of 100mm to 1000mm, in increments of 100mm. At each

sensor-to-transmitter distance, roll, elevation and azimuth were measured. The actual angles of the wooden blocks were measured by an inclinometer (Whyler WYLCL45: accuracy better than 30 arc sec). A similar procedure has been used for the determination of the angular accuracy of an electromagnetic tracking system [337]. The RMS error between the Fastrak estimates of the wooden block angles, and those determined with the inclinometer are shown in Figure A-4 to Figure A-6 for roll, elevation and azimuth, respectively.

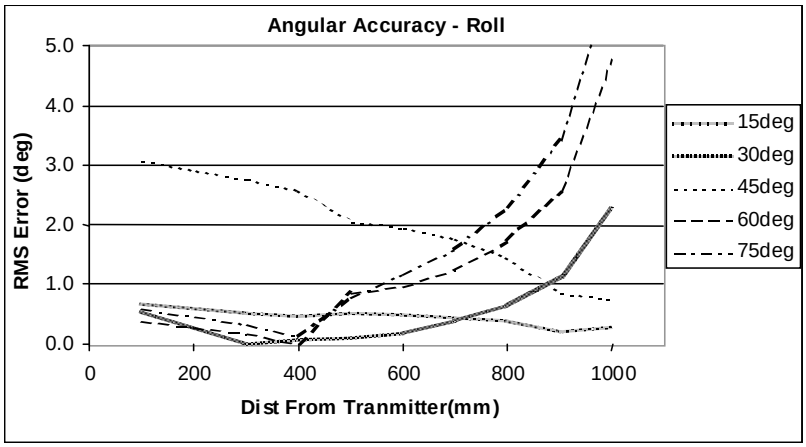


Figure A-4 – Angular accuracy of the Fastrak electromagnetic tracking system for roll orientation

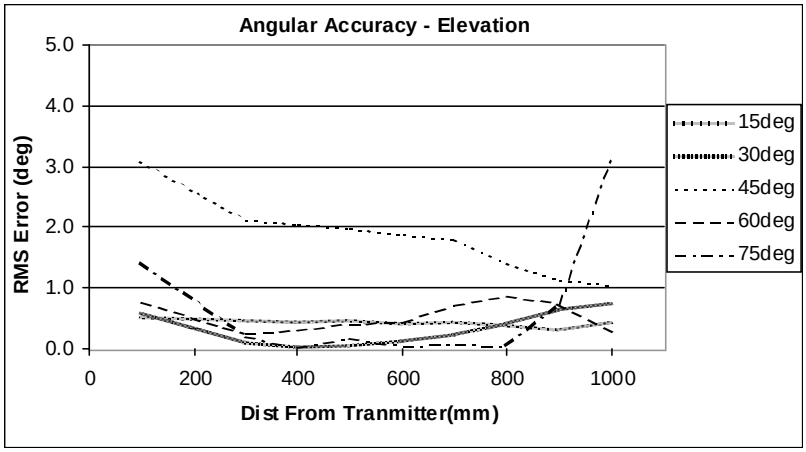


Figure A-5 – Angular accuracy of the Fastrak electromagnetic tracking system for elevation orientation

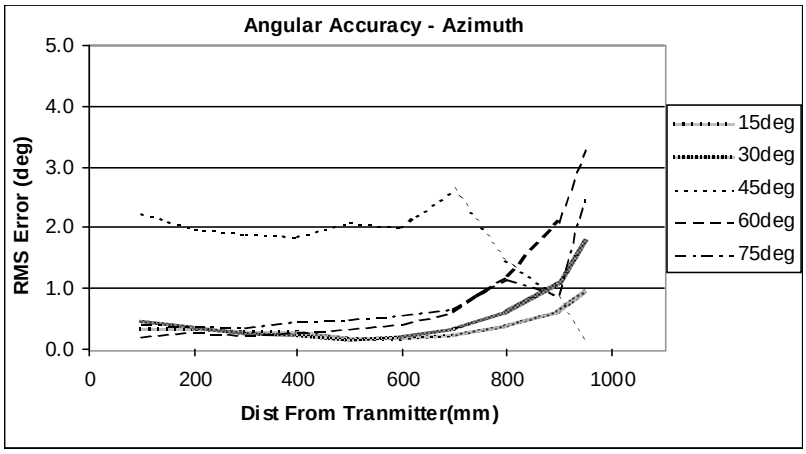


Figure A-6 – Angular accuracy of the Fastrak electromagnetic tracking system for azimuth orientation

Orientation accuracy at 45deg was not within the manufacturer's specifications [587]. Whether the error was associated with the sensor placed on the 45deg wooden block, or with the true alignment of the 45deg wooden block, which was not that determined by the inclinometer, is unknown. The error occurred for all orientation measurements (roll, elevation and azimuth). This suggests that the sensor was not at fault, as it consistently measured a specific angle at any orientation. It is more likely that the block may have moved slightly between measurement with the inclinometer and measurement with the Fastrak ETS. Most other orientation measurement RMS errors were low, at less than one degree error. However, most values were slightly higher than those reported by the manufacturer [587].

A.2 THREE-DIMENSIONAL COMPUTER ANIMATION

Animation is a technique in which the illusion of movement is created by the process of dynamically generating a series of frames (pictures) of a series of objects, in which each frame (picture) is an alteration of the previous frame. Conventional animation is generally based on a frame-by-frame technique and the advent of inexpensive and powerful computers has contributed to computer involvement in animation [589]. Computer animation systems provide the animator with operations that can be applied to objects (e.g., a human figure), such as rotation and translation. Computer animation can also include virtual camera operations like zoom, pan and tilt. Three-dimensional (3D) computer animation involves animating objects in three-dimensional space (i.e., with X, Y and Z coordinates) [589]. FWAP-Link utilises 3D computer animation to

visually represent human movement. The user can view the animated human figure from any angle and zoom and can focus on specific body segments.

Table A-1 lists common commercially available 3D animation packages; this list is not exhaustive. These packages vary greatly in price depending on features supplied and other software factors. The cost of most commercial packages varies between $5-15K (AUS). Poser[xviii] was approximately $400 (AUS) and provided direct importation of BioVision motion capture files (discussed below). Poser was selected for use with FWAP-Link based on ease of use, price and importantly the ability to link motion capture data and animation via its BioVision file import facility.

Commercial 3D Animation Packages	Web Site	Biomechanical Analysis Packages Incorporating 3D Representation	Web Site
CuriousLabs: Poser 4.0	www.curiouslabs.com	Skill Technologies Inc: 6D-Research*	www.skilltechnologies.com
Kinetix: 3D Studio Max	www.discreet.com	Innovative Sports Training: The MotionMonitor™*	www.innsport.com
Kaydara: Filmbox	www.kaydara.com	APAS: Ariel Performance Analysis System*	www.arielnet.com
Alias: Wavefront	www.aw.sgi.com	3D Static Strength Prediction Program	www.engin.umich.edu/dept/ioe/3DSSPP/
NewTek: Lightwave 3D	www.newtek.com	Safework	www.safework.com
DreamTeam: Typhoon	www.dreamteam-ltd.com		
Softimage 3D	www.softimage.com		
Protozoa: ALIVE	www.protozoa.com		
Hash: Animation Master	www.hash.com		

Table A-1 – Commercial animation software and analysis packages incorporating animation (* software incorporates biomechanical analysis)

Application of 3D animation to biomechanical analysis has been commercially developed and several specialised biomechanical software packages exist. These software packages provide biomechanical analysis of motion capture data coupled with 3D animation representation of motion capture measurements. However, no currently available software incorporates animation and MODAPTS or FWAP analysis. The purchase cost of commercial biomechanical software packages begins at approximately $6,000 (AUS).

[xviii] Curious Labs Inc, 655 Capitola Rd, Suite 200, Santa Cruz, CA 95062

A.2.1 MOTION CAPTURE DATA STORAGE FOR ANIMATION

The BioVision[xix] Hierarchical is an animation industry protocol used for the storage of motion capture data from various motion capture systems, for use with animation software. The BioVision Hierarchical (BVH) data file is a generic ASCII (plain text) file divided into two sections: *hierarchy* and *motion*. The *hierarchy* section describes the joint-to-joint connections of the animation figure and joint offsets for the sampled motion data. The *motion* section describes the rotation movement of individual joints named in the hierarchy section of the file on a per-sample basis [590]. Poser can read BVH motion capture data files. Poser imported the BVH file and during import, the stored joint rotation data was used to derive bone rotation data for the animated figure for each animation frame. The BVH files apply stored human motion to your 3D models [591].

A.3 KINEMATIC GEOMETRY

Kinematics involves observing and measuring movement without regard to forces that cause it [354]. A branch of kinematics, *kinematic geometry* deals with the description of body position and displacement (body posture) without regard to time derivatives; notions such as velocity and acceleration are not included in analysis [355]. Kinematic study represents the first stage of biomechanical analysis. The second stage is *kinetics*, which involves determining the forces that operate on the system to produce the observed or observable movement [592].

Kinematic geometry was used with the FWAP-Link system to describe the posture of the measured person by converting the data from the ETS sensors to anatomically meaningful information. Kinetic analysis was not investigated with the FWAP-Link system, and therefore there was no provision for analysis of forces that produced observed movements.

The human body can be viewed as a system of rigid links connected by joints. Kinematic geometry analysis provides a description of an individual link's position by

[xix] BioVision Motion Capture Studios, 9311 Blind Pass Rd, St. Pete Beach, Fl, 33706, USA

its location, orientation and joint configuration. Each link represents an *anatomical segment* of the measured person. Figure A-7 shows two example anatomical segments (links). The *arm* segment (link) begins at the right arm glenohumeral joint centre and extends distally to the elbow. The right forearm *ulna* anatomical segment begins at the elbow joint and terminates at the wrist at the styloid process of the ulna.

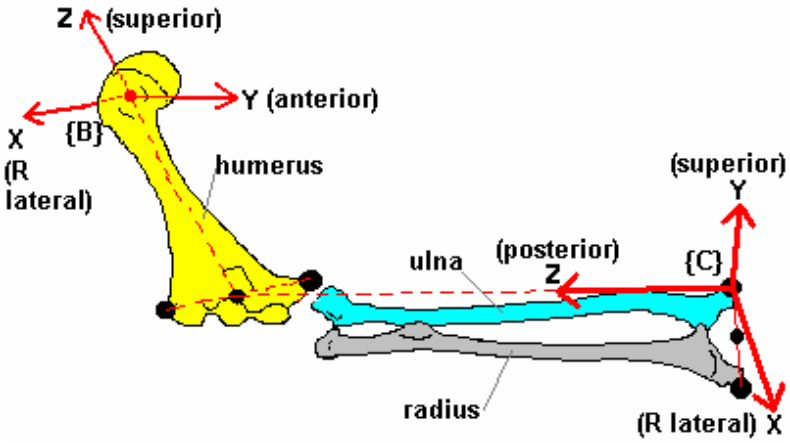


Figure A-7 – Right arm and forearm anatomical segments (links) with attached local segment reference systems (LSRS).

A.3.1 GLOBAL REFERENCE SYSTEM

To relate anatomical segments to each other, a *global reference system* (GRS) is required. Conventionally, a right-handed Cartesian (orthogonal) triad is used that has its origin affixed to a reference point in the vicinity of the measured person [355]. The FWAP-Link system used an ETS for motion capture and the ETS transmitter coordinate system represented the FWAP-Link global reference system (see Figure A-8).

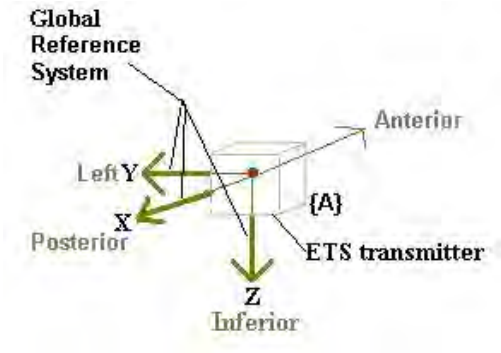


Figure A-8 – The ETS transmitter reference system was used as the Global Reference System (GRS) for the FWAP-Link posture measurement system

A.3.2 LOCAL SEGMENT REFERENCE SYSTEMS (TRANSFORM MATRIX)

A *local segment reference system* (LSRS) was attached to, or embedded with, each anatomical segment (link) of the measured person. Each LSRS contained a right-handed Cartesian coordinate system whose axes were aligned with, and defined, the three reference planes of movement (i.e. sagittal, frontal and transverse planes) for the segment [355]. The LSRS also indicated the origin of a particular position of the anatomical segment. The LSRS was represented mathematically by a *transform matrix*, which was a mathematical method of describing the position and orientation of an anatomical segment in space [354]. The transform matrix is described below. Figure A-7 shows pictorial examples of LSRSs for the arm and forearm.

A.3.3 THE ROTATION AND TRANSFORM MATRIX

The LSRS attached to an anatomical segment gives a description of the segment's coordinate system *relative* to the GRS [354]. For example, if coordinate system {A} was the fixed reference frame of the GRS, and {B} was a right-handed Cartesian coordinate system attached to a moving anatomical segment, then a description of the moving coordinate system {B} relative to the fixed GRS {A} would give the orientation of the anatomical segment relative to the GRS. The unit vectors ($\hat{X}_B, \hat{Z}_B, \hat{Y}_B$) for the principal axes {B} can be written in terms of the coordinate system {A}, ${}^A\hat{X}_B, {}^A\hat{Z}_B, {}^A\hat{Y}_B$. These three unit vectors for the columns of a 3 x 3 matrix called the *rotation matrix*. The rotation matrix defines {B} relative to {A} and the notation suggested by Craig [354] uses ${}^A_B R$:

$$ {}^A_B R = \left[\begin{array}{c|c|c} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{array}\right] $$

where the scalars $r_{i,j}$ are projections of that vector onto the unit directions of the reference frame. Hence, ${}^A_B R$ can be written as the dot product of unit vectors as:

$$ {}^{A}_{B}R = \left[\begin{array}{c|c|c} \hat{X}_B \cdot \hat{X}_A & \hat{Y}_B \cdot \hat{X}_A & \hat{Z}_B \cdot \hat{X}_A \\ \hat{X}_B \cdot \hat{Y}_A & \hat{Y}_B \cdot \hat{Y}_A & \hat{Z}_B \cdot \hat{Y}_A \\ \hat{X}_B \cdot \hat{Z}_A & \hat{Y}_B \cdot \hat{Z}_A & \hat{Z}_B \cdot \hat{Z}_A \end{array}\right] $$

Equation A-1 – Rotation matrix

The dot product of two vectors is defined as: [593]:

$$ A \cdot B = |A||B| \cos\theta $$

Equation A-2 – Dot product of two vectors

As unit vectors are equal to one, both $|A|$ and $|B|$ are equal to one: therefore, the dot product of two unit vectors yields the cosine of the angle between them. If the vectors are orthogonal then the dot product will be zero. The rotation matrix is sometimes called the direction-cosine matrix [354].

The three columns of the rotation matrix define the principal unit vectors of {B} relative to {A}, and the three rows are the principal unit vectors of {A} expressed in {B}. Furthermore, the unit vectors are orthogonal. Hence, {A} can be defined relative to {B} as:

$$ {}^{B}_{A}R = {}^{A}_{B}R^{T} $$

and ${}^{A}_{B}R^{T}\ {}^{A}_{B}R = I$ where I is the identity matrix. Hence,

$$ {}^{A}_{B}R = {}^{B}_{A}R^{-1} = {}^{B}_{A}R^{T} $$

Equation A-3 – Inverse rotation matrix

The rotation matrix can be used to describe a vector that is defined in reference frame {B}, relative to {A}. A vector ${}^{B}P$ describes a point relative to reference frame {B}. This vector is be *mapped* onto the reference frame {A} by:

$$ {}^{A}P = {}^{A}_{B}R\,{}^{B}P $$

which describes the same point in space, but relative to the reference frame {A}. However, the origin of reference frame {B} is often not located at the same position of the origin of {A}. Therefore,

$$^{A}P = {}^{A}_{B}R\,{}^{B}P + {}^{A}P_{Borg}$$

Equation A-4 – Vector mapping

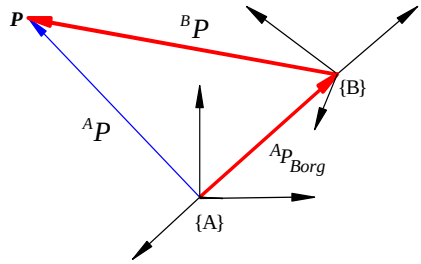


Figure A-9 – Vector mapping or change of reference.

(Modified from [594])

where $^{A}P_{Borg}$ is the vector from the origin of {A} to the origin of {B}. This equation simplifies to:

$$^{A}P = {}^{A}_{B}T\,{}^{B}P$$

Equation A-5 – Vector mapping with a transform matrix

where $^{A}_{B}T$ represents a 4 x 4 matrix termed a *homogeneous transform* or *transform matrix* [354]. The transform matrix is the description of a local reference system and describes the unit vectors and the origin of {B} relative to {A}. When a transform matrix is attached to an anatomical segment, it provides a mathematical description of the position and orientation of that segment relative to the global reference system (GRS). The local segment reference system (LSRS) of an anatomical segment is simply a transform matrix that is attached to the segment. The orientation of the axes of the LSRS or transform matrix are aligned with, and define, the three reference planes of movement (i.e. sagittal, frontal and transverse planes) for the segment [355]. The transform matrix is defined as:

$$ {}^{A}_{B}T = \left[\begin{array}{ccc|c} & {}^{A}_{B}R & & {}^{A}P_{Borg} \\ \hline 0 & 0 & 0 & 1 \end{array}\right] $$

Equation A-6 – The transform matrix

The inverse of ${}^{A}_{B}T$ is ${}^{B}_{A}T$ or ${}^{A}_{B}T^{-1}$ and provides a description of {A} relative to {B}:

$$ {}^{B}_{A}T = {}^{A}_{B}T^{-1} = \left[\begin{array}{ccc|c} & {}^{A}_{B}R^{T} & & -{}^{A}_{B}R^{T}\,{}^{A}P_{Borg} \\ \hline 0 & 0 & 0 & 1 \end{array}\right] $$

Equation A-7 – Inverse transform matrix

A.3.4 TRANSFORMATION ARITHMETIC

It is also possible to describe a LSRS transform matrix relative to another LSRS transform matrix. This allows analysis of the relative motion between the two LSRS or, in clinical terms, the relative clinical motions (displacement and angular rotations) of two anatomical segments. If the two anatomical segments are adjacent to one another, then the change in orientation between the two LSRSs describes the clinical rotations of the common joint. For example, if coordinate system {A} was the fixed reference frame of the GRS, {B} was a LSRS transform matrix attached to the arm anatomical segment, and {C} a LSRS transform matrix attached to the forearm anatomical segment, then a description of the moving frame {C} relative to the frame {B} would give the orientation of the forearm relative to the arm, or angular rotations about the elbow joint. The {A}, {B} and {C} LSRSs are indicated in Figure A-7 and Figure A-8.

Suppose there is a point in space that is defined by the vector ${}^{A}P$, relative to the GRS. To define the same point in space, but relative to the arm {B} and forearm {C}, this vector can be mapped onto the segment LSRSs with the transform matrices:

$$ {}^{A}P = {}^{A}_{B}T\,{}^{B}P $$
$$ {}^{A}P = {}^{A}_{C}T\,{}^{C}P $$

It is possible to define the forearm vector ${}^{C}P$ relative to the arm {B} LSRS:

$${}^{B}P={}^{B}_{A}T\,{}^{A}P$$

and substituting ${}^{A}P$ with ${}^{A}P={}^{A}_{C}T\,{}^{C}P$ the equation now becomes:

$${}^{B}P={}^{B}_{A}T\,{}^{A}_{C}T\,{}^{C}P$$

This equation can be simplified by:

$${}^{B}P={}^{B}_{C}T\,{}^{C}P$$

where ${}^{B}_{C}T$ is defined as:

$${}^{B}_{C}T={}^{B}_{A}T\,{}^{A}_{C}T={}^{A}_{B}T^{-1}\,{}^{A}_{C}T$$

Equation A-8 – Transform matrix arithmetic

The transform matrix ${}^{B}_{C}T$ provides a mathematical description of the position and orientation of the distal forearm LSRS {C}, relative to the proximal arm LSRS {B}. From the transform matrix, the angles of rotation about the principal axes can be derived to describe the clinical rotations of the forearm relative to the arm. This is discussed in the next section.

The angular rotations that can be derived from the transformation matrix ${}^{B}_{C}T$, describe the change in orientation of the distal forearm segment {C} relative to the arm {B}, *assuming* that the LSRSs are exactly coincident before any motion occurs. In this situation, the transform matrix ${}^{B}_{C}T$ completely describes the position and orientation motion of the forearm relative to the arm. However, it is rare that the LSRSs of two adjacent anatomical segments are exactly aligned before motion occurs. Therefore, it is necessary to describe the motion of the forearm {C} LSRS transform matrix relative to the arm {B} LSRS transform matrix with reference to the initial starting orientations of the two segments. Bull et al. [595] described a method for derivation of knee motion from two LSRSs that were not exactly aligned before motion occurred. This method is repeated here, but applied to the forearm anatomical segment {C} and arm segment {B} and in a slightly modified form.

Using the derivation applied above, the position and orientation of the forearm {C} relative to the arm {B} at the start position is:

$${}^{B}_{C}T_{S} = {}^{A}_{B}T_{S}^{-1}\,{}^{A}_{C}T_{S}$$

where *s* indicates that the anatomical segment's transform matrix is at the *start* position. Similarly, the position and orientation of {C} relative to {B} at the later position after movement has occurred is:

$${}^{B}_{C}T_{L} = {}^{A}_{B}T_{L}^{-1}\,{}^{A}_{C}T_{L}$$

where $_{L}$ indicates that the anatomical segment's transform matrix is at the *later* position. To find the change in orientation from the starting positions to the later positions of the forearm segment {C} relative to the arm segment {B} is:

$${}^{B}_{C}T_{S\to L} = {}^{B}_{C}T_{S}^{-1}\,{}^{B}_{C}T_{L}$$

Equation A-9 – Start and later position transform matrix comparison

where $_{S\to L}$ indicates that it is the transform matrix from the start position to the later position, or the later position relative to the start position.

A.3.5 EULER AND CARDAN ANGLES

The LSRS transform matrix attached to an anatomical segment, completely describes the location and orientation of the segment, relative to the global reference system (GRS). However, this information does not easily convey the clinical orientation of the segment. Another method of defining the orientation of the LSRS relative to the GRS is to perform three sets of rotations in sequence about the axes of the moving frame {B}. Assume that the moving frame {B} starts coincident with a fixed frame {A}. Rotate {B} about the $\hat{Z}_B$ by an angle α, then rotate {B} about the new $\hat{y}'_B$ by an angle β, and finally about the twice changed $\hat{x}''_B$ by an angle γ. Each rotation is performed about an axis of the moving reference frame {B} [354]. For each rotation a prime′ is added to each axis with each rotation. Therefore, the rotation matrix of the moving frame {B} at the start, when coincident with {A}, and end {B}″ of the three successive rotations about the Zy′x″ axes is:

$$
{}^{A}_{B}R(Zy'x'')(\alpha,\beta,\gamma) = R_Z(\alpha)R_Y(\beta)R_X(\gamma) = \begin{bmatrix} c\alpha & -s\alpha & 0 \\ s\alpha & c\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} c\beta & 0 & s\beta \\ 0 & 1 & 0 \\ -s\beta & 0 & c\beta \end{bmatrix}\begin{bmatrix} 0 & 0 & 0 \\ 0 & c\gamma & -s\gamma \\ 0 & s\gamma & c\gamma \end{bmatrix}
$$

$$
= \begin{bmatrix} c\alpha c\beta & c\alpha s\beta s\gamma - s\alpha c\gamma & c\alpha s\beta c\gamma + s\alpha s\gamma \\ s\alpha c\beta & s\alpha s\beta s\gamma + c\alpha c\gamma & s\alpha s\beta c\gamma - c\alpha s\gamma \\ -s\beta & c\beta s\gamma & c\beta c\gamma \end{bmatrix}
$$

Equation A-10 – Cardan/Euler Zy′x′′ angle sequence composition.

(From [354])

where *c* and *s* represent cosine and sine respectively.

In FWAP-Link, the ETS sensor orientation data was output as a Cardan angle rotation sequence of Zy′x′′ or azimuth, elevation, and roll. Equation A-10 was used by the FWAP-Link program to convert the orientation data from the ETS sensors to a transform matrix.

There are several ways of rotating the moving frame {B} relative to {A} to achieve a new orientation. The Cardan angles involve rotations about all three axes of the moving frame (e.g., Zy′x′′ or Yz′x′′). Euler angles involve rotations about one axis, rotation about another axis and rotation about the first rotated axis, again (e.g., Zy′z′′ or Xz′x′′). In total there are twelve angle set conventions (six Cardan and six Euler) for performing the three rotations about different axes of the moving frame {B} to orient {B} relative to {A}.

It is also possible to extract from a rotation matrix three Cardan or Euler angles that describe the orientation of the moving frame {B} for a given sequence of rotations. For the example given above for a Cardan rotation sequence of Zy′x′′, the angles α,β,γ can be derived as follows:

$$
\begin{aligned}
\beta &= a\sin(-r_{31}) \\
\alpha &= a\tan 2(r_{21}, r_{11}) \\
\gamma &= a\tan 2(r_{32}, r_{33})
\end{aligned}
$$

Equation A-11 – Euler/Cardan Zy′x′′ angle set decomposition

where, $a\tan 2(y,x)$ computes $\tan^{-1}(y/x)$ and the signs of both x and y determine the quadrant in which the resulting angles lies [354].

The angle β must be $-90.0 < \beta < 90.0$. At values of $\beta = \pm 90.0^{\circ}$ it is possible to derive a solution to the above rotation matrix but large errors can occur. This is because of gimbal-lock. Gimbal-lock describes the situation when the first and third axes of rotation coincide when the second rotation is +90 deg or –90 deg (for any order of three different rotation axis – the Cardan angle sets) or 0 deg or 180 deg (for any order of rotations with the first and third rotation about the same initial axis – the Euler angle sets) and no solution can be found for the decomposition into Cardan or Euler angles. Close to the gimbal-lock position (roughly within 20 deg) the rotations becomes very sensitive to measurement errors, and these errors will be amplified and large inaccuracies of the first and third rotations will result [596]. The first and third rotations do not have the same limitations to range-of-motion as the second rotation; they can vary between $\alpha, \gamma = \pm 180.0^{\circ}$. As a result of the gimbal-lock problem, it has been suggested assigning the axis with the largest expected angular range-of-motion to the first rotation [496].

A major disadvantage of using the Euler/Cardan angles is the dependence of results from the chosen angle set convention or sequence of rotations [355]. Different values of joint angulation will be calculated from identical attitudes for different user selected sequences of rotation [597]. Several angle set conventions have been used in biomechanics [356] and there is often no particular reason to favour one convention over another [354]. Generally, it does not matter which sequence of Euler/Cardan angles is used. Small angles have essentially the same values regardless of the sequence of rotations [496]. However, for larger angular motions, there can be large differences between the angular rotations derived from different angle set conventions [598].

A.3.6 JOINT COORDINATE SYSTEM

Grood and Suntay [356] reported a modified Euler/Cardan system for determining joint kinematics of the knee. This system was called a *joint coordinate system* (JCS). The major advantage of this system was that the derived angles were independent of the order in which the component rotations occurred, i.e. the JCS, unlike the Euler/Cardan methods, was not sequence dependent.

The JCS was used with the FWAP-Link program to determine the posture of the anatomical segments measured with the ETS sensors. Nineteen posture angles were derived using the JCS method. These posture codes are described in Ch. 3, Sec. 3.3.2. The FWAP-Link JCS coordinate axes and anatomical locations used to derive them, are defined below in Table A-2 and Table A-3.

The JCS system derives the clinical rotations of a distal segment {C} relative to a proximal segment {B} about a shared joint between the two segments. The orientation and location of a distal {C} and proximal {B} segment can be defined relative to the GRS by the respective LSRS transform matrices that are embedded in the anatomical segments. The JCS derives joint motion angles from two axes fixed within the anatomical segment LSRSs, both proximal and distal, and a floating axis. The JCS angles are anatomically meaningful; rotations about the defined fixed and floating axes match the clinical definitions for relative movement between two anatomical segments [355].

The JCS axes three lines in space whose orientation is to be specified relative to some physical objects, whose relative motion is to be described [357]. The three rotation axes comprise the JCS. Motion about these axes describes the rotations of the distal segment {C} relative to the proximal segment {B}, assuming that the proximal and distal segments are aligned before any motion occurs. The three rotation axes are unit vectors that are non-orthogonal (unlike the Euler/Cardan and rotation matrix described above) and define the coordinate system. They are denoted as $\mathbf{e_1}$, $\mathbf{e_2}$ and $\mathbf{e_3}$. Two of the axes, called *body fixed axes*, are embedded in the two bodies whose relative motion is to be described. Their direction is specified as unit vectors $\mathbf{e_1}$ in the proximal body B, and $\mathbf{e_3}$ in distal body C. The fixed axes move with the segment bodies. It is important that the two body fixed axes are selected so that rotations about them correspond to physically meaningful motions [357]. The third axis is the common perpendicular to the body fixed axes. Its orientation is given by the cross product of the body fixed axes and is referred to as the *floating axis,* $\mathbf{e_2}$. This axis, not fixed to either body, moves relative to both:

$$e_2 = \frac{e_3 \times e_1}{|e_3 \times e_1|}$$

Equation A-12 – Floating axis from the vector cross product of two body fixed axes

where e_3, e_1 are unit vectors of:

$$e_3 = a_1 i + a_2 j + a_3 k$$
$$e_1 = b_1 i + b_2 j + b_3 k$$

and the vector cross product of $e_3 \times e_1$ is:

$$e_3 \times e_1 = (a_2 b_3 - a_3 b_2) i + (a_3 b_1 - a_1 b_3) j + (a_1 b_2 - a_2 b_1) k$$

Equation A-13 – Vector cross product derivation

The two relative rotations between the bodies about the fixed axes are measured by the angles α, γ that are formed by the floating axis and reference lines embedded in each segment. The direction of the reference lines $e_1^{\,r}, e_3^{\,r}$ are perpendicular to the fixed reference axes and are aligned with axes of the LSRSs. The third rotation β occurs about the floating axis between the two body fixed axes:

$$\cos\beta = e_1 \cdot e_3$$

The application of the JCS to the knee joint was described in detail by Grood and Suntay [356]. This is repeated here because exactly the same description of the body fixed axes and reference axes were applied to other anatomical regions with FWAP-Link.

For the proximal anatomical segment {B} the axes I, J, K represent the base unit vectors of the Cartesian LSRS and for the distal anatomical segment {C} the axes i, j, k represent the base unit vectors of the embedded LSRS. The Cartesian LSRS is embedded in the anatomical segment such that K and k is positioned along the longitudinal axis of the segment pointing up, J and j is pointing forward, I and i is pointing to the right. The body fixed axes and reference lines are aligned with the proximal and distal LSRSs as follows:

$e_1 = I$

$e_3 = k$

$e_1^{\,r} = J$

$e_3^{\,r} = j$

e₁ and **e₃** and the reference lines $e_1^{\,r}, e_3^{\,r}$ are indicated on the segment LSRSs in Figure A-10:

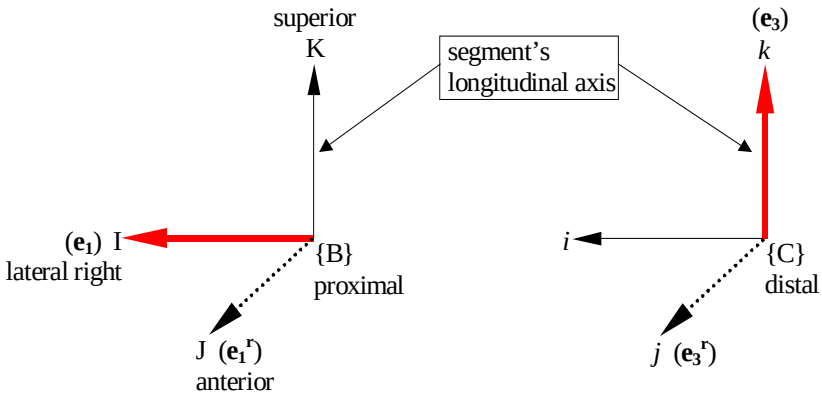


Figure A-10 – Cartesian coordinate systems defined in each anatomical segment for the joint coordinate system (JCS)

The three angle rotations about the JCS rotation axes **e₁**, **e₂** and **e₃** are shown in Figure A-11:

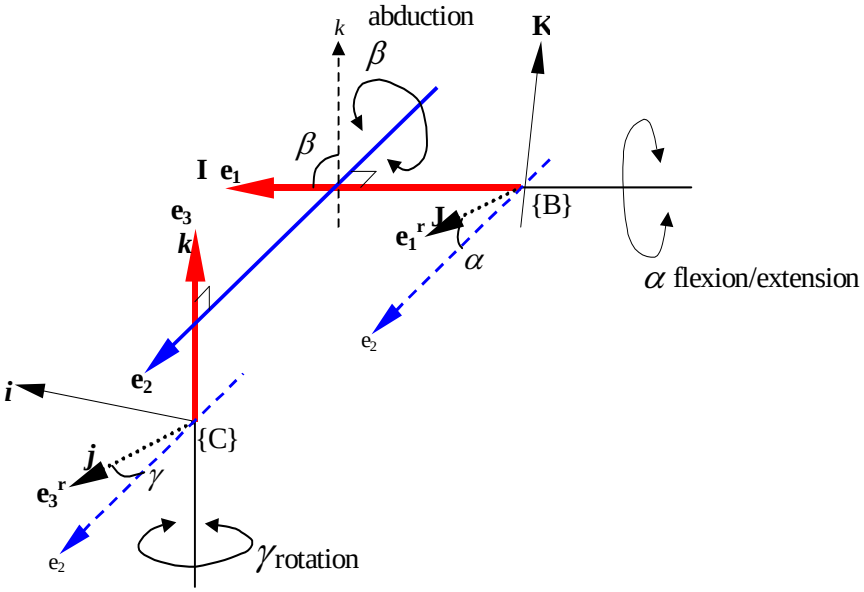


Figure A-11 – The three joint coordinate axes used in the JCS (rotations about the axes e_1, e_2 and e_3 define the joint rotation angles.

α, β, γ (From [356])

where α, β, γ represent the clinical rotations of flexion/extension, adduction/abduction and rotation, respectively. Flexion/extension occurs about the I or $\mathbf{e_1}$ body fixed axis in the proximal segment in the sagittal plane; abduction/adduction occurs about the floating axis $\mathbf{e_2}$ in the frontal plane; and rotation occurs about the k or $\mathbf{e_3}$ body fixed axis in the distal segment in the transverse plane. The magnitude of the rotation angles can be easily derived from the dot product between the floating axis and the reference axes, and the two body fixed axes:

$$\cos\alpha = e_1^{\,r} \cdot e_2 = \textit{flexion/extension}$$
$$\cos\gamma = e_3^{\,r} \cdot e_2 = \textit{rotation}$$
$$\cos\beta = I \cdot k = \textit{abduction/adduction} + \pi/2$$

Equation A-14 – Joint Coordinate System (JCS) rotations about three rotation axes

The clinical rotations flexion, adduction and right rotation for the right knee are positive. To derive the sign and magnitude of the clinical rotations the following equations are used:

$$e_2 \cdot K = -\sin\alpha = \textit{flexion/extension}$$
$$e_2 \cdot i = -\sin\gamma = \textit{rotation}$$
$$\beta - \pi/2 = \textit{abduction/adduction}$$

Equation A-15 – JCS clinical angular rotation derivations

It is also possible to derive the JCS angular rotations from a 3x3 rotation matrix that describes the orientation of the distal segment {C} relative to the proximal segment {B} where:

$$\underset{C}{^{B}}R = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix}$$

and

$$\alpha = \textit{flexion/extension} = a\tan 2(r_{23}, r_{33})$$
$$\beta = \textit{adduction/abduction} = a\cos(r_{13} - \pi/2)$$
$$\gamma = \textit{rotation} = a\tan 2(r_{12}, r_{11})$$

Equation A-16 – JCS clinical angular rotation derivations from a rotation matrix.

(From [356]).

where –90.0 deg< β <90.0 deg. Similarly to the Euler/Cardan conventions, the JCS suffers from problems of gimbal-lock when β is ± 90.0 [597]. Also, a sequence effect is imposed by the choice of imbedded and floating axis. Different numerical results may be obtained for specific joint attitudes given identical segment LSRSs, but different choices for the floating and imbedded axes [597].

A.3.7 TECHNICAL REFERENCE SYSTEM

The LSRS transform matrix for an anatomical segment is derived from the *technical reference system*, which for FWAP-Link is simply the reference system (or data output) of the ETS sensor attached to the anatomical segment. The ETS sensors output the Cardan angle rotation sequence of Zy′x″ or azimuth, elevation, and roll [587]. These three angle values were converted to a technical reference system rotation matrix using Equation A-10 given above.

The technical reference system rotation matrix was used to develop a segment's LSRS using *anatomical landmarks*. The offsets of the anatomical landmarks from the ETS sensor were used with vector analysis [593] to develop the LSRS. The coordinates of at least three noncolinear anatomical landmarks were required to fix the LSRS to the segment [355,599]. The anatomical landmarks used in the FWAP-Link system are defined below in Sec. A.4.

A.4 FWAP-LINK LOCAL SEGMENT REFERENCE SYSTEMS (LSRS)

A.4.1 FWAP-LINK ANATOMICAL LANDMARKS

The following anatomical landmarks were used with FWAP-Link:

Anatomical Segment	Anatomical Landmark	Description
Hips	HPL	Greater trochanter left side.
	HPR	Greater trochanter left side.
	*HP**	Derived location at mid-point between HPL and HPR.
Head	ML	Anterior part of the left mastoid process.
	MR	Anterior part of the right mastoid process.
	*HC**	Derived location of head centre at mid-point between ML and MR from head sensor.
	EY	Outer canthus of the eye.
	*NL**	Derived location approximately at the nose-lip intersection. Offsets determined initially at rest posture.
Neck	C7	Spinous process of vertebra C7.
	CH	Jugular notch at the level of the frontal cervical groove above the head of the clavicle.
	HC_2*	Derived location at head centre, between ML and MR. Vector from the neck sensor to HC_2, which at the start posture was HC determined from the head sensor.
	*NC**	Neck centre at mid-point between C7 and CH.
Spine	PX	Most caudal point on the sternum.
	T5	Spinous process of vertebra T5.
	*SC**	Derived location of upper thoracic spine centre. 35% along a vector from T5 to PX.
Arm	AC	Most dorsal point on Acromioclavicular joint (shared with clavicula).
	TS	Trigonum Spinae Scapulae, mid point of triangular surface on medial border of the scapula in line with the scapular spine.
	AI	Angulus Inferior, most caudal point of scapula.
	AA	Angulus Acromialis, most latero-dorsal point of scapula.
	PC	Most ventral point of processus coracoideus.
	*GH**	Derived location of glenohumeral rotation centre, estimated by regression [599].
	EM	Most caudal point on Medial Epicondyle.
	EL	Most caudal point on Lateral Epicondyle.
Forearm	US	Most caudo-medial point on ulnar styloid.
	RS	Most caudo-lateral point on radial styloid.
	TM_2	Most distal point of the third metacarpal on the ulna side. Vector from the forearm sensor to TM_2, which at the start posture was TM determined from the wrist sensor.
	UP_2	Midpoint between the distal ulna and the pisiform's volar edge. Vector from the forearm sensor to UP_2, which at the start posture was UP determined from the wrist sensor.
	CA_2	Depression in wrist over the capitate bone, approximately at the radius head. Vector from the forearm sensor to CA_2, which at the start posture was CA determined from the wrist sensor.
	CTR_2*	Derived location of wrist centre, from intersection of a plane through TM and CA and perpendicular to UP. Vector from the forearm sensor to CTR_2, which at the start posture was CTR determined from the wrist sensor.
Wrist	TM	Most distal point of the third metacarpal on the ulna side, from wrist sensor
	UP	Midpoint between the distal ulna and the pisiform's volar edge from wrist sensor.
	CA	Depression in wrist over the capitate bone, approximately at the radius head from wrist sensor.
	*CTR**	Derived location of wrist centre, from intersection of plane between TM and CA and perpendicular to UP from wrist sensor.

Table A-2 – Anatomical landmarks used to derive the local segment reference systems (* indicates that the anatomical location was determined through vector analysis and not physically measured)

A.4.2 FWAP-LINK LOCAL SEGMENT REFERENCE SYSTEMS

Definitions of the axes of the local segment reference systems (LSRS) at the rest or reference posture:

LSRS	Axis	Definition	Direction
Head (h)	Xh	(MR – HC) / | MR – HC |	Right lateral
	Yh	(NL – HC) / | NL – HC|	Anterior
	Zh	Xh x Yh	Superior
	O	HC	Origin
Neck (n)	Xn	(C7 – HC2) x (CH – HC2) / |(C7 – HC2) x (CH – HC2)|	Right lateral
	Yn	Zh x Xh	Anterior
	Zn	(HC2 – NC) / | HC2 – NC |	Superior
	O	NC	Origin
Arm1 (a1)	Xa1	Ya1 x Za1	Right lateral
	Ya1	Za1 x (EL – EM) / | Za1 x (EL – EM) |	Anterior
	Za1	(GH – [EL + EM] / 2) / | GH – [EL + EM] / 2 |	Superior
	O	GH	Origin
Arm2 (a2)	Xa2	Za2 x Zf (note: Zf is the forearm Z axis)	Right lateral
	Ya2	Za2 x Xa2	Anterior
	Za2	(GH – [EL + EM] / 2) / | GH – [EL + EM] / 2 |	Superior
	O	GH	Origin
Forearm (f)	Xf	Yf x Zf	Right lateral
	Yf	(US - [EL+EM]/2 x RS - [EL+EM]/2) / | US - [EL+EM]/2 x RS - [EL+EM]/2 |	Superior
	Zf	([EL+EM]/2 - [RS+US]/2) / | [EL+EM]/2 - [RS+US]/2 |	Posterior
	O	[RS+US]/2	Origin
Ulna (u)	Xu	Yu x Zu	Right lateral
	Yu	Zu x (EL-EM) / | Zu x (EL-EM) |	Superior
	Zu	([EL+EM]/2 - US) / | [EL+EM]/2 – US |	Posterior
	O	US	Origin
Radius (r)	Xr	Yu x Zu	Right lateral
	Yr	Zr x (US-RS) / | Zr x (US-RS) |	Superior
	Zr	(EL - RS) / | EL - RS |	Posterior
	O	RS	Origin
Wrist (w1)	Xw1	(UP - CTR) / | UP - CTR |	Right lateral
	Yw1	Zw1 x Xw1	Superior
	Zw1	(CA - TM) / | CA - TM |	Posterior
	O	CTR	Origin
Forearm Wrist (w2)	Xw2	(UP2 – CTR2) / | UP2 – CTR2 |	Right lateral
	Yw2	Zw2 x Xw21	Superior
	Zw2	(CA2 – TM2) / | CA2 – TM2 |	Posterior
	O	CTR2	Origin

Table A-3 – Definition of the axes of the local segment reference system for each anatomical segment (determined when the participant was in the start posture). 'x' indicates the cross product of two vectors

A.4.3 ANATOMICAL SEGMENT DESCRIPTION

A.4.3.1 GENERAL DESCRIPTION

The use of a joint coordinate system (JCS) to derive clinical rotations about a joint has been recommended by the International Society of Biomechanics (ISB) for the reporting of kinematic data [600]; the reporting of human joint motion for the ankle, hip and spine [601]; and for most joints of the upper extremity in the shoulder, elbow, wrist and hand [602]. The FWAP-Link system followed the ISB recommendations for the orientation of the three JCS joint rotation axes. In all anatomical segments (except for trunk motions, shoulder elevation and dorsal/ventral motion, and forearm pronation/supination) the first axis $\mathbf{e_1}$ was fixed to the proximal segment and was perpendicular to the sagittal plane pointing laterally and measured flexion/extension, the third axis $\mathbf{e_3}$ was fixed to the longitudinal axis of the distal segment pointing superiorly and was perpendicular to the transverse plane and measured rotation, and the floating axis $\mathbf{e_2}$ was perpendicular to e_1 and e_3 pointing anteriorly approximately perpendicular to the frontal plane and measured abduction/adduction. The FWAP-Link system fixed the LSRS to the anatomical segments similarly to that suggested by Grood and Suntay [356] (see Figure A-11). This was not the same as the ISB recommendations. However, the three rotation axes that comprise the JCS are similarly oriented to the recommendations of the ISB, and therefore the JCS measured angular orientation of a joint in the same manner. Also, flexion/extension was one of the largest angular rotations undertaken by most joints and by assigning this motion to the first rotation axis, the FWAP-Link JCS followed the recommendations of McGill et al. [496].

Each anatomical segment's LSRS at the **start** or neutral posture was measured and stored for comparison or reference purposes. These LSRS were recorded as the **start** LSRSs. The anatomical segments LSRSs during analysis, when the participant was not in the rest posture, were referred to as the **later** LSRSs and were compared with the start LSRSs to determine the posture of the participant.

For the **start posture**, participants assumed an upright seated posture, with the trunk in a vertical orientation and looking straight ahead. The right arm was placed next to the upper torso, in a vertical orientation pointing inferiorly. The forearm was flexed at 90 deg, such that it was placed in a horizontal orientation, pointing anteriorly. The forearm

was also pronated so that the palm was facing down. The wrist, hand and fingers were aligned with the longitudinal axis of the forearm.

A.4.3.2 TRUNK

The trunk FWAP-Link codes **SFH** and **SSH** measured the amount of trunk movement ventral/dorsal and to the sides of the hips, respectively. These angles were determined by the location of the ETS neck sensor compared with the anatomical landmark HP, which was the mid-point between the left and right hip greater trochanters. At the start posture, the angle between the ETS neck sensor and HP was recorded. All subsequent later postures were measured as the angle of the ETS neck sensor compared with HP with reference to the start posture trunk angles.

The FWAP-Link code **C** measured the angle of trunk curvature, or amount of upper torso 'slump'. This code was derived as the angle between the vectors from the mid-hips (HP) to the Spine Centre at T5-6 (SC), and from SC to the Neck Centre at C7-T1 (NC). The neck centre (SC) and spine centre (NC) locations were determined according to Harms-Ringdahl [410]. Harms-Ringdahl [410] measured upper thoracic movements about the vertebrae T5-6 and C7-T1 and defined the mid-neck as the mid-point between the C7 spinous process and the frontal cervical groove above the head of the clavicle [410]. The motion axis of the vertebrae T5-T6 was located at 35% along a vector from the T5 spinous process to the sternum (PX). The trunk FWAP-Link code C was measured at the start posture, and all subsequent later postures were measured as deviations from the start posture angle.

The trunk FWAP-Link code **TR** measured the amount of trunk rotation. This was determined by the amount of rotation of the neck LSRS, which was derived from the ETS neck sensor. The cosine angle (dot product) between the Y axis of the global reference system (GRS) and the y axis of the neck's LSRS measured the amount of rotation of the neck LSRS about the GRS in the transverse plane:

$$TR_L = (a\cos({}^{G}Y \cdot {}^{G}_{N}y) - \pi/2) - TR_S$$

Equation A-17 – Equation used to determine the amount of FWAP-Link trunk rotation

where G indicates the GRS and N indicates the neck LSRS, and $_S$ and $_L$ represent the start and later postures, respectively. This angle was measured at the start posture and

all subsequent later postures were measured as deviations from the start posture. It was assumed that the hips were completely stationary, but as there was no ETS sensor to measure the hips, it is unknown how much hip movement actually occurred.

A.4.3.3 HEAD AND NECK

Harms-Ringdahl [410] identified that the bilateral motion axis of the head was located at the anterior part of the mastoid processes. This axis was used in this investigation. The anterior part of the left (ML) and right (MR) mastoid processes were measured. The mid-point between these locations was defined as the head centre (HC). At the start posture, an imaginary location at approximately the nose-lip intersection (NL) was determined from the vector cross product between vectors ML to MR and the global Z axis. The vector from HC to NL, at the start posture, was aligned exactly with the transverse plane (horizontal) and directed approximately along the negative global X axis (anteriorly directed). The head start posture LSRS was used as a reference for all subsequent later head postures.

By comparing the start and later head LSRSs, the FWAP-Link program determined the head angular rotations of flex/extension, lateral flexion and rotation relative to the *vertical*. This meant that if the trunk, or neck, flexed or tilted, but the head stayed in the same position relative to the neck and trunk, the head angular rotations would still change and indicate the head posture relative to the vertical. These absolute head posture angles constitute the FWAP-LINK angles HF, HR and HT. In addition, the head's start LSRS was rotated about the Z axis of the GRS by the amount of trunk rotation TR. This was to account for rotation of the trunk. If the trunk rotated and the head start LSRS was not rotated, then it would appear as if the head were rotating also, which would not be the case since the rotation was from the trunk. Hence, the head's start LSRS was rotated also to match trunk rotation.

In contrast, the FWAP-LINK angles HNF, HNT and HNR were determined from the head LSRS compared with the neck LSRS. This comparison measured the head posture relative to the neck posture. If the neck flexed, and the head position relative to the neck did not change, then these FWAP-LINK angles would also not change. The comparison of the head LSRS relative to the neck LSRS at the start posture, was used as a reference for the head relative to the neck LSRSs at the later postures.

A.4.3.4 SHOULDER AND ARM

Meskers et al. [599] reported a method for *in vivo* estimation of the glenohumeral joint rotation centre from scapular bony landmarks and linear regression. This method was used in this investigation to estimate the location of the glenohumeral joint rotation centre (GH). The GH location was subsequently used in the construction of the arm LSRS, with the other two bony landmarks of the arm, the medial and lateral epicondyles (EL and EM).

The location of GH was mapped to the neck LSRS. The cosine angles between the vector from the origin of the neck LSRS (C7) to GH and the z axis and y axis of the neck LSRS were determined to measure shoulder elevation and dorsal/ventral motion, respectively. The angle between the vector and the axes of the neck LSRS was measured at the start posture. All later postures were measured relative to the start posture. Because the vector from C7 to GH was used to determine the FWAP-LINK shoulder codes **RSEV** and **RSF**, shoulder elevation and shoulder ventral/dorsal angles were measured relative to the base of the neck at C7.

van der Helm and colleagues [596,602] reported a different description for the arm bone rotations than that used with this investigation. The authors [602] suggest a Yx′y″ Euler decomposition for the arm (humerus) relative to the thorax LSRS (there was no thorax LSRS in the FWAP-Link system), where the y axis is aligned with the longitudinal axis of the arm and the x axis points anteriorly (when the arm is in the start posture). The Euler's decomposition provides a description of the plane of elevation with respect to the thorax LSRS (first rotation), elevation/depression about the local x axis (second rotation) and axial rotation of the arm about the local y axis again (third rotation). This method of rotation matrix decomposition was chosen to avoid as much as possible, the problem of gimbal lock [596]. By using the Euler angles, the second rotation can vary between 0 and 180 deg, giving this method the best chance of avoiding gimbal lock for the wide range of motion of the arm.

In contrast, the FWAP-Link system used the JCS method as described above, which, to avoid gimbal lock, limited the amount of rotation about the second rotation axis to ± 90 deg. The second rotation axis measured arm abduction/adduction. Near the gimbal lock position (roughly within 20 deg) measurement errors will be amplified and large

inaccuracies of the first and third rotations will result [596]. Therefore, the FWAP-Link system was limited in measuring arm abduction/adduction to within approximately ± 70 deg. This restriction requirement did not present a limitation for postural analysis with the FWAP-Link system when analysis was completed for a specific research application described in Ch. 4. Participants involved in research in Ch. 4 were not required to complete arm abduction/adduction near ± 70 deg. Also, use of the JCS angle rotation sequence provided clinically meaningful postural information. If FWAP-Link were required to measure arm abduction/adduction greater than ± 70 deg, then the Euler angle rotation sequence described by van der Helm et al. [602] is the ISB recommended method.

FWAP-Link compared the start and later arm LSRSs to determine the angular rotations of the arm relative to the *vertical*. Because the start posture of the arm was in a vertical orientation, any changes from this position would be measured as relative to a vertical orientation. If there was trunk motion (e.g., trunk flexion or tilting), but the arm stayed in the same position relative to the trunk, then the arm angular rotations would change and indicate the arm posture relative to vertical. These absolute arm posture angles constitute the FWAP-LINK angles REFS, RERS and RDS. The arm's start LSRS was rotated about the Z axis of the GRS by the amount of trunk rotation TR. This was to account for rotation of the trunk. This is similar to the method used to determine the head FWAP-LINK angles relative to vertical.

A.4.3.5 FOREARM

Pronation-supination occurs between the radius and the ulna, and elbow flexion-extension occurs between the ulna and the humerus [603]. The ISB recommendations for angular motions of the forearm were used in the FWAP-Link system [602]. Angular motion of the ulna LSRS (u) relative to the arm_2 (a_2) LSRS was about the humero-ulna joint. Angular motion of the radius LSRS (r) relative to the ulna LSRS (u) was about the radio-ulna joint and measured forearm pronation/supination.

A.4.3.6 WRIST

In the FWAP-Link system, the behaviour of individual carpal bones was ignored and the forearm and hand were assumed to be rigid bodies for the purposes of determining

overall kinematics of the wrist [604]. The wrist behaves like a simple hinge joint during radius-ulna and flexion-extension motions, with the hinge axis essentially fixed in the forearm segment [604]. The centres of rotation for flexion-extension and radial-ulna deviation are located in the head of the capitate [605]. The centre of rotation for radial-ulna deviation is slightly to the ulna side of the longitudinal axis of the capitate and for flexion-extension is on the longitudinal axis of the capitate just distal to its proximal cortex [605].

The axis of radius-ulna deviation was derived as the vector along the ulna border of the 3rd metacarpal towards the distal radius [606]. The capitate bone occupies a central position in the wrist and when approached from the dorsum, a slight depression indicates its location [607]. The axis of motion for ulnar and radial deviation goes through this bone [607], directed towards the third metacarpal, and the vector from the anatomical landmarks TM (third metacarpal) to CA (capitate bone) was used as the axis of ulna-radial deviation [606].

A vector, that was perpendicular to the line from TM to CA and the forearm bones, was extended ulnarly, until it reached the midpoint between the distal ulnar and the pisiform's volar edge [606]. This vector, that went through the anatomical location of the mid-point of the ulnar and pisiform (UP), was perpendicular to a plane that went through the points TM and CA [593]. The plane was also perpendicular to the transverse plane. The intersection of the plane and the vector that was normal to the plane and went through UP, was nominated as the wrist centre (CTR) and lay approximately in the capitate bone. The vector that went from the wrist centre (CTR) to UP was used as the wrist flexion-extension axis [606].

The wrist LSRS (w_1) was derived from the wrist ETS sensor using the anatomical landmarks of TM, RH, UP and CTR. The forearm wrist LSRS (w_2) was derived from the forearm ETS sensor that determined the same anatomical locations of TM_2, RH_2, UP_2 and CTR_2, except that these anatomical locations were derived from offsets from the forearm sensor. The JCS comparison between the wrist LSRS (w_1) and the forearm wrist LSRS (w_2) derived the clinical rotations of wrist flexion and wrist ulna-radial deviation.

APPENDIX B

ADDITIONAL RESULTS (CHAP 5)

B.1 POSTURE RESULTS

B.1.1 POSTURAL CHANGES OVER TIME

The posture did not vary during the testing sessions; Table B-1 shows that at each hourly interval the posture of participants was similar. The mean difference in posture between the four one-hour blocks of assessment was 1.9 deg (range 0-8 deg).

		Time 1		Time 2		Time 3		Time 4		Maximum
No	Code	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Difference
1	SFH	7.7	6.8	8.0	8.3	6.8	9.2	7.9	9.1	1.3
2	SSH	1.5	3.8	2.2	4.9	2.8	5.4	2.8	5.6	1.3
3	TR	0.5	8.7	1.1	8.9	-0.3	9.1	0.8	8.8	1.4
4	C	9.6	13.2	11.5	12.6	10.9	14.3	10.2	14.3	1.9
5	HF	-16.2	8.7	-15.6	8.1	-17.0	8.2	-17.9	7.8	2.3
6	HR	-3.7	9.7	-3.7	10.4	-3.6	10.8	-3.2	10.9	0.5
7	HT	1.4	4.3	0.6	5.7	0.6	5.3	0.4	5.4	1.0
8	HNF	-29.7	13.5	-29.8	12.6	-28.9	13.2	-30.0	13.1	1.1
9	HNT	1.8	7.2	1.6	8.7	1.2	8.5	1.1	8.6	0.7
10	HNR	-2.9	9.9	-2.5	11.6	-2.5	11.8	-2.1	11.7	0.9
11	RSEV	8.8	6.2	8.6	5.8	8.5	5.3	8.3	5.5	0.5
12	RSF	6.1	6.4	5.7	6.8	7.1	7.1	6.3	7.4	1.4
13	REFS	53.1	17.5	48.9	18.6	52.7	17.5	50.7	18.5	4.3
14	RERS	29.7	18.3	30.1	17.0	29.8	17.0	29.0	16.4	1.1
15	RDS	-29.0	15.3	-25.9	15.5	-27.2	16.1	-25.6	16.2	3.4
16	RFX	160.2	29.8	151.9	17.5	157.8	17.2	154.1	17.9	8.2
17	RPR	-19.3	17.8	-19.1	16.6	-19.9	17.8	-19.3	17.7	0.7
18	REX	-27.1	11.3	-25.2	9.8	-25.3	9.3	-25.2	9.3	1.9
19	RDV	4.8	9.0	7.5	8.8	5.1	8.6	6.3	8.2	2.6
								Average:		1.9

Table B-1 – Average posture for each hour of measurement (hours 1 to 4) when the lights were off.

B.1.2 POSTURAL CHANGES

Table B-2 and Figure B-1 show the average number of postural changes of participants, which was determined by counting the number of times a participants posture entered a posture category (categories were based on 2 deg bin widths starting at 0 deg). The average time spent in each posture is shown in Table B-3.

In Figure B-1, the head and wrist had the highest number of postural changes during the light-off time. These regions were engaged in highly repetitive work actions and were

directly involved with the interaction of the body and the computer workstation, via the monitor and the mouse.

		Neck-mobile					Neck-static						
No	Code	Time 1	Time 2	Time 3	Time 4	Total	Time 1	Time 2	Time 3	Time 4	Total	All data	SD
1	SFH	17.6	20.9	18.5	18.9	19.0	16.2	21.3	17.4	18.5	18.3	18.7	15.1
2	SSH	16.7	18.4	17.8	16.5	17.3	14.4	16.8	15.9	16.7	15.9	16.6	13.0
3	TR	31.4	30.8	31.3	31.3	31.2	28.9	31.5	28.0	30.1	29.7	30.4	21.0
4	C	49.4	51.8	51.8	51.6	51.1	50.9	53.0	48.5	50.9	50.8	51.0	27.7
5	HF	68.7	66.5	67.8	62.5	66.4	63.1	68.0	60.3	61.0	63.1	64.7	38.1
6	HR	71.1	62.9	69.5	60.7	66.1	65.9	63.2	59.6	60.3	62.3	64.2	38.2
7	HT	48.0	48.5	48.7	45.6	47.7	43.5	46.7	44.4	44.5	44.8	46.3	28.4
8	HNF	79.4	76.4	77.0	71.8	76.1	73.8	78.7	69.1	69.7	72.8	74.5	43.1
9	HNT	47.7	47.2	49.0	46.2	47.5	45.2	48.0	44.3	44.8	45.6	46.5	28.3
10	HNR	71.4	64.6	70.5	61.8	67.1	67.4	65.4	62.3	62.5	64.4	65.7	39.7
11	RSEV	34.8	32.9	31.6	32.6	33.0	31.4	31.9	29.7	30.1	30.8	31.9	19.5
12	RSF	35.9	36.4	34.8	34.8	35.5	33.0	34.9	33.4	32.7	33.5	34.5	21.8
13	REFS	32.2	38.4	32.0	34.1	34.2	30.7	39.1	32.2	35.1	34.3	34.2	23.5
14	RERS	40.9	40.3	39.8	38.3	39.8	38.7	40.9	38.0	37.9	38.9	39.4	23.1
15	RDS	51.9	53.8	49.2	48.2	50.8	50.6	56.1	47.4	50.8	51.2	51.0	28.8
16	RFX	40.0	49.6	41.2	44.0	43.7	39.9	50.9	43.9	46.7	45.4	44.5	27.0
17	RPR	58.8	53.5	56.4	52.2	55.2	54.3	56.8	56.6	55.5	55.8	55.5	27.1
18	REX	60.0	57.0	58.0	56.1	57.8	63.8	59.9	62.9	60.7	61.8	59.8	27.2
19	RDV	79.7	61.6	80.8	64.7	71.7	84.2	63.6	84.2	74.2	76.6	74.1	31.8

Table B-2 – Average number of postural changes during 50 secs of data when the lights were off. Postural changes were classified by a scale with 2 deg bin widths starting at zero.

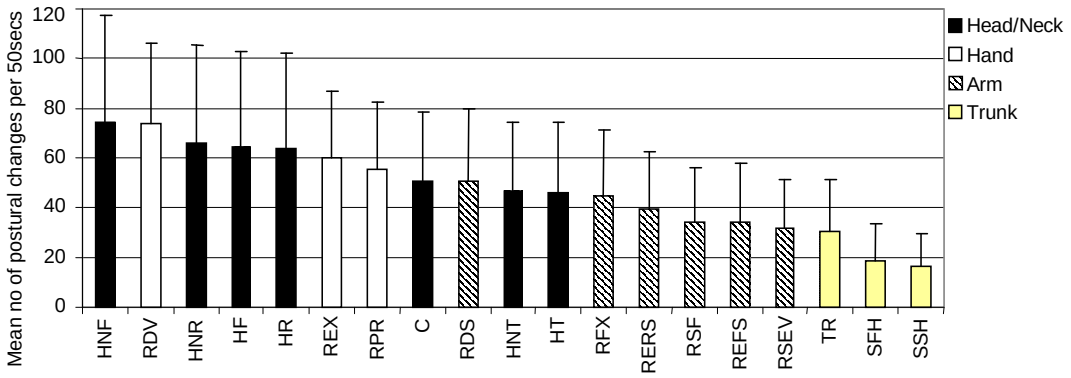


Figure B-1 – Average number of postural changes (>2 deg movements) per 50 secs when the lights were off. Error bars represent the SD.

		Neck-mobile					Neck-static						
No	Code	Time 1	Time 2	Time 3	Time 4	Total	Time 1	Time 2	Time 3	Time 4	Total	All data	SD
1	SFH	6.8	5.1	6.5	5.2	5.9	8.2	5.6	7.3	5.9	6.8	6.3	10.3
2	SSH	5.8	4.9	5.8	5.6	5.5	7.8	6.3	6.8	5.9	6.7	6.1	9.0
3	TR	3.2	3.2	3.9	3.5	3.4	3.4	2.8	3.4	3.1	3.2	3.3	6.2
4	C	1.8	1.5	1.8	1.7	1.7	1.5	1.4	2.0	1.7	1.7	1.7	3.5
5	HF	1.0	1.0	1.1	1.2	1.1	1.2	1.0	1.2	1.1	1.1	1.1	0.8
6	HR	1.0	1.2	1.1	1.2	1.1	1.2	1.0	1.1	1.1	1.1	1.1	1.0
7	HT	1.9	1.5	1.6	1.8	1.7	2.1	1.6	1.9	1.6	1.8	1.7	2.8
8	HNF	0.9	0.9	1.0	1.0	1.0	1.0	0.9	1.0	1.0	1.0	1.0	1.1
9	HNT	1.9	1.5	1.8	1.8	1.7	1.9	1.5	1.8	1.8	1.7	1.7	3.0
10	HNR	1.0	1.1	1.2	1.2	1.1	1.3	1.0	1.1	1.1	1.1	1.1	1.3
11	RSEV	2.9	2.8	3.0	2.9	2.9	3.4	2.8	3.0	3.2	3.1	3.0	6.0
12	RSF	2.5	2.7	3.2	3.3	2.9	3.9	3.1	3.0	3.4	3.4	3.1	6.5
13	REFS	3.0	2.2	2.9	2.4	2.6	3.7	2.0	2.8	2.8	2.8	2.7	4.8
14	RERS	1.8	1.8	2.1	1.9	1.9	2.4	1.7	2.1	2.0	2.1	2.0	3.1
15	RDS	1.4	1.3	1.5	1.4	1.4	1.5	1.2	1.6	1.4	1.4	1.4	1.4
16	RFX	1.9	1.4	1.8	1.7	1.7	2.1	1.4	1.7	1.7	1.7	1.7	2.4
17	RPR	1.2	1.3	1.2	1.3	1.2	1.2	1.1	1.1	1.1	1.1	1.2	1.0
18	REX	1.0	1.1	1.1	1.1	1.1	1.0	1.0	1.0	1.0	1.0	1.0	0.7
19	RDV	0.9	1.1	0.7	1.0	0.9	0.7	1.0	0.7	0.8	0.8	0.9	1.3

Table B-3 – Average time (secs) spent in each posture classification when the lights were off. Posture was classified with 2 deg bin widths.

B.1.3 POSTURE RESULTS ANALYSIS OF VARIANCE

Some posture codes demonstrated some change in posture over time. The post-hoc analysis is shown in Table B-4.

	Time 1	Time 2	Time 3	Time 4
Time0				
Time 1	--	REFS RFX RDV		RFX
Time 2		--	REFS RFX RDV	HF
Time 3			--	

Table B-4 – Post-hoc analysis of FWAP-Link posture codes for time of measurement (0 hr – 4 hr). Only differences of $p<0.01$ are shown.

B.1.4 POSTURE CORRELATION ANALYSIS

The correlation analysis of the posture codes revealed that some posture codes appeared to vary together (Table B-5). The association between some posture codes was as a result of the physical interaction of the participants with the work environment at the computer monitor and the mouse. The computer monitor and mouse had the effect of fixing the location and orientation of the eyes, head, and hand. The participants were 'free' to assume any posture so long as the head and hand fulfilled the task demands. Participants frequently varied the posture of various body-parts and because the location and orientation of the hand and head were relatively fixed, it was not possible to alter one body-part without changing the orientation of another.

In Figure B-2 the postures of the trunk, arm and elbow flexion are displayed for one participant during one measurement session. The posture codes appear to share a relationship, with major postural changes reflected in the graphs of the three posture codes at the same time. The correlation analysis indicated which posture codes were associated. The trunk, arm and forearm underwent postural changes together to provide support to the hand, and the posture of the neck, head and shoulder were associated to provide support to the head and eyes.

		Trunk				Head						Shoulder		Arm			Forearm		Wrist
		SFH	SSH	TR	C	HF	HR	HT	HNF	HNT	HNR	RSEV	RSF	REFS	RERS	RDS	RFX	RPR	REX
Trunk	SSH	-0.59*	--																
	TR			--															
	C	-0.56*			--														
Head	HF					--													
	HR			-0.65+			--												
	HT							--											
	HNF					0.76+			--										
	HNT							0.70+		--									
	HNR						0.91+				--								
Shoulder	RSEV					-0.67+						--							
	RSF						-0.62*						--						
Arm	REFS	-0.60*		0.54*	0.73*									--					
	RERS			-0.56*				-0.65+							--				
	RDS				-0.64+									-0.77+		--			
F/arm	RFX	-0.56*			0.60*									0.85+		-0.77+	--		
	RPR														-0.67+			--	
Wrist	REX																		--
	RDV						0.52*												

Table B-5 – Inter-relationship of the eighteen FWAP-Link posture codes. Only significant correlations are shown.

Figure B-2 shows the posture of one participant's trunk flexion, arm flexion and elbow flexion. These posture codes appear to share a relationship, with major postural changes reflected in the graphs of the three posture codes at the same time. These are shown at the dashed lines.

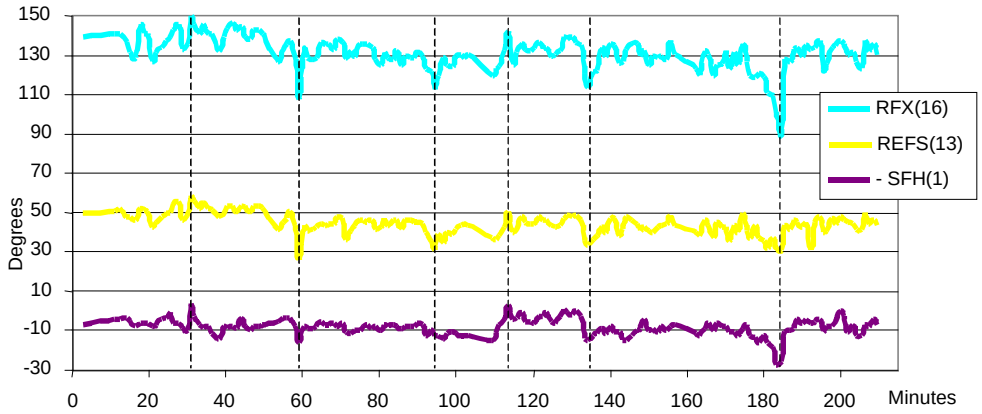


Figure B-2 – Average posture (per minute) of arm, elbow and trunk flexion/extension for one participant (not including the light-on posture data). The dashed lines show postural changes and the posture codes varying together. SFH has been inverted.

B.2 PRESSURE ALGOMETRY

B.2.1 TENDER POINT AND CONTROL POINT PRESSURE PAIN THRESHOLDS

B.2.1.1 SUMMARY OF TEP AND CP PPT RESULTS

One thousand and eighty pressure pain threshold (PPT) measurements were completed at eight tender points (TeP) and four control points (CP). The PPT results of each site are shown in Table B-6.

Neck Status	Time		Measurement Location												
			Right Upper Quadrant					Left Upper Quadrant					Lower TePs		Mean
			RThb	REpi	RDel	RTra	RSup	LSup	LTra	LDel	LEpi	LThb	RKne	LKne	
Neck Mobile	0 hr	Mean	70.1	22.2	42.7	26.6	41.0	42.7	27.3	45.7	31.2	60.1	45.7	50.3	42.1
		SD	27.0	4.5	12.8	16.2	13.6	17.2	13.5	13.8	19.0	19.6	9.0	10.9	20.4
		No	15	15	15	15	15	15	15	15	15	15	15	15	180
	2 hr	Mean	57.6	21.5	41.4	24.1	39.6	37.4	26.2	41.8	29.2	61.9	54.5	52.4	40.6
		SD	22.8	5.6	10.1	7.7	14.9	11.6	10.2	10.8	13.4	20.6	20.4	18.6	19.5
		No	15	15	15	15	15	15	15	15	15	15	15	15	180
	4 hr	Mean	58.8	19.9	37.6	22.9	36.5	37.4	28.2	44.6	25.6	62.5	43.1	46.4	38.6
		SD	22.9	6.9	9.9	7.8	13.1	17.0	13.2	11.1	8.7	22.1	10.0	10.9	18.5
		No	15	15	15	15	15	15	15	15	15	15	15	15	180
	Mean	Mean	62.1	21.2	40.6	24.5	39.0	39.2	27.2	44.1	28.6	61.5	47.7	49.7	40.5
		SD	24.4	5.7	11.0	11.2	13.7	15.4	12.1	11.8	14.2	20.4	14.6	13.8	19.5
		No	45	45	45	45	45	45	45	45	45	45	45	45	540
Neck Static	0 hr	Mean	60.3	20.2	39.3	26.3	42.5	40.1	32.4	39.5	23.4	57.2	43.7	44.6	39.1
		SD	17.7	5.1	10.5	11.3	15.9	14.9	13.3	11.6	5.7	13.8	12.0	12.1	16.9
		No	15	15	15	15	15	15	15	15	15	15	15	15	180
	2 hr	Mean	57.8	19.1	35.5	23.4	39.3	38.5	27.7	38.6	24.1	54.3	43.0	44.8	37.2
		SD	19.8	5.1	12.0	9.5	13.4	12.1	11.1	10.7	6.1	15.8	10.4	13.6	16.6
		No	15	15	15	15	15	15	15	15	15	15	15	15	180
	4 hr	Mean	53.5	18.6	33.6	23.8	37.6	35.7	27.3	41.5	23.4	58.3	41.6	44.7	36.6
		SD	15.5	4.4	12.8	9.0	11.8	11.1	9.6	11.4	6.7	18.7	10.4	14.1	16.4
		No	15	15	15	15	15	15	15	15	15	15	15	15	180
	Mean	Mean	57.2	19.3	36.1	24.5	39.8	38.1	29.1	39.9	23.7	56.6	42.8	44.7	37.6
		SD	17.6	4.8	11.8	9.8	13.6	12.6	11.4	11.1	6.0	15.9	10.8	13.0	16.6
		No	45	45	45	45	45	45	45	45	45	45	45	45	540
Mean		Mean	59.7	20.3	38.3	24.5	39.4	38.6	28.2	42.0	26.1	59.1	45.3	47.2	39.1
		SD	21.3	5.3	11.5	10.4	13.6	14.0	11.8	11.6	11.1	18.4	13.0	13.6	18.2
		No	90	90	90	90	90	90	90	90	90	90	90	90	1080

Table B-6 – Average pressure pain threshold (PPT) in Newtons for each tender point (TeP) and control point (CP)

B.2.1.2 CHANGE IN PPT

The change in PPT at each site between the start-to-middle (0hr - 2 hr) and start-to-end (0 hr - 4 hr) is shown in Table B-7.

Neck Status	ΔTime	Measurement Location												
		Right Upper Quadrant					Left Upper Quadrant					Lower		Mean
		RThb	REpi	RDel	RTra	RSup	LSup	LTra	LDel	LEpi	LThb	RKne	LKne	
Neck Mobile	Δ 0 hr – 2 hr	-12.0	-1.1	-1.9	-2.7	-1.3	-5.8	-1.2	-4.8	-1.5	1.1	8.6	0.9	-1.8
	Δ 0 hr – 4 hr	-11.3	-2.2	-5.9	-3.2	-4.2	-5.6	1.2	-0.9	-5.4	2.1	-3.4	-3.7	-3.5
Neck Static	Δ 0 hr – 2 hr	-3.1	-0.7	-3.3	-2.8	-3.2	-1.1	-4.6	0.0	0.2	-2.1	-0.5	1.4	-1.6
	Δ 0 hr – 4 hr	-6.8	-1.7	-4.9	-2.9	-5.2	-4.1	-5.4	1.9	-0.2	1.4	-1.3	-0.2	-2.5
Mean	Δ 0 hr – 2 hr	-7.5	-0.9	-2.6	-2.7	-2.3	-3.4	-2.9	-2.4	-0.6	-0.5	4.0	1.1	-1.7
	Δ 0 hr – 4 hr	-9.0	-2.0	-5.4	-3.1	-4.7	-4.8	-2.1	0.5	-2.8	1.8	-2.4	-1.9	-3.0

Table B-7 – Average change in PPT at each measurement location for each time segment

B.2.1.3 PERCENTAGE CHANGE IN PPT

The average percentage change in PPT between the start and end of the neck-static and the neck-mobile measurement sessions, for each location, is shown in Table B-8 and Figure B-3.

The average percentage change was similar for each measurement session, although the neck-mobile session had a slightly larger percentage change in PPT. There was also large variability in the percentage change between the measurement locations. In the working regions of the musculoskeletal system the percentage change was greatest. These locations were in the right arm and right shoulder.

The percentage change in PPT results **did not support** a significant difference in pain sensitivity change between the two measurement sessions. This was not consistent with the PPT results described above, which did show a significant difference (see Table 4-9). This made interpretation of the pain sensitivity results difficult and is discussed further in Sec. 4.6.4.

Neck Status	RThb	REpi	RDel	RTra	RSup	LSup	LTra	LDel	LEpi	LThb	RKne	LKne	Mean
Neck-mobile	-12.1%	-9.3%	-10.1%	-2.8%	-7.3%	-11.4%	7.1%	2.4%	-4.2%	4.1%	-6.7%	-6.0%	-4.7%
Neck-static	-10.6%	-3.7%	-10.5%	-8.1%	-8.6%	-6.1%	-14.2%	7.8%	0.5%	1.7%	0.0%	2.6%	-4.1%

Table B-8 – Average percentage change in PPT of each TeP and CP between the start and end of each measurement session

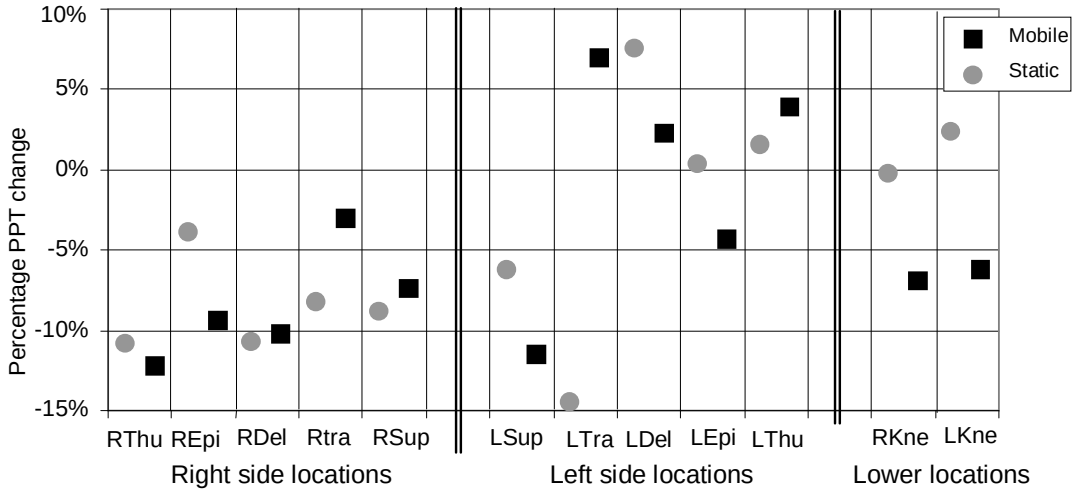


Figure B-3 – Average percentage change in PPT of each TeP and CP between the start and end of each measurement session

B.2.1.4 QUADRANT PPT RESULTS

Average PPT values for the upper left and right quadrants and changes within these quadrants, between each measurement time, are shown in Table B-9 and Figure B-4. Lower quadrant values are not shown for clarity.

As can be seen in Figure B-4, there was a reduction in PPT in the upper left and right quadrants, and the lower quadrant. This included a decrease in PPT in the upper left quadrant and the lower quadrant, even though these quadrants did undertake any work during the measurement sessions. The change in PPT was greatest in the upper right quadrant, which was not unexpected given that the right arm was active during the measurement sessions.

							Δ 0 hr – 2 hr		Δ 2 hr – 4 hr		Δ 0 hr – 4 hr	
Neck status	Upper quadrant	TeP or CP	Time	Mean	SD	No	Mean	SD	Mean	SD	Mean	SD
Neck Mobile	Left	TeP	0hr	33.7	17.6	45	-2.8	10.1			-3.3	11.5
			2hr	30.9	12.5	45			-0.4	8.9		
			4hr	30.4	14.0	45						
		CP	0hr	52.9	18.2	30	-1.9	15.0			0.6	11.5
			2hr	51.0	20.0	30			2.5	13.6		
			4hr	53.5	19.5	30						
		TeP and CP	0hr	41.4	20.1	75	-2.4	12.2			-1.7	11.6
			2hr	39.0	18.6	75			0.7	11.0		
			4hr	39.7	19.9	75						
	Right	TeP	0hr	29.9	14.6	45	-1.7	9.3			-3.2	9.2
			2hr	28.2	13.1	45			-1.5	7.3		
			4hr	26.7	11.7	45						
		CP	0hr	56.4	25.0	30	-6.9	16.7			-8.6	16.4
			2hr	49.5	19.2	30			-1.7	12.7		
			4hr	47.8	20.8	30						
		TeP and CP	0hr	40.5	23.3	75	-3.8	13.0			-5.4	12.8
			2hr	36.7	18.9	75			-1.6	9.7		
			4hr	35.2	19.0	75						
Neck Static	Left	TeP	0hr	32.0	13.6	45	-1.8	7.6			-3.2	8.2
			2hr	30.1	11.7	45			-1.4	6.8		
			4hr	28.8	10.5	45						
		CP	0hr	48.3	15.4	30	-1.0	9.1			1.7	8.4
			2hr	47.3	14.7	30			2.7	8.3		
			4hr	50.0	17.4	30						
		TeP and CP	0hr	38.5	16.4	75	-1.5	8.2			-1.3	8.6
			2hr	37.0	15.4	75			0.2	7.6		
			4hr	37.2	17.2	75						
	Right	TeP	0hr	29.7	14.8	45	-2.2	6.4			-3.3	6.9
			2hr	27.4	12.9	45			-1.0	4.5		
			4hr	26.4	12.0	45						
		CP	0hr	49.8	17.8	30	-3.2	8.3			-5.9	9.9
			2hr	46.6	19.6	30			-2.7	8.7		
			4hr	43.9	16.9	30						
		TeP and CP	0hr	37.7	18.8	75	-2.6	7.2			-4.3	8.2
			2hr	35.1	18.4	75			-1.7	6.5		
			4hr	33.4	16.5	75						

Table B-9 – Left and right upper quadrant average PPT and changes in PPT between the start and end of each measurement session

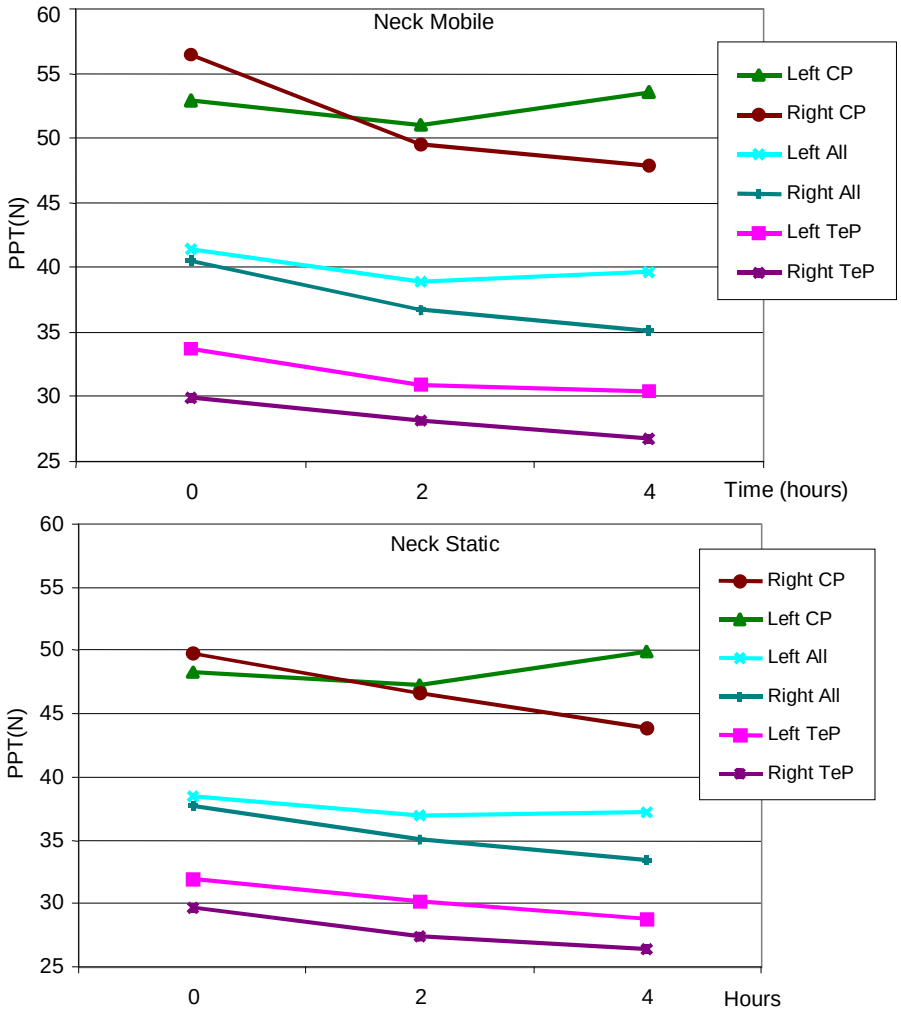


Figure B-4 – Average PPT values for the upper left and right upper quadrants for the tender points (TeP), control points (CP) and all PPT measurement locations during the neck-mobile (top graph) and neck-static (bottom graph) measurement sessions

B.2.1.5 TeP and CP PPT analysis of variance post-hoc analysis

There was a significant difference in PPT between the measurement locations. This was not an unexpected outcome given that some sites were tender points, which are known to be sensitive to mechanical pressure, and control points, which are not as sensitive. The two thumb control points were significantly higher than almost all other sites, and the trapezius and epicondyles were significantly lower than most other sites. The post-hoc analysis is shown in Table B-10

The Newman-Keuls post-hoc analyses for time confirmed that comparison of the start PPT values with the middle (2 hr) and end (4 hr) PPT values, there were significant differences. The pain sensitivity increased over time – see Table B-11.

Location		REpi	RTra	LEpi	LTra	RDel	LSup	RSup	LDel	RKne	LKne	LThb	RThb
	Mean	20.3	24.5	26.1	28.2	38.3	38.6	39.4	42.0	45.3	47.2	59.1	59.7
REpi	20.3	--	4.2	5.9	7.9*	18.1+	18.4+	19.1+	21.7+	25.0+	26.9+	38.8+	39.4+
RTra	24.5		--	1.6	3.7	13.8+	14.1+	14.9+	17.4+	20.7	22.7+	34.5+	35.1+
LEpi	26.1			--	2.0	12.2+	12.5+	13.3+	15.8+	19.1+	21.0+	32.9+	33.5+
LTra	28.2				--	10.2+	10.4+	11.2+	13.8+	17.1+	19.0+	30.9+	31.5+
RDel	38.3					--	0.3	1.1	3.6	6.9	8.8*	20.7+	21.3+
LSup	38.6						--	0.8	3.3	6.6	8.6*	20.4+	21.0+
RSup	39.4							--	2.6	5.9	7.8	19.7+	20.3+
LDel	42.0								--	3.3	5.2	17.1+	17.7+
RKne	45.3									--	1.9	13.8+	14.4+
LKne	47.2										--	11.9+	12.5+
LThb	59.1											--	0.6
RThb	59.7												--

Table B-10 – Post-hoc analysis of all PPT data between measurement locations (1 to 12)

	Time 4 hours	Time 2 hours	Time 0 hours	
Time 4 hours	--	Loc11+	U Right Quad (TeP and CP)+ U Right Quad (TeP only)+ U Right Quad (CP only)+ U Left Quad (TeP only)*	All data+ RThub+ RSup * LSup *
Time 2 hours		--	U Right Quad (TeP and CP)+ U Right Quad (TeP only)* U Right Quad (CP only)* U Left Quad (TeP only)*	RThub + LSup * RKne *
Time 0 hours			--	

Table B-11 – Summary of post-hoc analysis for significant difference between PPT at measurement times 0, 2 and 4 hour

B.2.1.6 TeP AND CP CORRELATION ANALYSIS

Correlation analysis showed that some measurement locations were associated. Some locations that were close in proximity had good to excellent correlation. The total PPT value had fair to good correlation with all locations.

		right TeP and CPs					left TeP and CPs					lower TeP	
		RThb	REpi	RDel	RTra	RSup	LSup	LTra	LDel	LEpi	LThb	RKne	LKne
right TeP and CPs	REpi	0.81+	--										
	RDel			--									
	RTra				--								
	RSup				0.71+	--							
left TeP and CPs	LSup			0.56*	0.87+	0.91+	--						
	LTra				0.83+	0.60*	0.82+	--					
	LDel	0.51*	0.61*	0.80+		0.52*	0.58*		--				
	LEpi			0.63*	0.64+		0.66+	0.78+	0.68+	--			
	LThb	0.87+	0.75+			0.60*	0.53*		0.52*		--		
lower TeP	RKne									0.70+		--	
	LKne		0.54*				0.54*	0.54*	0.52*	0.78+	0.71+	0.80+	--
All	Tot_PPT	0.67+	0.65+	0.69+	0.68+	0.81+	0.85+	0.69+	0.76+	0.81+	0.80+	0.63*	0.81+

Table B-12 – Inter-relationship of the TeP and CP PPTs. Only significant correlations are shown

B.2.2 CERVICAL PRESSURE PAIN THRESHOLD

B.2.2.1 SUMMARY OF CERVICAL PPT RESULTS

Two thousand, one hundred and sixty PPT measurements were completed in the cervical region. The PPT scores for each location are reported in Table B-13. This table shows that the PPT at most cervical locations decreased between the start and end of each measurement session.

Measure Location	Neck status	start or end	Mean	SD	No	Measure Location	Neck status	start or end	Mean	SD	No
L1	mobile	start	25.6	4.9	45	R1	mobile	start	25.7	3.9	45
		end	26.1	6.0	45			end	25.0	5.6	45
	static	start	28.0	7.6	45		static	start	25.9	6.1	45
		end	24.4	5.8	45			end	23.1	5.5	45
	Mean		26.0	6.2	180		Mean		24.9	5.4	180
L2	mobile	start	29.3	6.9	45	R2	mobile	start	27.2	5.4	45
		end	27.0	6.5	45			end	26.7	6.5	45
	static	start	28.5	7.3	45		static	start	27.7	5.4	45
		end	26.0	5.2	45			end	23.5	3.9	45
	Mean		27.7	6.6	180		Mean		26.3	5.6	180
L3	mobile	start	28.2	5.7	45	R3	mobile	start	26.2	5.8	45
		end	26.5	5.5	45			end	24.4	5.9	45
	static	start	28.0	6.6	45		static	start	26.6	6.4	45
		end	25.9	5.0	45			end	24.7	4.2	45
	Mean		27.1	5.8	180		Mean		25.5	5.7	180
L4	mobile	start	31.2	5.1	45	R4	mobile	start	28.7	5.6	45
		end	27.4	5.7	45			end	27.0	6.1	45
	static	start	29.1	5.6	45		static	start	27.0	4.5	45
		end	28.0	3.7	45			end	25.4	4.4	45
	Mean		28.9	5.2	180		Mean		27.0	5.3	180
L5	mobile	start	38.1	6.3	45	R5	mobile	start	36.1	6.9	45
		end	36.9	8.2	45			end	37.2	8.4	45
	static	start	38.8	7.8	45		static	start	37.5	7.3	45
		end	37.6	8.0	45			end	36.4	8.3	45
	Mean		37.8	7.6	180		Mean		36.8	7.7	180
TL	mobile	start	33.0	8.3	45	TR	mobile	start	38.5	8.7	45
		end	34.1	7.8	45			end	32.7	9.0	45
	static	start	36.1	8.2	45		static	start	35.8	7.2	45
		end	33.7	7.3	45			end	32.5	7.4	45
	Mean		34.2	7.9	180		Mean		34.9	8.4	180
Left Average	mobile	start	30.9	7.4	270	Right Average	mobile	start	30.4	7.9	270
		end	29.6	7.9	270			end	28.8	8.4	270
		mean	30.3	7.7	540			mean	29.6	8.2	540
	static	start	31.4	8.4	270		static	start	30.1	7.8	270
		end	29.3	7.6	270			end	27.6	7.7	270
		mean	30.3	8.1	540			mean	28.8	7.8	540
	Mean	start	31.2	7.9	540		Mean	start	30.3	7.8	540
		end	29.5	7.7	540			end	28.2	8.0	540
		mean	30.3	7.9	1080			mean	29.2	8.0	1080
All Locations	mobile	start	30.7	7.7	540						
		end	29.2	8.1	540						
	static	start	30.8	8.1	540						
		end	28.4	7.7	540						
	Mean	Start	30.7	7.9	1080						
		End	28.8	7.9	1080						
		mean	29.8	8.0	2160						

Table B-13 – Average pressure pain threshold (PPT) at the twelve posterior cervical spine measurement locations for the start and end of the neck-static and neck-mobile measurement sessions. The consecutive measurements were averaged.

B.2.2.2 CERVICAL PPT RELIABILITY

The reliability of PPT measurements between the three measurements taken consecutively at each measurement location was **good** with an Intraclass Correlation Coefficient (ICC[2,1])=0.88 (95% CI: 0.86-0.89) from 720 comparisons. The reliability of the total PPT (derived by adding PPT values of each measurement location) between

the three consecutive measurements was **high** at ICC(2,1)=0.95 (95% CI: 0.92-0.97) from 60 comparisons.

B.2.2.3 CERVICAL PPT ANALYSIS OF VARIANCE POST-HOC ANALYSIS

There was a significant difference in pain sensitivity between the cervical measurement locations. The cervical spine was significantly more sensitive to mechanical pressure in the upper cervical spine, compared with the lower. This pattern was consistent on both sides of the neck. See the Newman-Keuls post-hoc analyses in Table B-14.

Location		R1	R3	L1	R2	R4	L3	L2	L4	TL	TR	R5	L5
	Mean	24.9	25.5	26	26.3	27	27.1	27.7	28.9	34.2	34.9	36.8	37.8
R1	24.9	--	0.6	1.1	1.4	2.1	2.2	2.8	4.0*	9.3+	9.9+	11.9+	12.9+
R3	25.5		--	0.5	0.8	1.5	1.6	2.2	3.4*	8.7+	9.4+	11.3+	12.3+
L1	26.0			--	0.3	1.0	1.1	1.7	2.9	8.2+	8.8+	10.7+	11.8+
R2	26.3				--	0.7	0.8	1.4	2.6	7.9+	8.6+	10.5+	11.5+
R4	27.0					--	0.1	0.7	1.9	7.2+	7.8+	9.7+	10.8+
L3	27.1						--	0.6	1.8	7.1+	7.7+	9.6+	10.7+
L2	27.7							--	1.2	6.5+	7.2+	9.1+	10.1+
L4	28.9								--	5.3+	5.9+	7.9+	8.9+
TL	34.2									--	0.6	2.5	3.6*
TR	34.9										--	1.9	3.0*
R5	36.8											--	1.0
L5	37.8												--

Table B-14 – Post-hoc analysis of all PPT data between measurement locations (L1 to TR).

B.2.2.4 CERVICAL PPT CORRELATION ANALYSIS

Correlation analysis showed that there was good to high correlation between most cervical measurement locations (Table B-15). This indicated that although there was large variability in PPT between some of the measurement sites, what the sites were measuring was probably common to each site.

The cervical PPT measurement sites were all in close proximity to one another, which probably contributed to the high correlation outcomes. The cervical total PPT value had good to high correlation with all locations.

		left cervical						right cervical					
		L1	L2	L3	L4	L5	TL	R1	R2	R3	R4	R5	TR
left cervical	L2	0.94+	--										
	L3	0.80+	0.86+	--									
	L4	0.76+	0.79+	0.81+	--								
	L5	0.78+	0.73+	0.55*	0.79+	--							
	TL		0.56*				--						
right cervical	R1	0.89+	0.91+	0.71+	0.67+	0.69*	0.62*	--					
	R2	0.81+	0.84+	0.60*	0.71+	0.70+	0.69+	0.85+	--				
	R3	0.69+	0.57*		0.61*	0.57*		0.52*	0.74+	--			
	R4	0.57*			0.63*	0.52*			0.58*	0.84+	--		
	R5	0.61*	0.60*	0.59*	0.70+			0.59*	0.71+	0.54*		--	
	TR	0.55*	0.59*		0.64*		0.76+	0.61*	0.68+		0.62*	0.66+	--
All	Total	0.90+	0.92+	0.76+	0.86+	0.76+	0.66+	0.89+	0.93+	0.73+	0.69+	0.76+	0.79+

Table B-15 – Inter-relationship of the cervical pressure pain thresholds. Only significant correlations are shown

B.2.2.5 TREND ANALYSIS OF PPT IN CERVICAL SPINE

Analysis of trend results are shown in Table B-16. On average 68.7%, 4.7%, 5.8% and 18.1% of the variation within PPT scores could be predicted by a linear, quadratic, cubic and quartic regression equation, respectively.

This outcome confirmed the results of Ch. 6. The mechanical pressure pain threshold was not uniform in the cervical spine and generally displayed a **linear** change in PPT along the cervical spine. The cervical spine was **more tender in the upper cervical spine** and less in the lower region. This trend can be seen visually in Figure 4-15.

			polynomial degree			
Neck status	Measurement Side	Start/End	linear	quadratic	cubic	quartic
mobile	left	start	+[1]		+[2]	+[3]
		end	+[4]			+[5]
	right	start	+[6]	+[7]		+[8]
		end	+[9]		+[10]	+[11]
static	left	start	+[12]			+[13]
		end	+[14]		+[15]	+[16]
	right	start	+[17]			+[18]
		end	+[19]		+[20]	+[21]

Table B-16 – Analysis of trend of the left and right cervical spine measurement locations

1: ($F_{(1,264)}$ = 71.0), 2: ($F_{(1,264)}$ = 8.4) , 3: ($F_{(1,264)}$ = 24.7) , 4: ($F_{(1,264)}$ = 71.7), 5: ($F_{(1,264)}$ = 20.5) , 6: ($F_{(1,264)}$ = 144.4) , 7: ($F_{(1,264)}$ = 19.5) , 8: ($F_{(1,264)}$ = 10.6) , 9: ($F_{(1,264)}$ = 67.7) , 10: ($F_{(1,264)}$ = 10.1) , 11: ($F_{(1,264)}$ = 31.7) , 12: ($F_{(1,264)}$ = 64.1) , 13: ($F_{(1,264)}$ = 17.1) , 14: ($F_{(1,264)}$ = 123.7) , 15: ($F_{(1,264)}$ = 12.6) , 16: ($F_{(1,264)}$ = 27.1) , 17: ($F_{(1,264)}$ = 84.8) , 18: ($F_{(1,264)}$ = 28.3) , 19: ($F_{(1,264)}$ = 139.4) , 20: ($F_{(1,264)}$ = 15.1) , 21: ($F_{(1,264)}$ = 26.5).

B.3 BODY-PART DISCOMFORT SCORES

B.3.1 SUMMARY OF BODY-PART DISCOMFORT SCORES

The average body part (BP) severity (BP Severity), frequency (BP Frequency) and frequency multiplied by severity (BP Frequency Severity) for each body-part is shown in Table B-17 and Ch. 4 in Figure 4-21. In almost all the body parts in which musculoskeletal discomfort and pain was reported, the discomfort was greater during the neck-static session compared with the neck-mobile session. As well, the BP Frequency Severity for most body regions steadily increased during the four-hour measurement tasks. This indicated that the participants experiencing discomfort that increased during the measurement sessions.

Neck		RN			LN			RS			LS			RUA			LUA			RE			RUF			RLF		
status	T	F	S	B	F	S	B	F	S	B	F	S	B	F	S	B	F	S	B	F	S	B	F	S	B	F	S	B
mobile	0	3	30	89	3	23	70	2	51	101	2	27	53	0			0			0			0			0		
mobile	1	4	33	133	6	41	243	2	54	107	2	49	97	1	63	63	0			1	51	51	5	42	208	0		
mobile	2	8	42	339	9	44	400	4	59	236	1	49	49	3	54	162	0			2	46	93	6	65	389	1	65	65
mobile	3	9	52	469	13	45	579	6	48	289	3	53	158	3	65	195	0			2	47	94	5	69	344	1	65	65
mobile	4	11	51	563	12	55	656	6	47	284	2	61	123	5	46	231	1	22	22	3	35	104	6	70	418	1	76	76
Mobile Total		35	45	1591	43	45	1948	20	51	1017	10	48	480	12	54	651	1	22	22	8	43	342	22	62	1359	3	69	206
static	0	1	42	42	1	42	42	0			0			0			0			0			0			0		
static	1	9	41	373	11	39	424	2	59	118	1	36	36	5	43	216	0			1	47	47	3	44	132	0		
static	2	12	46	546	13	44	573	2	65	129	1	54	54	5	41	204	0			3	42	125	5	48	238	0		
static	3	13	54	697	13	58	755	4	58	231	2	46	92	6	63	377	1	13	13	4	49	196	5	71	357	2	68	136
static	4	15	58	876	14	64	899	6	49	293	4	48	193	5	77	385	1	19	19	4	54	216	7	64	450	1	89	89
Static Total		50	51	2533	52	52	2692	14	55	770	8	47	374	21	56	1182	2	16	32	12	49	583	20	59	1177	3	75	225
TOTAL		85	49	4124	95	49	4640	34	53	1787	18	47	854	33	56	1832	3	18	54	20	46	925	42	60	2535	6	72	431

neck		LLF			RW			RT			RH			UB			MB			LB			UL			LL		
status	T	F	S	B	F	S	B	F	S	B	F	S	B	F	S	B	F	S	B	F	S	B	F	S	B	F	S	B
mobile	0	0			0		0	0			0			0			0			3	27	82	0			0		
mobile	1	0			3	40	119	0			7	35	248	1	22	22	1	20	20	4	46	184	1	58	58	1	24	24
mobile	2	0			3	48	145	1	50	50	9	39	350	3	47	140	1	16	16	4	53	211	0			0		
mobile	3	0			5	45	226	2	32	64	11	50	552	5	58	292	1	27	27	8	50	398	0			0		
mobile	4	0			6	44	261	2	37	73	12	50	594	7	48	336	3	56	167	9	53	474	2	48	95	0		
Mobile Total		0	0	0	17	44	752	5	37	187	39	45	1745	16	49	790	6	38	229	28	48	1348	3	51	153	1	24	24
static	0	0			0			0			0			1	5	5	0			0			0			0		
static	1	0			3	49	148	0			6	18	108	1	6	6	0			3	50	151	0			0		
static	2	1	17	17	5	41	205	2	29	57	10	47	470	4	34	136	2	65	131	4	24	97	1	27	27	0		
static	3	0			7	52	362	2	48	96	10	51	512	7	45	317	3	51	152	9	44	397	1	11	11	0		
static	4	1	29	29	9	52	464	3	49	148	9	58	521	9	57	517	3	61	183	11	48	523	1	78	78	1	22	22
Static Total	2	23	46		24	49	1179	7	43	301	35	46	1610	22	45	980	8	58	466	27	43	1168	3	39	116	1	22	22
TOTAL	2	23	46		41	47	1930	12	41	488	74	45	3355	38	47	1770	14	50	694	55	46	2516	6	45	269	2	23	46

Table B-17 – Body-part Frequency (F), BP Severity (S), and BP Frequency Severity (B) for each body-part. Data is split for each measurement time (T) and neck status (only non-zero scores are reported). See the body maps above for codes.

B.3.2 WHOLE OF BODY DISCOMFORT SCORES

The whole of body region BP Frequency, BP Severity and BP Frequency Severity scores are shown in Table B-18. There was greater musculoskeletal discomfort and pain in the neck-static session, compared with the neck-mobile, and the pain and discomfort increased steadily during the four-hour sessions in response to the imposed postural load.

neck status	time	BP Frequency Mean	BP Frequency SD	BP Severity Mean	BP Severity SD	BP Frequency Severity Mean	BP Frequency Severity SD
mobile	0	1	1	12	19	26	45
mobile	1	3	2	31	19	108	116
mobile	2	4	2	38	23	185	179
mobile	3	5	3	45	25	262	230
mobile	4	6	3	45	22	310	241
Mobile mean		4	3	34	25	178	201
static	0	0	1	3	11	6	22
static	1	3	2	31	21	120	122
static	2	5	3	39	22	211	180
static	3	6	3	48	21	325	231
static	4	8	4	53	25	418	255
Static mean		4	4	35	26	216	230

Table B-18 – Average body-part (BP) Frequency, BP Severity and BP Frequency Severity for all body regions combined. Average (Mean), standard deviation (SD) and number (No) values are reported. Data is split for each measurement time and neck status

B.3.3 BODY-PART DISCOMFORT ANALYSIS OF VARIANCE

Newman-Keuls post-hoc analyses of significant outcomes from Ch. 4 in Table 4-14 are shown below. Table B-19 and Table B-21 confirmed that in the comparison of the start of the measurement session discomfort scores with the middle (2, and 3 hr) and end (4 hr) VAS scores there were significant differences, and that at the end of the measurement sessions the musculoskeletal discomfort and pain had significantly increased.

Table B-21 demonstrates that the neck and to some extent the right hand, participants experienced significantly more discomfort than other body regions. Table B-21 shows that for the significant interaction effect of neck status by time, the 3 hr and 4 hr body part scores in the neck static session were significantly greater than all other cells, including the neck mobile scores at time 3 hr and 4 hr. This table is further discussed in Sec. 4.6.5.

	Time 1 (1hr)	Time 2 (2hr)	Time 3 (3hr)	Time 4 (4hr end)
Time 0 (start)	LN BP Frequency Severity	RN, LN RUA, RH BP Frequency Severity	RN, LN, RS, RUA, RW, RH, UB, MB, LB BP Frequency Severity	RN, LN, RS, RUA RW, RH, UB, LB BP Frequency Severity
Time 1 (1hr)	--	RH	RN, LN, RH, UB BP Frequency Severity	RN, LN, RW, RH UB, LB, BP Frequency Severity
Time 2 (2hr)		--	LB	RN, LN, UB, LB BP Frequency Severity
Time 3 (3hr)			--	

Table B-19 – Summary post-hoc analysis for significant difference between measurement times 0 to time 4. Significant was set at $p<0.01$

	m0	m1	s1	m2	s2	m3	m4	s3	s4
s0		BP Frequency Severity	BP Frequency Severity RN RUA	BP Frequency Severity	BP Frequency Severity RN RUA	BP Frequency Severity RN RUA	BP Frequency Severity RN RUA	BP Frequency Severity RN RUA	BP Frequency Severity RN RUA
m0	--	BP Frequency Severity	BP Frequency Severity RUA	BP Frequency Severity RUA	BP Frequency Severity RN RUA	BP Frequency Severity RN RUA	BP Frequency Severity RN RUA	BP Frequency Severity RN RUA	BP Frequency Severity RN RUA
m1		--		BP Frequency Severity	BP Frequency Severity RN	BP Frequency Severity RN	BP Frequency Severity RN	BP Frequency Severity RN RUA	BP Frequency Severity RN RUA
s1			--	BP Frequency Severity	BP Frequency Severity	BP Frequency Severity	BP Frequency Severity	BP Frequency Severity RN RUA	BP Frequency Severity RN RUA
m2				--		BP Frequency Severity	BP Frequency Severity	BP Frequency Severity RN RUA	BP Frequency Severity, RN
s2					--		BP Frequency Severity	BP Frequency Severity RUA	BP Frequency Severity, RN
m3						--		RUA	BP Frequency Severity, RN
m4							--	RUA	BP Frequency Severity, RN
s3								--	BP Frequency Severity

Table B-20 – Summary of post-hoc analysis for interaction between neck status (mobile [m] and static [s]) X measurement time (time 0 hr to time 4 hr [0 - 4]). Significant was set at $p<0.01$. Only RN, RUA and BP Frequency Severity are shown (the post hoc analysis of other significant interactions were similar and are not repeated)

Body Part		LS	RE	EY	UB	RS	RUA	RW	LB	RUF	RH	RN	LN
	Mean	5.7	6.2	8.0	11.8	11.9	12.2	12.9	16.8	16.9	22.4	27.5	30.9
LS	5.7	--	0.5	2.3	6.1	6.2	6.5	7.2	11.1	11.2	16.7+	21.8+	25.2+
RE	6.2		--	1.8	5.6	5.7	6.1	6.7	10.6	10.7	16.2+	21.3+	24.8+
EY	8.0			--	3.8	3.9	4.2	4.9	8.8	8.9	14.4+	19.5+	23.0+
UB	11.8				--	0.1	0.4	1.1	5.0	5.1	10.6	15.7+	19.1+
RS	11.9					--	0.3	1.0	4.9	5.0	10.5	15.6+	19.0+
RUA	12.2						--	0.7	4.6	4.7	10.2	15.3+	18.7+
RW	12.9							--	3.9	4.0	9.5	14.6+	18.1+
LB	16.8								--	0.1	5.6	10.7*	14.2+
RUF	16.9									--	5.5	10.6*	14.0+
RH	22.4										--	5.1	8.6
RN	27.5											--	3.4

Table B-21 – Post-hoc analysis of musculoskeletal discomfort data between body parts. Only sites with large discomfort are shown

B.3.4 BODY-PART DISCOMFORT CORRELATION ANALYSIS

The correlation analysis of the body-part (BP) discomfort scores showed that in the working regions of the musculoskeletal system, there were significant associations between most body regions (Table B-22). This occurred mostly in the upper right quadrant of the body. The BP Frequency Severity score had good to high correlation with most body parts.

	RN	LN	RS	RUA	RE	RUF	RLF	RW	RT	RH	UB	LB	BP Frequency	BP Severity
LN	0.79+	--												
RS			--											
RUA			0.59*	--										
RE			0.54*		--									
RUF	0.68+	0.61	0.73+	0.67*		--								
RLF			0.57*				--							
RW			0.67*	0.79+	0.66*	0.59*		--						
RT									--					
RH	0.54*					0.55*	0.52*			--				
UB			0.77+		0.60*			0.68+			--			
LB			0.87+	0.76+	0.66*	0.65*		0.75+			0.66*	--		
BP Frequency			0.80+	0.80+		0.80+		0.81+	0.62*	0.56*	0.66*	0.75+	--	
BP Severity	0.71+	0.82+	0.73+	0.64		0.79+		0.63*		0.53*	0.66*	0.74+	0.69+	--
BP Frequency Severity	0.58*	0.62*	0.88+	0.78+		0.87+		0.78+		0.63*	0.72+	0.85+	0.91+	0.91+

Table B-22 – Inter-relationship of the body-part discomfort scores between each body part (only significant correlations are shown)

B.4 CERVICAL RANGE OF MOTION (ROM) RESULTS

There were some interaction outcomes between neck status and time of measurement as reported in Ch. 4 in Table 4-18. The post-hoc analysis in Table B-23 for the interaction effect of neck status and time for rotation ROM, shows that at the end of the neck-mobile measurement session, the rotation ROM was significantly larger, probably due to the requirement of participants turning the head to observe the lights at once a minute intervals.

Rotation ROM		static end	mobile start	static start	mobile end
	Mean	139.56	140.71	141.03	146.82
static end	139.56	--	1.15	1.46	7.26+
mobile start	140.71		--	0.31	6.11+
static start	141.03			--	5.79+

Table B-23 – Post-hoc analysis of rotation cervical range of motion for interaction between neck status (mobile or static) X measurement time (start or finish)

B.4.1 CERVICAL ROM CORRELATION ANALYSIS

Table B-24 shows that most cervical ROM planes shared moderate to good correlation. All planes shared good to high correlation with total ROM.

	Flex/Ext	Lat Flex	Rotation
Lat Flex	0.52*	--	
Rotation	0.37ns	0.64+	--
total ROM	0.82+	0.86+	0.77+

Table B-24 – Pearson's R inter-relationship of the cervical range of motion results. * $p<0.05$, + $p<0.01$, ns – not significant

B.4.2 CERVICAL ROM RELIABILITY

The reliability (ICC) of the ROM measurements between the first and second measurements was **high** for all whole-plane motions (Table B-25). This confirmed the good reliability reported in Ch. 5 for a electromagnetic tracking as a tool for measuring cervical ROM.

Plane of motion	ICC(95% CI)
Right Rotation	0.67(.48-.79)
Left Rotation	0.79(.54-.89)
Rotation: whole-plane (left to right)	**0.90(.83-.94)**
Right lateral Flexion	0.82(.28-.93)
Left Lateral Flexion	0.92(.76-.97)
Lateral Flexion: w hole-plane (left to right)	**0.94(.84-.97)**
Flexion	0.62(.43-.75)
Extension	0.76(.63-.85)
Flexion/Extension: whole-plane (flex to ext)	**0.93(.89-.96)**
Total ROM (all whole-plane motions)	**0.96(.93-.97)**

Table B-25 – Intraclass Correlation Coefficient (ICC) reliability for cervical ROM between the first and second measurements for each plane of motion

B.5 MEASURES CORRELATION ANALYSIS

A correlation analysis was completed to better understand if the different measurement variables were varying together in some manner during the measurement sessions.

The PPT values of the TeP and CP locations and the cervical measurement locations were compared with correlation analysis (see Table B-26). The TeP and CP sites that were in the closest proximity to the neck shared the strongest correlations with the cervical spine measurement locations. This included the right and left supraspinatus and trapezius sites. **The close proximity of these sites to the neck probably contributed to the fair to high correlation outcomes**.

		right TeP and CPs					left TeP and CPs					lower TeP		All
		RThb	REpi	RDel	RTra	RSup	LSup	LTra	LDel	LEpi	LThb	RKne	LKne	Total
left cervical	L1				0.72+	0.72+	0.72+	0.71+		0.56*		0.57*	0.57*	0.75+
	L2				0.82+	0.83+	0.83+	0.75+		0.57*			0.54*	0.79+
	L3				0.68+	0.64+	0.58*		0.56*					0.65+
	L4		0.58*		0.69+	0.68+	0.68*				0.58*			0.70+
	L5				0.59*	0.54*	0.61*	0.62*		0.56*	0.54*	0.69+	0.61*	0.69+
	TL				0.54*	0.75+	0.74+	0.56*						
right cervical	R1				0.63*	0.78+	0.71+	0.65+			0.57*	0.54*	0.62*	0.73+
	R2				0.84+	0.75+	0.85+	0.83+		0.58*		0.58*	0.58*	0.73+
	R3				0.66+			0.54*		0.52*		0.59*		0.52*
	R4													
	R5					0.59*	0.56*							
	TR				0.55*	0.82+	0.71+							
All	Total				0.80+	0.83+	0.83+	0.69+			0.55*			0.72+

Table B-26 – Pearson's R correlation coefficients of pain sensitivity between the musculoskeletal tender points and control points and the cervical measurement locations (only significant correlations are shown)

Correlation analysis of the **body part discomfort scores** and the cervical and musculoskeletal **PPT values** is shown in Table B-27. There were some correlations between the pressure pain thresholds (PPT) and the self-reported musculoskeletal discomfort. However, there were not many correlations and most were only fair. This outcome **did not support** the notion that the pain sensitivity measurements were correlated with the self-reported body part discomfort and pain.

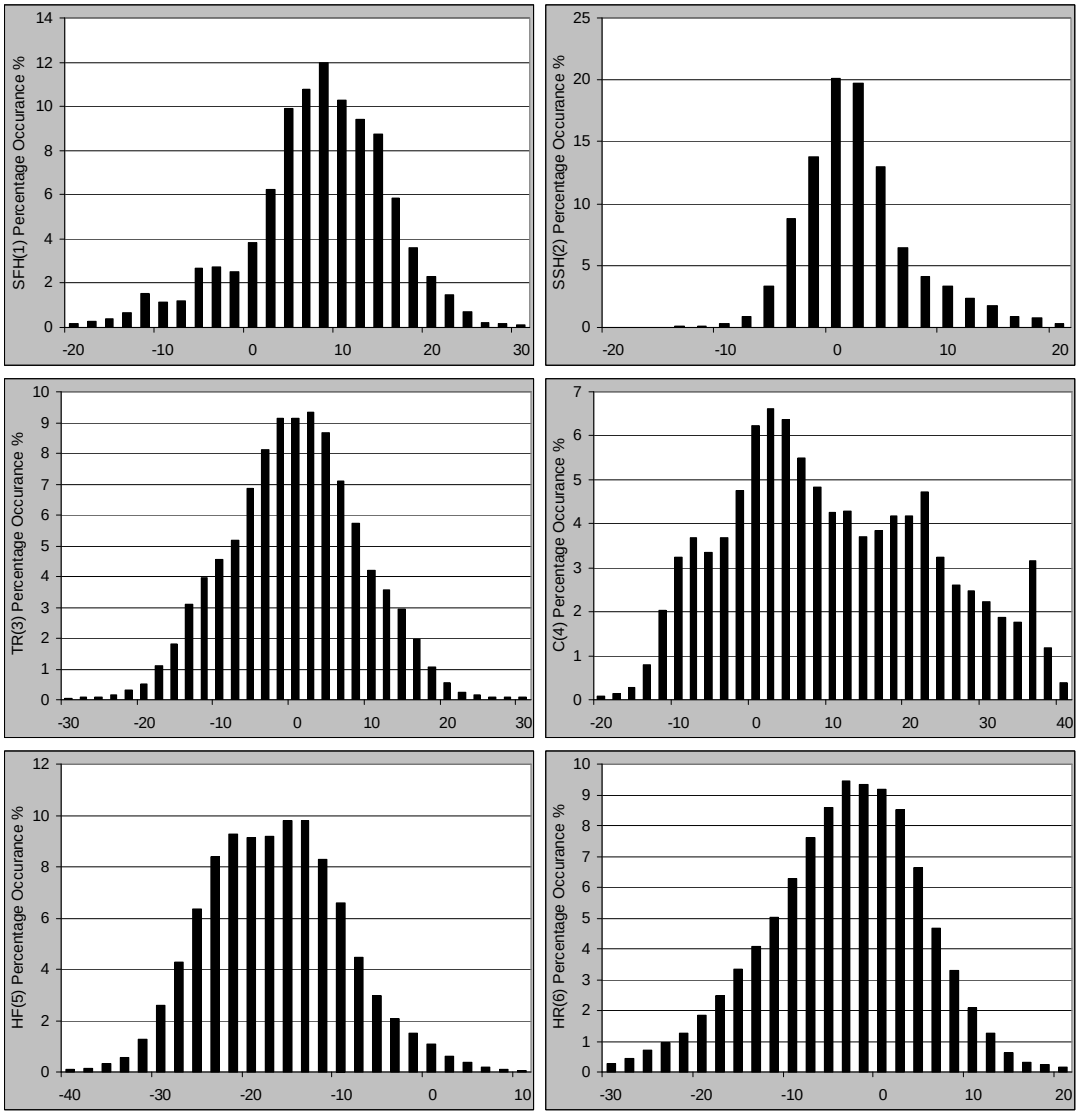
	Region	Site	RN	LN	RS	LS	RUA	RLF	RT	RH	UB	MB	LB	BP Freq	BP Sev	BP Freq Sev
Somatic pain sensitivity (TeP and CP PPT)	right TeP and CPs	RThb				0.60*										
		REpi			-0.54*	0.53*							-0.62*			
		RDel							0.80+							
		RTra							0.57*							
	left TeP and CPs	RSup							0.60*							
		LSup					0.52*		0.87+							
		LTra			-0.51*											
		LDel							0.71+							
		LEpi				0.62*										
	Lower TeP	LThb							0.68+							
		RKne				0.63*			0.58*							
	All	Total				0.61*			0.53*							
Cervical pain sensitivity (Cervical PPT)	Left cervical	L1	0.56*	0.60*				0.63*				0.52*			0.53*	
		L2		0.55*				0.77+				0.65+				
		L3		0.59*				0.65+				0.70+			0.57*	
		L4						0.67+				0.60*				
		TL			0.52*			0.74+		0.64*				0.52*		
	Right cervical	R1		0.53*				0.59*								
		R2						0.70+				0.62*				
		R3						0.53*			0.58*	0.56*			0.57*	0.54*
		TR						0.65+								
	All	Total							0.59*							

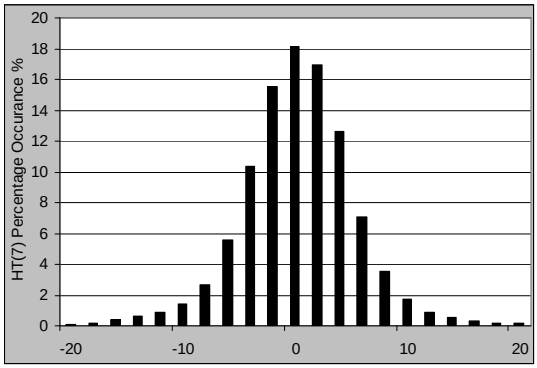
Table B-27 – Pearson's R correlation coefficients for pain sensitivity in the musculoskeletal TeP and CP locations and the cervical measurement locations and the self-reports of discomfort (only significant correlations are shown)

APPENDIX C

POSTURE CUMULATIVE GRAPHS (CHAP 5)

Figure C-1 – Cumulative percentage frequency of each FWAP posture code during the chapter seven posture experiments (bin widths of 2 deg were used)




HT(7) Percentage Occurance %
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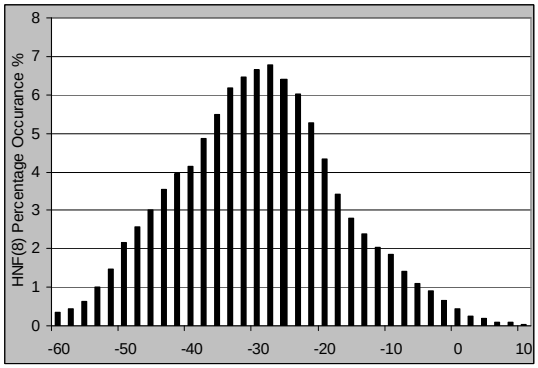
18
16
14
12
10
8
6
4
2
0
-20
-10
0
10
20


HNF(8) Percentage Occurance %
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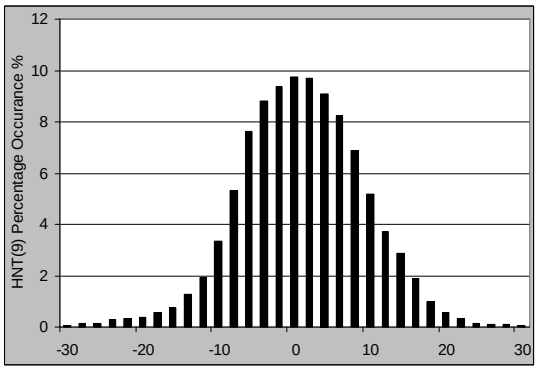
7
6
5
4
3
2
1
0
-60
-50
-40
-30
-20
-10
0
10


HNT(9) Percentage Occurance %
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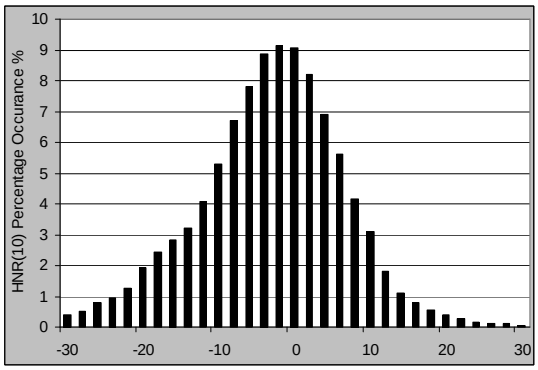
10
8
6
4
2
0
-30
-20
-10
0
10
20
30


HNR(10) Percentage Occurance %
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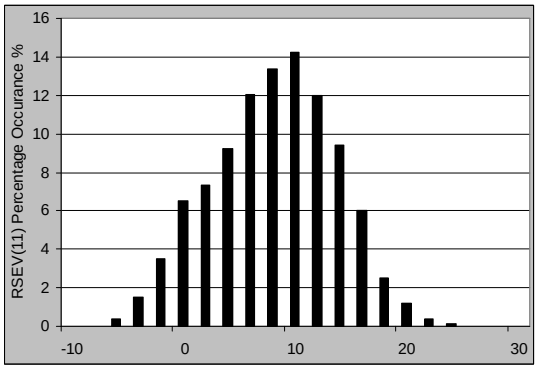
8
7
6
5
4
3
2
1
0
-30
-20
-10
0
10
20
30


RSEV(11) Percentage Occurance %
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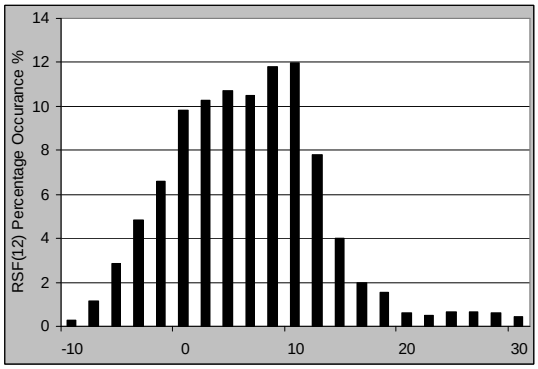
14
12
10
8
6
4
2
0
-10
0
10
20
30


RSF(12) Percentage Occurance %
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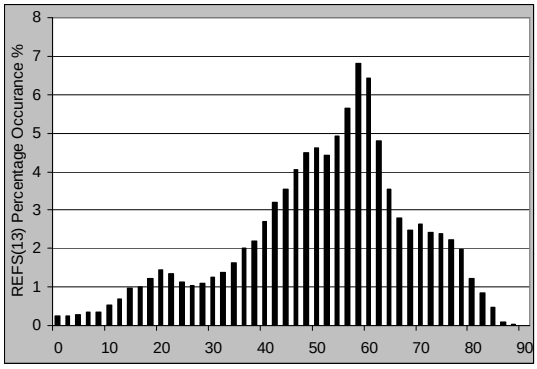
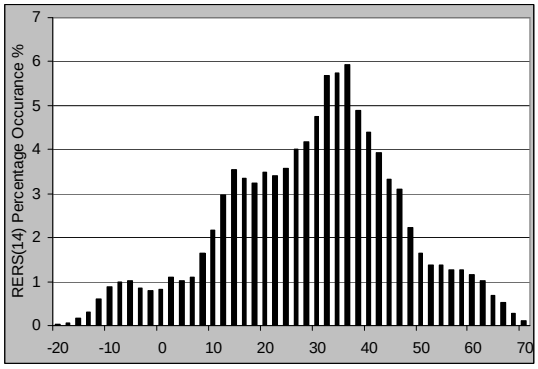
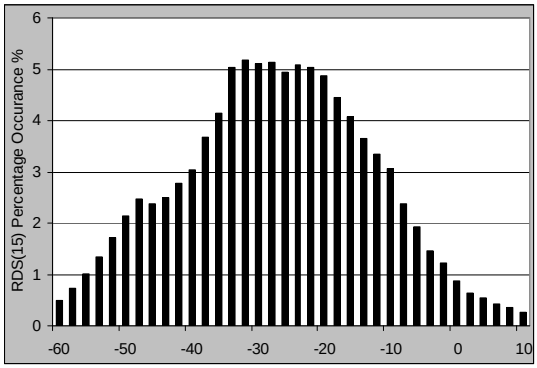
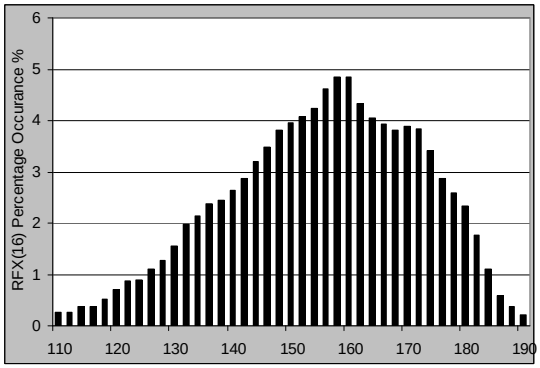
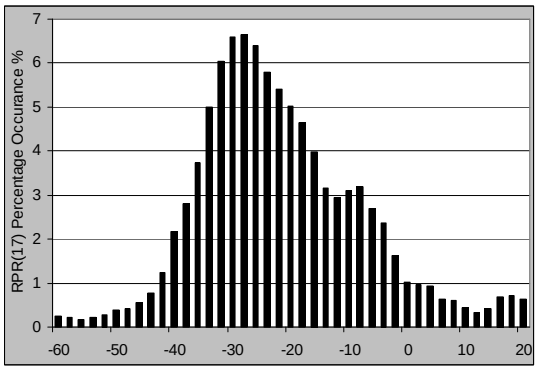
12
10
8
6
4
2
0
-10
0
10
20
30

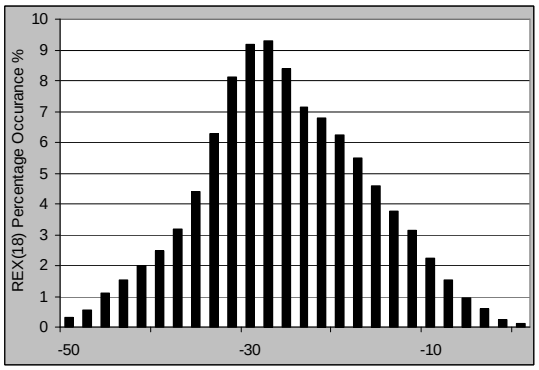

REFS(13) Percentage Occurance %
8
7
6
5
4
3
2
1
0
0
10
20
30
40
50
60
70
80
90

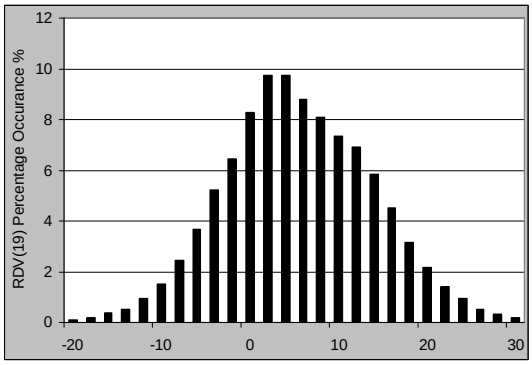

RERS(14) Percentage Occurance %
7
6
5
4
3
2
1
0
-20
-10
0
10
20
30
40
50
60
70


RDS(15) Percentage Occurance %
0
1
2
3
4
5
6
-60
-50
-40
-30
-20
-10
0
10


RFX(16) Percentage Occurance %
0
1
2
3
4
5
6
110
120
130
140
150
160
170
180
190


RPR(17) Percentage Occurance %
0
1
2
3
4
5
6
7
-60
-50
-40
-30
-20
-10
0
10
20


REX(18) Percentage Occurance %
0
1
2
3
4
5
6
7
8
9
10
-50
-30
-10


RDV(19) Percentage Occurance %
0
2
4
6
8
10
12
-20
-10
0
10
20
30

APPENDIX D

POSTURE GRAPHICAL OUTPUTS (CHAP 5)

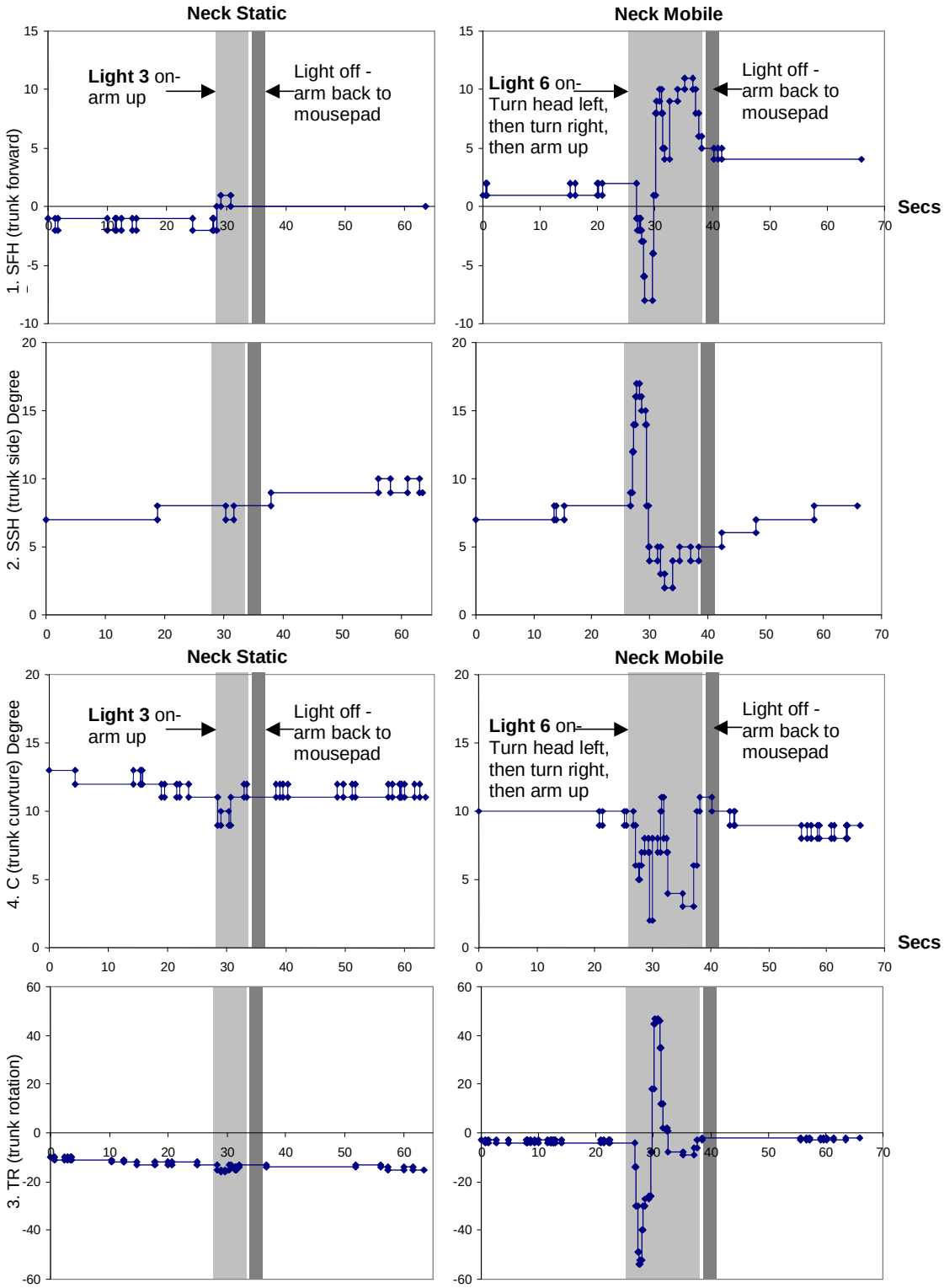
In App. E in Table E-1 and **Error! Reference source not found.**, the FWAP for Windows© analysis of the static and mobile neck experiment sessions for one participant for one cycle are shown. Based on this MODAPTS spreadsheet data of one cycle, the below FWAP for Windows© graphs were developed.

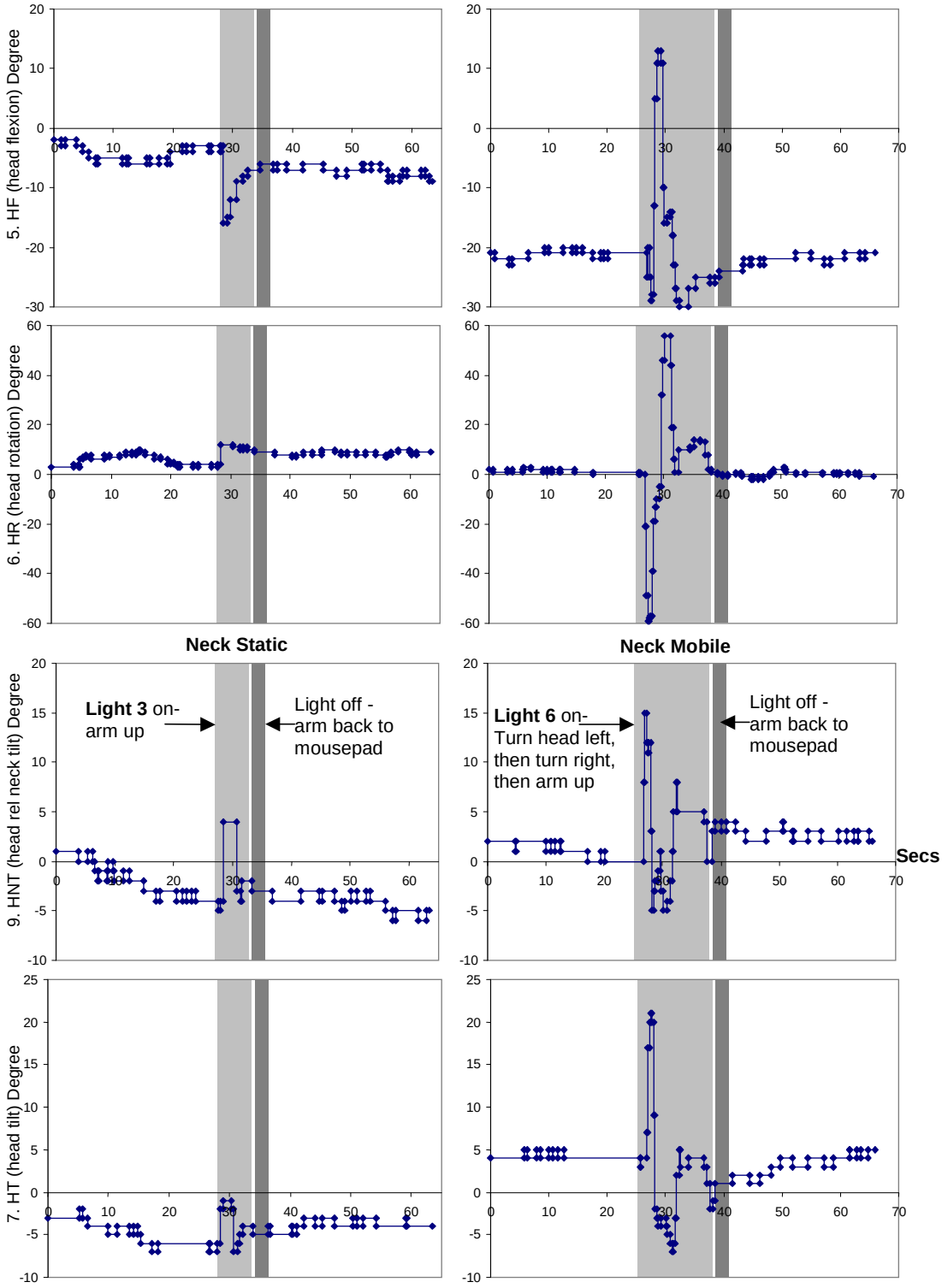
The graphs start 30 secs before a light goes on, and finish 30 secs after a light goes off.

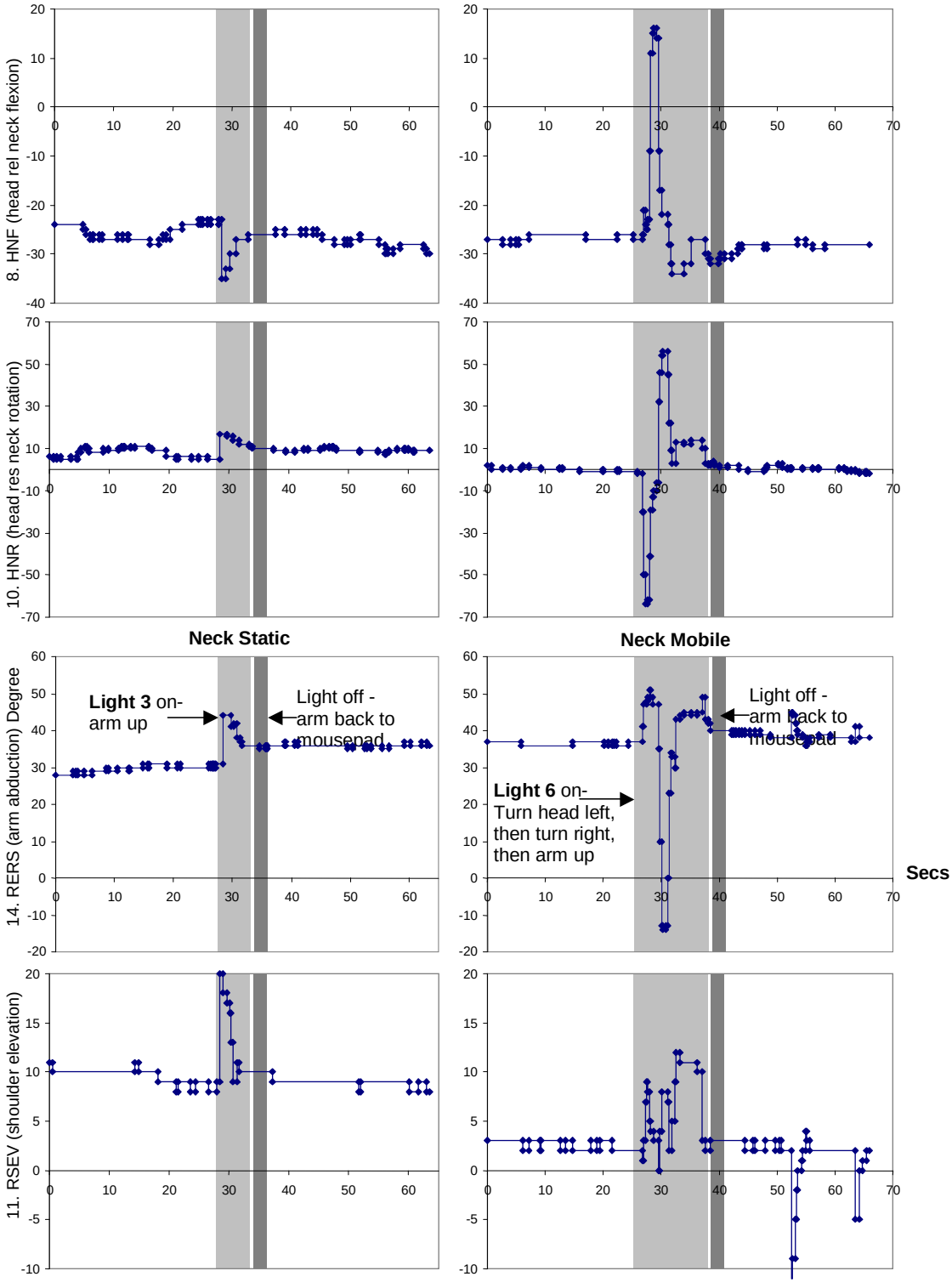
The left and right side graphs are for the neck-static and neck-mobile experiments, respectively. For the left side graphs, Light3 was turned on at 28.38 and off at 31.60secs. For the right side graphs, Light6 was turned on at 26.70 and off at 38.44secs. The horizontal axis of each graph is in secs. See Figure # in Ch. 4 for layout of the lights.

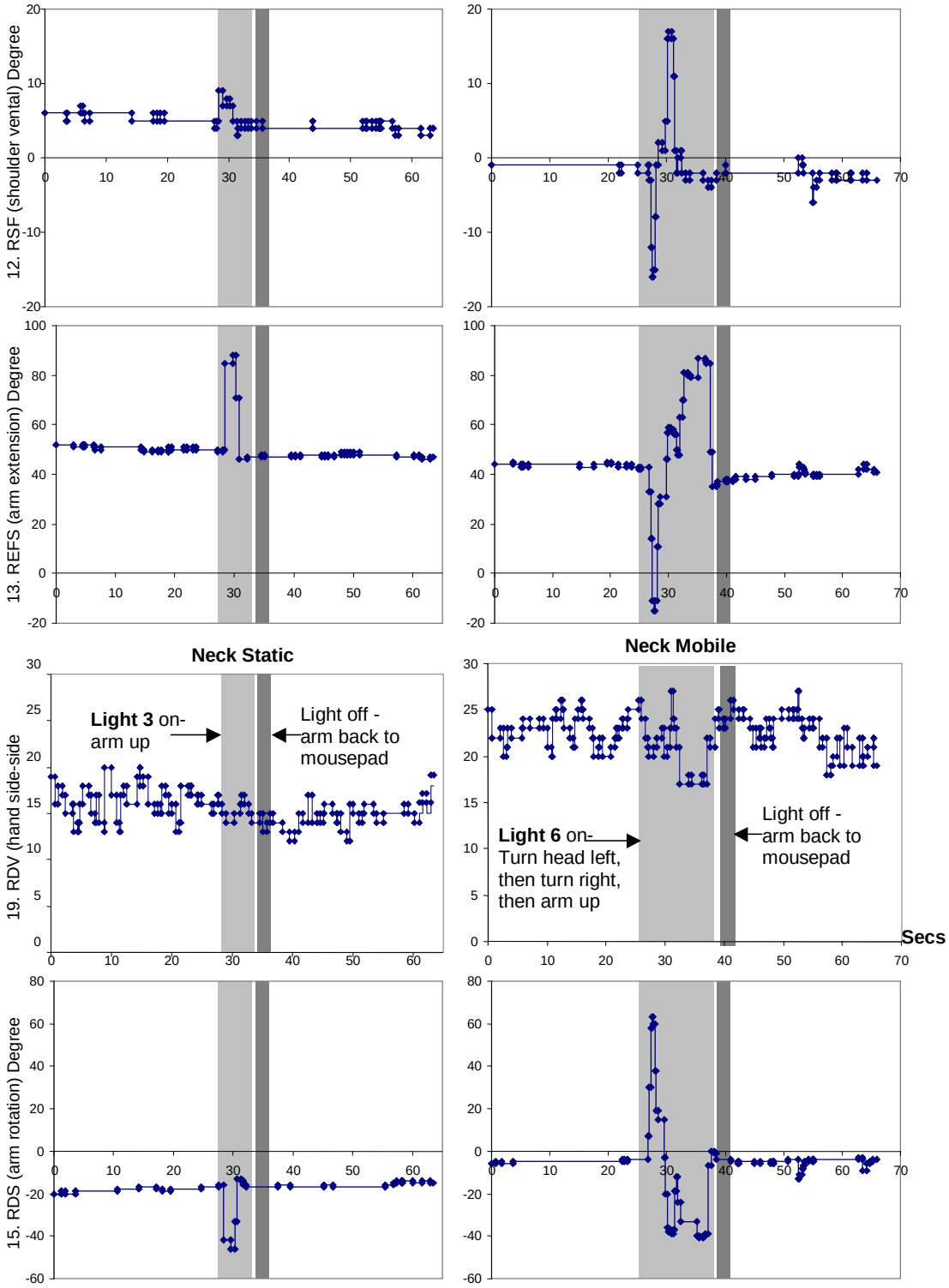
See Ch. 4 for a full description of this experiment that these graphs are derived from.

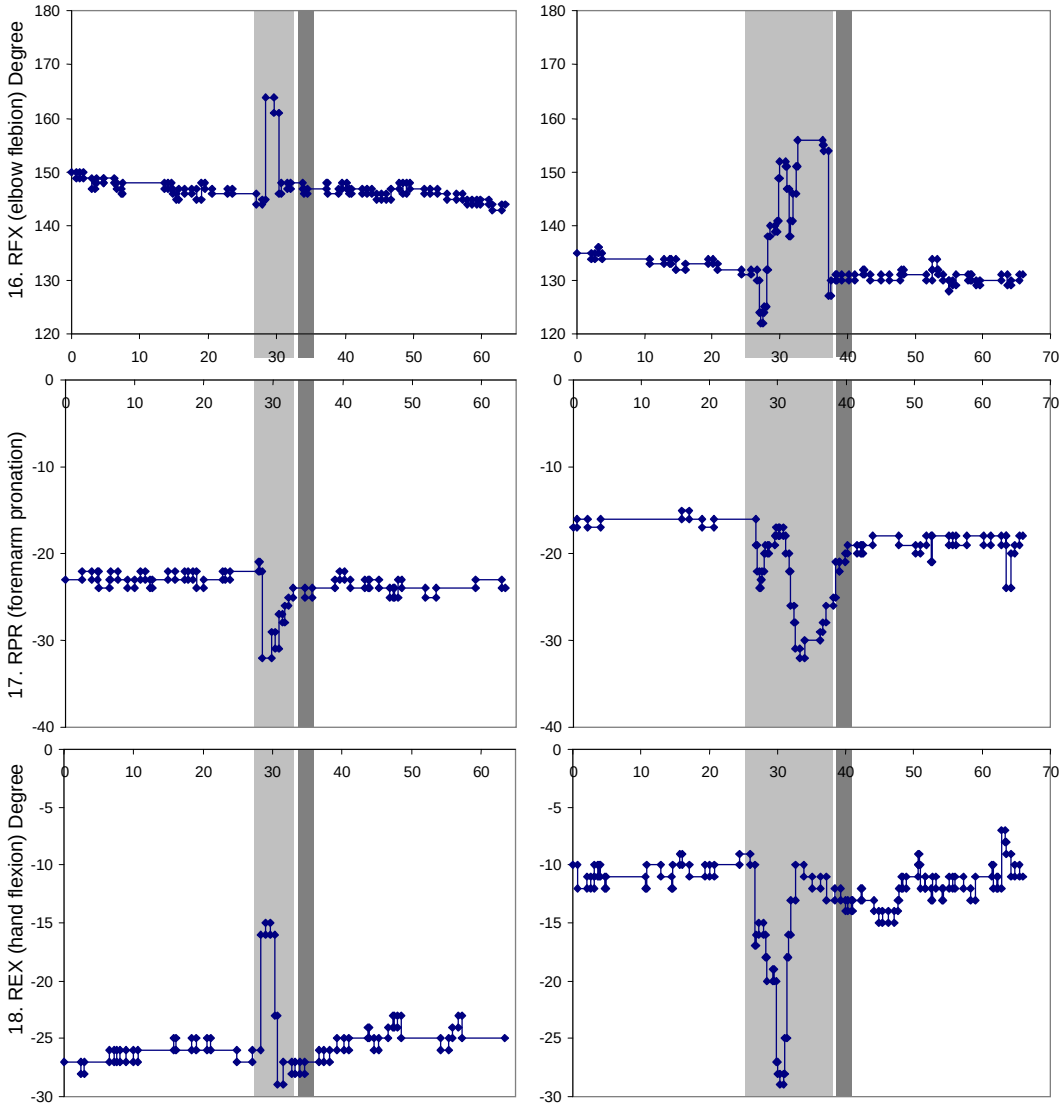
Figure D-1 – FWAP for Windows analysis graphs of each posture code for one participant from the Ch. 4 experiment. The left graphs are for the neck-static session, and the right for the neck-mobile.


Neck Static
Neck Mobile
Light 3 on- arm up
Light off - arm back to mousepad
Light 6 on- Turn head left, then turn right, then arm up
Light off - arm back to mousepad
1. SFH (trunk forward)
2. SSH (trunk side) Degree
4. C (trunk curvture) Degree
3. TR (trunk rotation)
Secs


5. HF (head flexion) Degree
6. HR (head rotation) Degree
Neck Static
Neck Mobile
9. HNT (head rel neck tilt) Degree
Light 3 on- arm up
Light off - arm back to mousepad
Light 6 on- Turn head left, then turn right, then arm up
Light off - arm back to mousepad
Secs
7. HT (head tilt) Degree


8. HNF (head rel neck flexion)
10. HNR (head res neck rotation)
Neck Static
Neck Mobile
14. RERS (arm abduction) Degree
Light 3 on- arm up
Light off - arm back to mousepad
Light 6 on- Turn head left, then turn right, then arm up
Light off - arm back to mousepad
Secs
11. RSEV (shoulder elevation)


12. RSF (shoulder ventral) Degree
13. REFS (arm extension) Degree
Neck Static
Neck Mobile
19. RDV (hand side-side
Light 3 on- arm up
Light off - arm back to mousepad
Light 6 on- Turn head left, then turn right, then arm up
Light off - arm back to mousepad
Secs
15. RDS (arm rotation) Degree


16. RFX (elbow flebion) Degree
17. RPR (forearm pronation)
18. REX (hand flexion) Degree

APPENDIX E

FWAP SPREADSHEET EXAMPLES (CHAP 5)

The FWAP for Windows© data spreadsheets for one participant measured during the experiment reported in Ch. 4 are shown below. Shown in Table E-1 and Table E-2 are the MODAPTS codes for each action undertaken by this one participant during one cycle. The posture of participant at the end of each MODAPTS action is reported on the same line for each posture code. For reasons of clarity, the MODAPTS code of a put with zero MOD units (P0) was not added after each mouse click move with one MOD unit (M1).

Table E-1 – FWAP for Windows analysis of one participant over a cycle (67 secs) during the neck static measurement session

		MODAPTS				FWAP POSTURE TRUNK				FWAP POSTURE HEAD						FWAP POSTURE ARM		FWAP POSTURE SHOULDER			FWAP POSTURE Forearm		FWAP POSTURE HAND			
		R	R	R	R	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19		
Right hand	No	M	T	T	Ot	SF	SS						HN	HN	HN	RS	RS	RE	RE	R	R	R	R	R	Timer1	Frame
Description		v	U	l	hr	H	H	TR	C	HF	HR	HT	F	T	R	EV	F	FS	RS	DS	FX	PR	EX	DV		No
	1	m2	2			-1	7	-10	13	-2	3	-3	-24	1	6	11	6	52	28	-20	150	-23	-27	19	0.9	9
	2		2	p2		-1	7	-10	13	-2	3	-3	-24	1	6	11	6	52	28	-20	150	-23	-27	19		
mouse click	3	m1	1			-1	7	-10	13	-2	3	-3	-24	1	6	10	6	52	28	-20	150	-23	-27	19	1.0	10
	4	m2	2			-1	7	-11	13	-2	3	-3	-24	1	5	10	6	52	28	-20	149	-23	-27	16	1.9	18
	5		2	p2		-1	7	-11	13	-2	3	-3	-24	1	5	10	6	52	28	-20	149	-23	-27	16		
	6	m2	2			-2	7	-11	13	-3	3	-3	-24	1	6	10	6	52	28	-19	150	-23	-27	18	2.3	22
	7		2	p2		-2	7	-11	13	-3	3	-3	-24	1	6	10	6	52	28	-19	150	-23	-27	18		
mouse click	8	m1	1			-1	7	-11	13	-3	3	-3	-24	1	6	10	6	52	28	-19	150	-23	-27	18	2.3	23
	9		4		/4	-1	7	-11	13	-2	3	-3	-24	1	5	10	6	52	28	-20	149	-23	-27	17	2.8	28
	10	m2	2			-1	7	-10	13	-2	3	-3	-24	1	5	10	6	52	28	-20	149	-22	-28	15	3.3	33
	11		2	p2		-1	7	-10	13	-2	3	-3	-24	1	5	10	6	52	28	-20	149	-22	-28	15		
mouse click	12	m1	1			-1	7	-10	13	-2	3	-3	-24	1	5	10	6	52	28	-20	149	-22	-28	15	3.4	34
	13		4		/4	-1	7	-11	13	-2	3	-3	-24	1	5	10	6	51	29	-20	147	-22	-27	15	4.0	39
mouse click	14	m1	1			-1	7	-10	13	-2	3	-3	-24	1	5	10	5	51	28	-20	148	-22	-27	15	4.1	40
mouse click	15	m1	1			-1	7	-11	13	-2	3	-3	-24	1	6	10	6	51	28	-19	148	-22	-27	16	4.3	43
	16	m2	2			-1	7	-11	13	-3	4	-3	-24	0	6	10	6	51	29	-19	149	-23	-27	13	5.0	50
	17		2	p2		-1	7	-11	13	-3	4	-3	-24	0	6	10	6	51	29	-19	149	-23	-27	13		
mouse click	18	m1	1			-1	7	-11	13	-3	4	-3	-24	0	6	10	6	51	29	-19	149	-23	-27	13	5.2	51
mouse click	19	m1	1			-1	7	-11	12	-3	4	-3	-24	0	6	10	6	52	29	-19	149	-23	-27	14	5.3	53
mouse click	20	m1	1			-1	7	-11	12	-3	4	-3	-24	0	6	10	6	52	29	-19	149	-23	-27	13	5.4	54
mouse click	21	m1	1			-1	7	-11	12	-3	3	-3	-24	0	5	10	6	51	29	-19	148	-22	-27	14	5.8	57
	22	m2	2			-1	7	-11	12	-4	6	-3	-25	0	8	10	6	52	28	-19	149	-24	-27	16	6.7	66
	23		2	p2		-1	7	-11	12	-4	6	-3	-25	0	8	10	6	52	28	-19	149	-24	-27	16		
	24	m2	2			-1	7	-11	12	-4	7	-2	-26	1	10	10	6	52	28	-19	149	-24	-27	18	7.0	69
	25		2	p2		-1	7	-11	12	-4	7	-2	-26	1	10	10	6	52	28	-19	149	-24	-27	18		
mouse click	26	m1	1			-1	7	-11	12	-5	8	-3	-26	1	10	10	7	52	28	-19	149	-24	-27	18	7.0	70
	27		2		/2	-1	7	-11	12	-5	8	-3	-27	1	11	10	7	52	28	-19	149	-24	-27	18	7.2	73
mouse click	28	m1	1			-1	7	-11	12	-5	8	-3	-27	1	11	10	6	52	29	-19	149	-24	-27	18	7.5	74
mouse click	29	m1	1			-1	7	-11	12	-5	8	-3	-27	0	10	10	6	51	29	-19	148	-23	-27	17	7.8	78
mouse click	30	m1	1			-1	7	-11	12	-5	8	-3	-26	0	10	10	6	51	29	-19	148	-23	-27	17	8.1	81
	31	m2	2			-1	7	-11	12	-5	6	-4	-27	-1	8	10	5	50	29	-19	147	-22	-26	15	8.7	87
	32		2	p2		-1	7	-11	12	-5	6	-4	-27	-1	8	10	5	50	29	-19	147	-22	-26	15		
mouse click	33	m1	1			-1	7	-11	12	-6	6	-4	-27	-2	8	10	5	50	29	-19	147	-22	-26	15	8.8	88
	34		1		/1	-1	7	-11	12	-6	6	-4	-27	-2	8	10	5	50	29	-19	147	-22	-27	14	8.9	90
mouse click	35	m1	1			-1	7	-11	12	-5	6	-4	-27	-1	8	10	6	50	29	-19	146	-22	-27	14	9.1	91
	36	m2	2			-1	7	-11	12	-5	6	-4	-26	-1	8	10	6	51	29	-19	148	-23	-26	17	9.4	94
	37		2	p2		-1	7	-11	12	-5	6	-4	-26	-1	8	10	6	51	29	-19	148	-23	-26	17		
	38	m2	2			-1	7	-11	12	-5	6	-4	-27	-1	8	10	6	51	29	-19	148	-23	-27	14	10.1	100
	39		2	p2		-1	7	-11	12	-5	6	-4	-27	-1	8	10	6	51	29	-19	148	-23	-27	14		
mouse click	40	m1	1			-1	7	-11	12	-5	6	-4	-27	-1	8	10	6	51	29	-19	148	-23	-27	14	10.1	101
mouse click	41	m1	1			-1	7	-11	12	-5	6	-4	-27	-2	8	10	6	51	30	-19	148	-23	-27	14	10.3	102
mouse click	42	m1	1			-1	7	-11	12	-5	6	-4	-27	-1	8	10	6	51	30	-19	148	-23	-27	13	10.5	105
	43	m2	2			-1	7	-11	12	-5	8	-4	-27	0	10	10	6	51	29	-19	148	-24	-26	20	10.8	108
	44		2	p2		-1	7	-11	12	-5	8	-4	-27	0	10	10	6	51	29	-19	148	-24	-26	20		
	45		2		/2	-1	7	-11	12	-5	8	-4	-27	0	10	10	6	51	29	-19	148	-24	-26	20	11.1	110
mouse click	46	m1	1			-1	7	-11	12	-5	7	-4	-27	-1	10	10	6	51	29	-19	148	-24	-26	20	11.1	111
mouse click	47	m1	1			-1	7	-11	12	-5	7	-4	-27	-1	9	10	6	51	29	-19	148	-24	-26	20	11.4	114
	48	m2	2			-2	7	-11	12	-5	7	-5	-27	-2	9	10	6	51	29	-19	148	-23	-27	17	11.8	118
	49		2	p2		-2	7	-11	12	-5	7	-5	-27	-2	9	10	6	51	29	-19	148	-23	-27	17		
mouse click	50	m1	1			-2	7	-12	12	-5	7	-5	-27	-2	9	10	6	51	30	-19	148	-23	-27	17	12.0	119
mouse click	51	m1	1			-2	7	-12	12	-5	7	-5	-26	-2	9	10	6	51	30	-18	148	-23	-27	17	12.1	121
mouse click	52	m1	1			-2	7	-12	12	-5	7	-5	-26	-2	9	10	6	51	30	-18	148	-23	-26	17	12.3	123
	53	m2	2			-2	7	-12	12	-5	7	-5	-26	-2	9	10	6	51	30	-18	148	-22	-26	14	13.1	130
	54		2	p2		-2	7	-12	12	-5	7	-5	-26	-2	9	10	6	51	30	-18	148	-22	-26	14		
mouse click	55	m1	1			-1	7	-12	12	-5	7	-5	-26	-2	9	10	6	51	30	-18	148	-22	-26	13	13.1	131
	56	m2	2			-2	7	-12	12	-6	8	-4	-27	-1	10	10	6	51	30	-18	148	-23	-26	17	13.7	137
	57		2	p2		-2	7	-12	12	-6	8	-4	-27	-1	10	10	6	51	30	-18	148	-23	-26	17		
mouse click	58	m1	1			-2	7	-12	12	-6	8	-4	-27	-1	11	10	6	51	30	-18	148	-23	-26	18	13.9	139
mouse click	59	m1	1			-2	7	-12	12	-5	8	-4	-27	-1	11	10	6	51	30	-18	148	-24	-26	18	14.2	142
mouse click	60	m1	1			-1	7	-12	12	-5	8	-4	-27	-1	11	10	6	51	30	-18	148	-24	-26	18	14.3	143
mouse click	61	m1	1			-1	7	-11	12	-5	8	-4	-26	-1	10	10	6	51	29	-18	148	-24	-26	18	14.5	145
wait	62		7		/7	-1	7	-12	12	-6	9	-4	-27	-2	11	10	6	51	30	-18	148	-23	-26	16	15.5	155
mouse click	63	m1	1			-1	7	-12	12	-6	9	-4	-27	-2	11	10	6	51	30	-18	148	-23	-26	16	15.6	156
	64		4		/4	-1	7	-12	12	-6	8	-5	-27	-2	10	10	6	51	30	-18	147	-23	-26	16	16.1	161
mouse click	65	m1	1			-1	7	-12	12	-6	8	-5	-27	-2	10	10	6	51	30	-18	148	-23	-26	16	16.2	162
	66	m2	2			-2	7	-12	13	-6	9	-4	-27	-2	11	11	5	50	30	-17	148	-23	-26	19	16.6	166
	67		2	p2		-2	7	-12	13	-6	9	-4	-27	-2	11	11	5	50	30	-17	148	-23	-26	19		
mouse click	68	m1	1			-2	7	-13	13	-6	10	-4	-27	-2	11	11	5	50	30	-17	147	-23	-26	20	16.8	167
	69	m2	2			-1	7	-13	13	-6	9	-5	-27	-3	11	10	5	49	31	-17	146	-22	-26	18	17.2	172
	70		2	p2		-1	7	-13	13	-6	9	-5	-27	-3	11	10	5	49	31	-17	146	-22	-26	18		
	71		2		/2	-1	7	-13	12	-6	9	-6	-27	-3	11	10	5	49	31	-17	145	-22	-26	19	17.5	175
mouse click	72	m1	1			-1	7	-13	13	-5	9	-6	-27	-3	11	10	5	49	30	-17	145	-22	-26	19	17.6	176
	73		3		/3	-1	7	-13	12	-5	8	-6	-27	-3	11	10	5	49	31	-17	147	-23	-25	19	18.0	180
	74	m2	2			-1	7	-13	12	-6	8	-6	-28	-3	11	10	5	50	31	-17	147	-23	-26	16	18.5	184
	75		2	p2		-1	7	-13	12	-6	8	-6	-28	-3	11	10	5	50	31	-17	147	-23	-26	16		
mouse click	76	m1	1			-1	7	-13	12	-6	8	-6	-28	-3	10	10	5	50	31	-17	146	-23	-26	16	18.6	186
	77		2		/2	-1	7	-13	12	-6	8	-6	-28	-3	10	10	5	50	31	-17	146	-23	-26	16	18.8	189
mouse click	78	m1	1			-1	7	-13	12	-6	8	-6	-28	-4	10	10	5	50	31	-17	146	-23	-26	16	19.0	190
	79	m2	2			-1	7	-13	12	-6	6	-7	-28	-4	9	10	5	49	31	-18	146	-22	-26	15	19.3	193
	80		2	p2		-1	7	-13	12	-6	6	-7	-28	-4	9	10	5	49	31	-18	146	-22	-26	15		
	81	m2	2			-1	7	-12	12	-5	6	-7	-27	-3	9	10	6	50	31	-18	147	-23	-26	16	19.8	197
	82		2	p2		-1	7	-12	12	-5	6	-7	-27	-3	9	10	6	50	31	-18	147	-23	-26	16		
mouse click	83	m1	1			-1	7	-12	12	-5	7	-6	-27	-3	9	9	6	50	31	-19	147	-23	-26	15	20.0	200
	84	m2	2			-1	7	-12	12	-5	6	-6	-26	-3	9	9	5	50	31	-19	145	-22	-25	18	20.8	208
	85		2	p2		-1	7	-12	12	-5	6	-6	-26	-3	9	9	5	50	31	-19	145	-22	-25	18		
mouse click	86	m1	1			-1	8	-12	12	-5	6	-6	-27	-3	9	9	5	49	31	-19	145	-22	-25	18	20.9	209
	87	m2	2			-1	8	-12	11	-6	6	-6	-27	-3	9	9	6	51	30	-19	148	-24	-26	17	21.8	218
	88		2	p2		-1	8	-12	11	-6	6	-6	-27	-3	9	9	6	51	30	-19	148	-24	-26	17		
	89	m2	2			-1	8	-12	12	-4	4	-6	-25	-3	6	9	5	50	30	-18	147	-24	-26	15	22.4	224
	90		2	p2		-1	8	-12	12	-4	4	-6	-25	-3	6	9	5	50	30	-18	147	-24	-26	15		
	91		4		/4	-1	8	-13	12	-4	5	-6	-25	-3	6	9	5	50	30	-18	147	-23	-26	16	22.6	226
mouse click	92	m1	1			-1	8	-13	12	-4	4	-6	-25	-4	6	9	5	50	30	-18	146	-23	-26	16	22.7	227
	93	m2	2			-1	8	-12	12	-4	4	-6	-25	-4	6	9	5	50	31	-18	146	-23	-25	13	23.2	232
	94		2	p2		-1	8	-12	12	-4	4	-6	-25	-4	6	9	5	50	31	-18	146	-23	-25	13		

FAP WA		MODAPTS				FWAP POSTURE TRUNK				FWAP POSTURE HEAD						FWAP POSTURE ARM		FWAP POSTURE SHOULDER			FWAP POSTURE Forearm		FWAP POSTURE HAND			
		R	R	R	R	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19		
Right hand	No	M	T	T	Ot	SF	SS						HN	HN	HN	RS	RS	RE	RE	R	R	R	R	R	Timer1	Frame
Description		v	U	l	hr	H	H	TR	C	HF	HR	HT	F	T	R	EV	F	FS	RS	DS	FX	PR	EX	DV		No
	95		3		/3	-1	8	-12	12	-4	3	-6	-25	-4	5	8	5	50	30	-18	146	-23	-26	14	23.6	236
	96	m2	2			-1	8	-12	11	-3	4	-6	-24	-3	6	9	5	51	30	-18	146	-23	-26	18	24.2	241
	97		2	p2		-1	8	-12	11	-3	4	-6	-24	-3	6	9	5	51	30	-18	146	-23	-26	18		
mouse click	98	m1	1			-1	8	-12	12	-3	4	-6	-24	-3	6	9	5	50	30	-18	146	-23	-26	18	24.4	244
	99	m2	2			-1	8	-12	12	-4	4	-6	-24	-4	6	9	5	50	30	-18	146	-23	-26	18	24.9	249
	100		2	p2		-1	8	-12	12	-4	4	-6	-24	-4	6	9	5	50	30	-18	146	-23	-26	18		
mouse click	101	m1	1			-1	8	-12	12	-4	4	-6	-24	-4	6	9	5	50	30	-18	146	-22	-26	17	25.1	251
	102		2		/2	-1	8	-12	12	-4	4	-6	-24	-4	6	9	5	50	30	-18	147	-22	-26	17	25.4	254
mouse click	103	m1	1			-1	8	-12	12	-4	4	-6	-24	-3	6	9	5	51	30	-18	147	-23	-26	18	25.5	255
	104		3		/3	-1	8	-12	12	-3	4	-6	-24	-3	6	9	5	51	30	-18	147	-23	-26	17	25.9	259
mouse click	105	m1	1			-1	8	-12	11	-3	4	-6	-24	-3	6	8	5	50	30	-18	146	-23	-26	17	26.0	260
	106	m2	2			-1	8	-12	11	-3	3	-6	-24	-4	5	8	5	50	30	-18	146	-22	-26	17	26.3	263
	107		2	p2		-1	8	-12	11	-3	3	-6	-24	-4	5	8	5	50	30	-18	146	-22	-26	17		
mouse click	108	m1	1			-1	8	-12	11	-3	3	-6	-24	-4	5	8	5	50	30	-18	146	-22	-26	16	26.4	264
	109		2		/2	-2	8	-12	11	-3	3	-6	-23	-4	5	9	5	50	30	-18	146	-22	-26	17	26.6	266
mouse click	110	m1	1			-2	8	-12	11	-3	4	-6	-23	-4	5	9	5	50	30	-17	146	-22	-26	17	26.6	267
mouse click	111	m1	1			-2	8	-12	11	-3	4	-6	-24	-4	5	9	5	50	30	-17	146	-22	-26	17	26.8	268
	112		1		/1	-2	8	-13	11	-3	4	-6	-24	-4	6	9	5	50	30	-17	146	-22	-27	16	26.9	270
mouse click	113	m1	1			-2	8	-13	11	-3	4	-6	-23	-4	6	9	5	50	30	-17	146	-22	-27	16	27.1	271
mouse click	114	m1	1			-2	8	-13	11	-3	4	-6	-23	-4	6	9	5	50	30	-17	146	-22	-27	16	27.2	272
mouse click	115	m1	1			-2	8	-13	11	-3	4	-6	-23	-4	6	9	5	50	30	-17	146	-22	-27	16	27.4	274
mouse click	116	m1	1			-2	8	-13	11	-3	4	-6	-23	-4	6	9	5	50	30	-17	146	-22	-27	16	27.7	277
	117		3		/3	-2	8	-13	11	-3	4	-6	-23	-4	6	9	5	50	30	-17	146	-22	-27	16	27.9	279
mouse click	118	m1	1			-2	8	-13	11	-4	4	-6	-24	-4	6	9	5	50	31	-17	146	-22	-27	16	27.9	280
mouse click	119	m1	1			-2	8	-13	11	-4	4	-6	-24	-4	6	9	5	50	31	-17	146	-22	-27	16	28.1	281
mouse click	120	m1	1			-2	8	-13	11	-4	4	-6	-24	-4	6	9	5	50	31	-17	146	-22	-27	16	28.2	282
	121		1		/1	-2	8	-13	11	-3	4	-6	-24	-4	6	9	5	50	30	-17	146	-22	-27	16	28.3	284
mouse click	122	m1	1			-2	8	-13	11	-3	4	-6	-23	-4	5	9	5	50	30	-17	146	-22	-27	16	28.5	285
mouse click	123	m1	1			-2	8	-13	11	-3	4	-7	-23	-4	5	8	5	50	31	-17	146	-22	-27	15	28.6	287
mouse click	124	m1	1			-2	8	-13	11	-3	3	-6	-23	-4	5	8	5	50	30	-17	146	-22	-27	15	28.8	288
	125		1		/1	-2	8	-13	11	-3	3	-7	-23	-4	5	8	5	50	31	-17	146	-22	-27	15	28.9	290
mouse click	126	m1	1			-2	8	-13	11	-3	3	-7	-23	-4	5	8	5	50	30	-17	146	-22	-27	16	29.1	291
	127	m2	2			-2	8	-13	11	-3	3	-7	-23	-4	5	8	5	49	31	-17	144	-22	-26	16	29.3	293
	128		2	p2		-2	8	-13	11	-3	3	-7	-23	-4	5	8	5	49	31	-17	144	-22	-26	16		
mouse click	129	m1	1			-2	8	-13	11	-3	3	-7	-23	-5	5	8	5	49	31	-16	144	-22	-26	16	29.4	294
mouse click	130	m1	1			-1	8	-13	11	-3	4	-7	-24	-5	5	8	4	49	31	-16	144	-22	-26	17	29.5	295
mouse click	131	m1	1			-2	8	-13	11	-4	4	-7	-23	-5	5	9	4	49	31	-16	145	-21	-26	16	29.9	299
Light3 on - wait	132		3		/3	-2	8	-13	11	-3	4	-6	-23	-4	5	9	5	50	31	-16	145	-22	-26	16	30.2	302
arm up	133	m5	5			0	8	-15	9	-16	12	-2	-35	4	17	20	9	85	44	-42	164	-32	-16	15	31.5	315
	134		5	p5		1	8	-16	10	-15	12	-1	-33	4	17	18	7	85	44	-42	164	-32	-15	14	31.6	316
arm up a bit	135	m3	3			1	8	-15	10	-12	12	-1	-30	4	16	17	8	88	41	-46	161	-29	-16	14	32.0	321
place dot carefully	136		2	p2		1	8	-15	10	-12	12	-1	-30	4	16	16	8	88	41	-46	161	-29	-16	14	32.2	322
mouse click and light off	137	m1	1			1	7	-13	9	-12	11	-2	-30	4	16	13	7	71	42	-33	146	-31	-23	15	32.5	325
	138		2	p2		1	7	-13	9	-12	11	-2	-30	4	16	13	7	71	42	-33	146	-31	-23	15		
arm back down	139	m5	5			0	7	-14	11	-9	11	-7	-27	-3	14	9	5	46	38	-13	148	-27	-29	15	32.8	328
place mouse on pad	140		2	p2		0	7	-15	11	-9	11	-6	-27	-4	14	11	3	46	37	-14	148	-28	-29	16	32.9	329
adjust mouse	141	m2	2			0	8	-14	11	-8	10	-5	-27	-2	12	10	4	46	36	-16	147	-26	-27	17	33.1	331
	142		2	p2		0	8	-14	11	-8	10	-5	-27	-2	12	10	4	46	36	-16	147	-26	-27	17		
	143		3		/3	0	8	-13	11	-8	11	-4	-27	-2	12	10	5	47	36	-17	148	-25	-27	16	33.4	334
mouse click	144	m1	1			0	8	-13	11	-7	11	-4	-27	-2	12	10	5	47	36	-17	148	-25	-27	16	33.4	335
mouse click	145	m1	1			0	8	-13	11	-7	11	-4	-27	-2	12	10	5	47	36	-17	148	-25	-27	16	33.6	336
	146	m2	2			0	8	-13	12	-7	10	-4	-26	-2	12	10	4	47	36	-17	148	-24	-28	15	34.2	342
	147		2	p2		0	8	-13	12	-7	10	-4	-26	-2	12	10	4	47	36	-17	148	-24	-28	15		
wait	148		4		/4	0	8	-13	11	-7	10	-4	-26	-3	11	10	5	47	36	-17	148	-24	-27	14	34.7	347
mouse click	149	m1	1			0	8	-13	11	-7	10	-4	-26	-3	11	10	4	47	36	-17	147	-24	-27	14	34.8	348
	150	m2	2			0	8	-13	11	-7	9	-5	-26	-3	10	10	4	47	36	-17	146	-24	-28	14	35.4	354
	151		2	p2		0	8	-13	11	-7	9	-5	-26	-3	10	10	4	47	36	-17	146	-24	-28	14		
mouse click	152	m1	1			0	8	-13	11	-7	9	-5	-26	-3	10	10	4	47	36	-17	146	-24	-28	14	35.5	355
	153	m2	2			0	8	-13	11	-6	9	-5	-26	-3	10	10	5	48	35	-17	147	-25	-27	15	36.1	362
	154		2	p2		0	8	-13	11	-6	9	-5	-26	-3	10	10	5	48	35	-17	147	-25	-27	15		
	155	m2	2			0	8	-13	11	-6	9	-5	-26	-3	10	10	5	47	35	-17	147	-25	-27	13	36.6	366
	156		2	p2		0	8	-13	11	-6	9	-5	-26	-3	10	10	5	47	35	-17	147	-25	-27	13		
mouse click	157	m1	1			0	8	-13	11	-6	9	-5	-26	-3	10	10	4	47	36	-17	147	-24	-27	13	36.8	369
	158		2		/2	0	8	-13	11	-6	9	-5	-26	-3	10	10	4	47	35	-17	147	-24	-27	14	37.1	372
mouse click	159	m1	1			0	8	-13	11	-6	9	-5	-26	-3	10	10	4	47	36	-17	147	-24	-27	14	37.3	373
	160		1		/1	0	8	-13	11	-6	9	-5	-26	-3	10	10	4	47	36	-17	147	-24	-27	14	37.4	375
mouse click	161	m1	1			0	8	-13	11	-6	9	-5	-26	-3	10	10	4	47	36	-17	147	-24	-27	14	37.6	376
	162		2		/2	0	8	-13	11	-6	9	-4	-26	-3	10	10	4	47	36	-17	147	-24	-27	15	37.8	378
mouse click	163	m1	1			0	8	-14	11	-6	9	-4	-26	-3	10	10	4	47	36	-17	147	-24	-26	15	37.9	379
	164	m2	2			0	8	-14	11	-7	9	-5	-26	-4	10	10	4	47	36	-17	147	-24	-26	14	38.3	383
	165		2	p2		0	8	-14	11	-7	9	-5	-26	-4	10	10	4	47	36	-17	147	-24	-26	14		
mouse click	166	m1	1			0	8	-14	11	-7	9	-5	-26	-4	10	9	4	47	36	-17	148	-24	-26	14	38.4	384
	167	m2	2			0	8	-14	11	-6	8	-5	-25	-4	9	9	4	47	36	-16	146	-24	-27	14	38.8	389
	168		2	p2		0	8	-14	11	-6	8	-5	-25	-4	9	9	4	47	36	-16	146	-24	-27	14		
wait	169		2		/2	0	9	-14	11	-6	8	-5	-25	-4	9	9	4	47	36	-16	146	-24	-27	14	39.1	392
mouse click	170	m1	1			0	9	-14	11	-6	8	-5	-25	-4	9	9	4	47	36	-16	146	-24	-27	14	39.3	393
	171	m2	2			0	9	-14	12	-6	8	-5	-25	-4	9	9	4	47	36	-16	146	-24	-26	13	39.9	399
	172		2	p2		0	9	-14	12	-6	8	-5	-25	-4	9	9	4	47	36	-16	146	-24	-26	13		
mouse click	173	m1	1			0	9	-14	12	-6	8	-5	-25	-4	9	9	4	47	37	-16	146	-23	-26	13	40.1	401
wait	174		3		/3	0	9	-14	11	-7	8	-5	-26	-4	9	9	4	47	36	-16	147	-23	-26	13	40.5	406
mouse click	175	m1	1			0	9	-14	11	-7	8	-5	-26	-4	9	9	4	47	36	-16	147	-23	-25	13	40.8	408
	176		6		/6	0	9	-14	12	-7	8	-5	-26	-4	8	9	4	48	36	-17	148	-22	-25	12	41.5	416
mouse click	177	m1	1			0	9	-14	11	-7	7	-4	-26	-4	8	9	4	47	36	-17	147	-23	-25	12	41.7	417
	178		1		/1	0	9	-14	11	-7	7	-5	-26	-4	8	9	4	47	36	-17	147	-23	-26	13	41.8	419
mouse click	179	m1	1			0	9	-14	11	-7	7	-5	-26	-4	8	9	4	47	36	-17	147	-23	-26	13	42.0	420
	180		2		/2	0	9	-14	11	-7	7	-5	-26	-4	8	9	4	47	37	-17	146	-23	-26	13	42.2	422
mouse click	181	m1	1			0	9	-14	11	-7	7	-5	-26	-4	8	9	4	47	37	-17	146	-23	-26	13	42.3	423
	182	m2	2			0	9	-14	11	-7	8	-4	-26	-4	9	9	4	48	36	-17	147	-24	-25	15	42.6	427
	183		2	p2		0	9	-14	11	-7	8	-4	-26	-4	9	9	4	48	36	-17	147	-24	-25	15		
mouse click	184	m1	1			0	9	-14	11	-7	8	-4	-26	-4	9	9	4	48	36	-17	147	-24	-25	15	42.8	428
wait	185		3		/3	0	9	-14	11	-6	8	-4	-25	-3	9	9	4	48	36	-17	147	-24	-25	14	43.2	432
mouse click	186	m1	1			0	9	-14	11	-6	8	-4	-25	-3	9	9	4	48	36	-17	147	-24	-25	14	43.2	433
	187		2		/2	0	9	-14	11	-6	9	-3	-25	-3	9	9	4	48	36	-17	147	-24	-25	14	43.5	435
mouse click	188	m1	1			0	9	-14	11	-6	9	-3	-25	-3	10	9	4	48	36	-17	147	-24	-25	14	43.5	436

		MODAPTS				FWAP POSTURE				FWAP POSTURE						FWAP POSTURE					FWAP POSTURE					
						TRUNK				HEAD						ARM		SHOULDER			Forearm		HAND			
		R	R	R	R	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19		
Right hand	No	M	T	T	Ot	SF	SS						HN	HN	HN	RS	RS	RE	RE	R	R	R	R	R	Timer1	Frame
Description		v	U	l	hr	H	H	TR	C	HF	HR	HT	F	T	R	EV	F	FS	RS	DS	FX	PR	EX	DV		No
	189	m2	2			0	9	-14	11	-6	9	-3	-26	-3	10	9	4	48	36	-17	146	-24	-25	17	43.9	439
	190		2	p2		0	9	-14	11	-6	9	-3	-26	-3	10	9	4	48	36	-17	146	-24	-25	17		
mouse click	191	m1	1			0	9	-14	11	-6	9	-3	-26	-3	10	9	4	48	36	-17	146	-24	-25	17	43.9	440
	192	m2	2			0	9	-14	11	-6	9	-3	-26	-3	9	9	4	48	36	-17	147	-23	-25	14	44.2	443
	193		2	p2		0	9	-14	11	-6	9	-3	-26	-3	9	9	4	48	36	-17	147	-23	-25	14		
mouse click	194	m1	1			0	9	-14	11	-6	8	-3	-25	-3	9	9	5	48	36	-17	147	-24	-24	14	44.5	445
mouse click	195	m2	2			0	9	-14	11	-6	8	-3	-25	-3	9	9	4	48	36	-17	146	-23	-25	14	44.6	447
	196		2		/2	0	9	-14	11	-6	8	-4	-25	-3	9	9	4	48	36	-17	146	-23	-25	15	44.9	449
mouse click	197	m1	1			0	9	-14	11	-6	8	-4	-26	-3	9	9	4	48	36	-17	146	-23	-25	15	45.0	450
mouse click	198	m1	1			0	9	-14	11	-6	8	-4	-26	-3	9	9	4	48	36	-17	146	-23	-25	15	45.0	451
	199		2		/2	0	9	-14	11	-6	8	-4	-26	-4	9	9	4	47	36	-17	145	-23	-26	14	45.2	453
mouse click	200	m1	1			0	9	-14	11	-6	8	-4	-26	-4	9	9	4	47	36	-17	145	-23	-26	14	45.4	454
mouse click	201	m1	1			0	9	-14	11	-6	8	-4	-26	-4	9	9	4	47	36	-17	145	-23	-26	14	45.5	455
mouse click	202	m1	1			0	9	-14	11	-7	9	-4	-26	-4	9	9	4	47	36	-16	145	-24	-26	15	45.6	457
	203	m2	2			0	9	-14	11	-7	10	-3	-27	-3	10	9	4	48	36	-16	146	-24	-25	16	46.2	463
	204		2	p2		0	9	-14	11	-7	10	-3	-27	-3	10	9	4	48	36	-16	146	-24	-25	16		
mouse click	205	m1	1			0	9	-14	11	-7	10	-3	-27	-3	11	9	4	47	36	-16	146	-24	-25	16	46.3	464
mouse click	206	m1	1			0	9	-14	11	-7	10	-3	-27	-3	11	9	4	47	36	-16	146	-24	-25	16	46.5	465
	207	m2	2			0	9	-14	11	-7	10	-3	-27	-3	11	9	4	47	36	-16	145	-24	-25	16	46.6	467
	208		2	p2		0	9	-14	11	-7	10	-3	-27	-3	11	9	4	47	36	-16	145	-24	-25	16		
mouse click	209	m1	1			0	9	-14	11	-7	10	-3	-27	-3	11	9	4	47	36	-16	145	-24	-25	16	46.8	468
	210	m2	2			0	9	-14	11	-7	10	-3	-27	-3	10	9	4	48	36	-17	147	-25	-24	15	47.3	474
	211		2	p2		0	9	-14	11	-7	10	-3	-27	-3	10	9	4	48	36	-17	147	-25	-24	15		
mouse click	212	m1	1			0	9	-14	11	-7	10	-3	-27	-3	11	9	4	48	36	-17	147	-25	-24	15	47.5	475
mouse click	213	m1	1			0	9	-14	11	-8	10	-4	-28	-4	10	9	4	48	36	-17	147	-24	-23	14	47.8	478
	214	m2	2			0	9	-14	11	-8	9	-4	-28	-4	10	9	4	48	36	-17	147	-25	-24	15	48.3	483
	215		2	p2		0	9	-14	11	-8	9	-4	-28	-4	10	9	4	48	36	-17	147	-25	-24	15		
	216	m2	2			0	9	-14	11	-8	9	-4	-28	-4	9	9	4	49	36	-17	148	-23	-23	13	48.6	486
	217		2	p2		0	9	-14	11	-8	9	-4	-28	-4	9	9	4	49	36	-17	148	-23	-23	13		
	218	m2	2			0	9	-14	12	-8	8	-4	-28	-5	9	9	4	48	36	-17	146	-24	-25	13	49.3	493
	219		2	p2		0	9	-14	12	-8	8	-4	-28	-5	9	9	4	48	36	-17	146	-24	-25	13		
	220	m2	2			0	9	-14	12	-7	8	-4	-27	-4	9	9	4	49	36	-17	148	-24	-25	12	50.1	502
	221		2	p2		0	9	-14	12	-7	8	-4	-27	-4	9	9	4	49	36	-17	148	-24	-25	12		
	222	m2	2			0	9	-14	11	-7	9	-4	-28	-4	9	9	4	48	35	-17	147	-24	-25	16	50.7	508
	223		2	p2		0	9	-14	11	-7	9	-4	-28	-4	9	9	4	48	35	-17	147	-24	-25	16		
	224		2		/2	0	9	-14	11	-7	9	-4	-27	-3	9	9	4	49	35	-17	147	-24	-25	15	51.0	510
mouse click	225	m1	1			0	9	-14	11	-7	9	-3	-27	-3	9	9	4	49	36	-17	147	-24	-25	15	51.0	511
mouse click	226	m1	1			0	9	-14	11	-7	9	-3	-27	-3	9	9	4	49	36	-17	147	-24	-25	15	51.2	512
	227	m2	2			0	9	-14	11	-7	9	-3	-27	-3	9	9	4	49	36	-17	147	-24	-25	15	51.3	513
	228		2	p2		0	9	-14	11	-7	9	-3	-27	-3	9	9	4	49	36	-17	147	-24	-25	15		
	229	m2	2			0	9	-14	12	-7	8	-4	-27	-4	9	9	4	48	36	-17	147	-24	-25	14	51.7	517
	230		2	p2		0	9	-14	12	-7	8	-4	-27	-4	9	9	4	48	36	-17	147	-24	-25	14		
mouse click	231	m1	1			0	9	-14	11	-6	8	-4	-26	-4	9	8	4	48	36	-17	146	-24	-25	15	51.8	518
mouse click	232	m1	1			0	9	-14	11	-6	8	-4	-26	-4	8	8	4	48	36	-17	146	-24	-25	15	52.0	521
mouse click	233	m1	1			0	9	-13	11	-6	8	-4	-27	-4	9	8	4	48	36	-17	146	-24	-25	15	52.2	522
	234	m2	2			0	9	-13	11	-7	8	-3	-27	-4	9	9	5	48	36	-17	146	-25	-25	16	52.4	525
	235		2	p2		0	9	-13	11	-7	8	-3	-27	-4	9	9	5	48	36	-17	146	-25	-25	16		
mouse click	236	m1	1			0	9	-13	11	-7	9	-3	-27	-4	9	9	4	48	35	-17	147	-25	-25	16	52.7	528
mouse click	237	m1	1			0	9	-13	11	-7	9	-3	-27	-3	9	9	5	48	35	-17	147	-25	-25	16	52.8	529
	238	m2	2			0	9	-13	11	-7	9	-3	-27	-3	9	9	5	48	36	-17	147	-25	-25	16	53.0	530
	239		2	p2		0	9	-13	11	-7	9	-3	-27	-3	9	9	5	48	36	-17	147	-25	-25	16		
mouse click	240	m1	1			0	9	-13	11	-6	9	-3	-27	-3	9	9	5	48	36	-17	147	-25	-25	16	53.0	531
mouse click	241	m1	1			0	9	-13	11	-6	9	-3	-27	-4	9	9	5	48	35	-17	147	-25	-25	16	53.3	533
	242	m2	2			0	9	-13	11	-6	9	-3	-27	-4	9	9	4	48	36	-17	146	-24	-25	15	53.6	537
	243		2	p2		0	9	-13	11	-6	9	-3	-27	-4	9	9	4	48	36	-17	146	-24	-25	15		
mouse click	244	m1	1			0	9	-13	11	-6	9	-3	-27	-4	9	9	4	48	36	-17	146	-24	-25	14	53.7	538
	245		3		/3	0	9	-13	11	-6	8	-4	-27	-4	9	9	5	48	36	-17	146	-24	-26	14	54.0	541
mouse click	246	m1	1			0	9	-13	11	-6	8	-4	-27	-4	9	9	4	48	36	-17	146	-24	-26	14	54.1	542
mouse click	247	m1	1			0	9	-13	11	-7	8	-4	-27	-4	9	9	5	48	36	-17	146	-24	-26	14	54.3	543
mouse click	248	m1	1			0	9	-13	11	-7	8	-4	-28	-4	8	9	4	48	36	-17	145	-24	-26	14	54.4	545
mouse click	249	m1	1			0	9	-13	11	-7	8	-4	-28	-4	8	9	5	48	36	-17	145	-24	-26	14	54.7	548
mouse click	250	m1	1			0	9	-13	11	-7	8	-4	-28	-4	8	9	5	48	36	-17	145	-24	-26	14	55.0	550
mouse click	251	m1	1			0	9	-13	11	-7	8	-4	-28	-4	8	9	5	48	36	-17	145	-24	-26	15	55.3	553
	252		3		/3	0	9	-13	11	-7	8	-4	-28	-4	8	9	5	48	35	-16	145	-24	-25	15	55.7	557
mouse click	253	m1	1			0	9	-13	11	-7	8	-4	-28	-4	8	9	5	48	35	-16	145	-24	-25	15	55.7	558
mouse click	254	m1	1			0	9	-13	11	-7	8	-4	-28	-4	8	9	5	48	35	-16	145	-24	-25	15	56.0	560
mouse click	255	m1	1			0	10	-13	11	-9	7	-4	-30	-5	7	9	5	48	35	-16	145	-24	-24	15	56.1	562
	256		2		/2	0	10	-14	11	-8	8	-4	-29	-5	8	9	5	48	35	-16	145	-24	-24	15	56.3	564
mouse click	257	m1	1			0	10	-14	11	-8	8	-4	-30	-5	8	9	5	48	35	-16	146	-24	-24	15	56.4	565
mouse click	258	m1	1			0	10	-14	11	-8	8	-4	-30	-5	8	9	5	48	35	-16	146	-24	-24	15	56.5	566
mouse click	259	m1	1			0	10	-14	11	-8	8	-4	-30	-5	8	9	5	48	36	-16	146	-24	-24	15	56.7	568
	260		3		/3	0	10	-14	11	-9	9	-4	-30	-5	9	9	4	48	36	-15	146	-24	-23	15	57.1	571
mouse click	261	m1	1			0	10	-14	12	-9	9	-4	-30	-5	9	9	4	48	36	-15	145	-24	-23	15	57.1	572
	262	m2	2			0	10	-15	12	-9	9	-4	-29	-6	9	9	3	47	36	-14	145	-24	-25	15	57.5	576
	263		2	p2		0	10	-15	12	-9	9	-4	-29	-6	9	9	3	47	36	-14	145	-24	-25	15		
mouse click	264	m1	1			0	10	-15	12	-9	9	-4	-29	-5	9	9	4	47	36	-14	145	-24	-25	15	57.7	577
mouse click	265	m1	1			0	10	-15	11	-8	10	-4	-29	-5	9	9	4	47	36	-14	144	-24	-25	15	57.9	580
	266		1		/1	0	9	-15	11	-8	10	-4	-29	-5	10	9	4	47	36	-14	144	-24	-25	15	58.0	581
mouse click	267	m1	1			0	9	-15	11	-8	10	-4	-29	-5	10	9	4	47	36	-15	144	-24	-25	15	58.1	582
	268		1		/1	0	9	-15	11	-8	10	-4	-29	-5	10	9	4	47	36	-14	144	-24	-25	15	58.2	583
mouse click	269	m1	1			0	9	-15	11	-8	10	-4	-29	-5	10	9	4	47	36	-14	144	-24	-25	15	58.4	584
	270	m2	2			0	9	-15	11	-7	10	-4	-28	-5	10	9	4	47	36	-14	145	-24	-25	16	58.8	588
	271		2	p2		0	9	-15	11	-7	10	-4	-28	-5	10	9	4	47	36	-14	145	-24	-25	16		
mouse click	272	m1	1			0	9	-15	12	-7	10	-3	-28	-5	10	9	4	47	36	-14	145	-24	-25	16	58.9	590
mouse click	273	m1	1			0	9	-15	11	-8	10	-4	-28	-5	9	9	4	47	37	-14	144	-23	-25	15	59.4	594
	274	m2	2			0	9	-15	12	-8	10	-4	-28	-5	10	9	4	47	37	-14	144	-23	-25	15	59.5	596
	275		2	p2		0	9	-15	12	-8	10	-4	-28	-5	10	9	4	47	37	-14	144	-23	-25	15		
mouse click	276	m1	1			0	9	-15	12	-8	9	-4	-28	-5	9	9	4	47	37	-14	145	-23	-25	15	59.7	597
mouse click	277	m1	1			0	9	-15	11	-8	9	-4	-28	-5	9	9	4	47	37	-14	145	-23	-25	15	59.7	599
mouse click	278	m1	1			0	9	-14	11	-8	9	-4	-28	-5	9	8	4	47	36	-15	145	-23	-25	15	60.1	601
	279	m2	2			0	9	-14	11	-8	8	-4	-28	-5	9	8	4	48	36	-15	145	-23	-25	14	60.5	605
	280		2	p2		0	9	-14	11	-8	8	-4	-28	-5	9	8	4	48	36	-15	145	-23	-25	14		
mouse click	281	m1	1			0	9	-14	11	-8	8	-4	-28	-5	8	8	4	48	36	-15	145	-23	-25	14	60.5	606
mouse click	282	m1	1			0	10	-14	11	-8	8	-4	-28	-5	8	8	4	48	36	-15	145	-23	-25	14	60.7	607

		MODAPTS				FWAP POSTURE TRUNK				FWAP POSTURE HEAD						FWAP POSTURE ARM		FWAP POSTURE SHOULDER			FWAP POSTURE Forearm		FWAP POSTURE HAND			
		R	R	R	R	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19		
Right hand	No	M	T	T	Ot	SF	SS						HN	HN	HN	RS	RS	RE	RE	R	R	R	R	R	Timer1	Frame
Description		v	U	l	hr	H	H	TR	C	HF	HR	HT	F	T	R	EV	F	FS	RS	DS	FX	PR	EX	DV		No
	283	m2	2			0	10	-14	11	-8	9	-4	-28	-5	9	8	4	47	36	-15	144	-23	-25	15	61.0	610
	284		2	p2		0	10	-14	11	-8	9	-4	-28	-5	9	8	4	47	36	-15	144	-23	-25	15		
	285	m2	2			0	10	-15	12	-7	9	-4	-28	-6	9	9	3	46	36	-14	143	-23	-25	16	61.4	615
	286		2	p2		0	10	-15	12	-7	9	-4	-28	-6	9	9	3	46	36	-14	143	-23	-25	16		
mouse click	287	m1	1			0	10	-15	12	-7	9	-4	-28	-6	9	9	3	46	37	-14	143	-23	-25	16	61.5	616
mouse click	288	m1	1			0	10	-15	12	-8	9	-4	-28	-6	9	9	3	46	37	-14	143	-23	-25	16	61.6	617
mouse click	289	m1	1			0	10	-15	12	-8	9	-4	-28	-6	9	9	3	46	37	-14	143	-23	-25	15	62.1	621
	290	m2	2			0	10	-15	11	-8	9	-4	-29	-6	9	9	3	46	37	-14	143	-23	-25	15	62.2	622
	291		2	p2		0	10	-15	11	-8	9	-4	-29	-6	9	9	3	46	37	-14	143	-23	-25	15		
	292	m2	2			0	9	-15	11	-9	9	-4	-30	-5	9	8	4	47	36	-15	144	-24	-25	18	62.4	625
	293		2	p2		0	9	-15	11	-9	9	-4	-30	-5	9	8	4	47	36	-15	144	-24	-25	18		

Table E-2 – FWAP for Windows analysis of one participant over a cycle (67 secs) during the neck mobile measurement session

		MODAPTS				FWAP POSTURE TRUNK				FWAP POSTURE HEAD						FWAP POSTURE ARM		FWAP POSTURE SHOULDER			FWAP POSTURE Forearm		FWAP POSTURE HAND			
		R	R	R	R	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19		
Right hand	No	M	T	T	Ot	SF	SS						HN	HN	HN	RS	RS	RE	RE	R	R	R	R	R	Timer1	Frame
Description		v	U	l	hr	H	H	TR	C	HF	HR	HT	F	T	R	EV	F	FS	RS	DS	FX	PR	EX	DV		No
	1	m2	2			1	7	-3	10	-21	2	4	-27	2	2	3	-1	44	37	-6	135	-17	-10	25	0.4	6
	2		2	p2		1	7	-3	10	-21	2	4	-27	2	2	3	-1	44	37	-6	135	-17	-10	25		
mouse click	3	m1	1			2	7	-3	10	-21	2	4	-27	2	2	3	-1	44	37	-6	135	-16	-10	25	0.5	7
	4	m2	2			1	7	-4	10	-22	1	4	-27	2	0	3	-1	44	37	-5	135	-16	-12	22	1.0	14
	5		2	p2		1	7	-4	10	-22	1	4	-27	2	0	3	-1	44	37	-5	135	-16	-12	22		
	6		4		/4	1	7	-3	10	-22	1	4	-27	2	0	3	-1	44	37	-5	135	-16	-12	22	1.4	19
mouse click	7	m1	1			1	7	-3	10	-22	1	4	-27	2	0	3	-1	44	37	-5	135	-16	-12	22	1.5	20
mouse click	8	m1	1			1	7	-3	10	-22	1	4	-27	2	0	3	-1	44	37	-6	135	-16	-12	22	1.6	22
mouse click	9	m1	1			1	7	-3	10	-22	1	4	-27	2	0	3	-1	44	37	-6	135	-16	-12	22	2.1	28
	10	m2	2			1	7	-3	10	-22	1	4	-27	2	0	3	-1	44	37	-6	134	-17	-11	23	2.7	36
	11		2	p2		1	7	-3	10	-22	1	4	-27	2	0	3	-1	44	37	-6	134	-17	-11	23		
	12	m2	2			1	7	-4	10	-22	1	4	-28	2	1	3	-1	44	37	-6	135	-17	-12	20	3.0	41
	13		2	p2		1	7	-4	10	-22	1	4	-28	2	1	3	-1	44	37	-6	135	-17	-12	20		
mouse click	14	m1	1			1	7	-4	10	-22	2	4	-28	2	1	3	-1	45	37	-6	136	-17	-11	21	3.2	42
	15	m2	2			1	7	-4	10	-23	2	4	-28	2	1	3	-1	44	37	-6	135	-17	-10	23	3.4	46
	16		2	p2		1	7	-4	10	-23	2	4	-28	2	1	3	-1	44	37	-6	135	-17	-10	23		
mouse click	17	m1	1			1	7	-4	10	-22	2	4	-28	2	1	3	-1	44	37	-5	134	-17	-11	23	3.5	47
mouse click	18	m1	1			1	7	-4	10	-22	2	4	-28	2	1	3	-1	44	37	-5	134	-17	-10	23	3.6	48
	19	m2	2			1	7	-4	10	-22	1	4	-27	2	0	3	-1	44	37	-5	134	-16	-11	22	3.9	53
	20		2	p2		1	7	-4	10	-22	1	4	-27	2	0	3	-1	44	37	-5	134	-16	-11	22		
mouse click	21	m1	1			1	7	-4	10	-22	1	4	-27	2	0	3	-1	44	37	-5	134	-16	-11	22	4.0	54
mouse click	22	m1	1			1	7	-3	10	-22	1	4	-27	2	0	3	-1	43	37	-5	134	-16	-11	22	4.2	56
mouse click	23	m1	1			1	7	-4	10	-22	1	4	-27	1	0	3	-1	44	37	-5	134	-16	-12	22	4.4	59
	24		3		/3	1	7	-4	10	-22	1	4	-28	2	0	3	-1	43	37	-5	134	-16	-11	22	4.7	64
mouse click	25	m1	1			1	7	-4	10	-22	1	4	-28	2	0	3	-1	43	37	-5	134	-16	-11	22	4.9	65
mouse click	26	m1	1			1	7	-4	10	-22	1	4	-27	2	0	3	-1	43	37	-5	134	-16	-11	22	5.0	68
mouse click	27	m1	1			1	7	-4	10	-22	1	4	-27	2	0	3	-1	43	37	-5	134	-16	-11	22	5.3	71
mouse click	28	m1	1			1	7	-4	10	-22	1	4	-27	2	0	3	-1	43	37	-5	134	-16	-11	23	5.5	74
mouse click	29	m1	1			1	7	-4	10	-22	2	5	-27	2	1	3	-1	44	36	-5	134	-16	-11	24	5.7	78
mouse click	30	m1	1			1	7	-4	10	-22	3	5	-27	2	1	3	-1	44	36	-5	134	-16	-11	24	6.0	80
mouse click	31	m1	1			1	7	-4	10	-22	3	5	-27	2	2	2	-1	44	36	-5	134	-16	-11	24	6.2	83
mouse click	32	m1	1			1	7	-4	10	-22	3	5	-27	2	2	2	-1	44	36	-5	134	-16	-11	24	6.3	85
mouse click	33	m1	1			1	7	-4	10	-22	3	4	-27	2	2	2	-1	44	36	-5	134	-16	-11	24	6.7	89
	34		4		/4	1	7	-4	10	-21	3	4	-27	2	2	2	-1	44	36	-5	134	-16	-11	24	7.1	95
mouse click	35	m1	1			1	7	-4	10	-21	3	4	-27	2	2	2	-1	44	36	-5	134	-16	-11	24	7.2	96
	36		6		/6	1	7	-4	10	-21	2	4	-26	2	1	3	-1	44	36	-5	134	-16	-11	23	8.0	107
mouse click	37	m1	1			1	7	-3	10	-21	2	5	-26	2	1	3	-1	44	36	-5	134	-16	-11	23	8.1	108
	38		4		/4	1	7	-4	10	-21	2	5	-26	2	1	3	-1	44	36	-5	134	-16	-11	23	8.5	114
mouse click	39	m1	1			1	7	-4	10	-21	2	4	-26	2	1	3	-1	44	36	-5	134	-16	-11	23	8.5	115
	40		4		/4	1	7	-3	10	-21	2	4	-26	2	1	3	-1	44	36	-5	134	-16	-11	24	9.1	122
mouse click	41	m1	1			1	7	-3	10	-21	2	4	-26	2	1	2	-1	44	36	-5	134	-16	-11	24	9.2	123
	42		5		/5	1	7	-4	10	-20	1	4	-26	2	0	3	-1	44	36	-5	134	-16	-11	23	9.8	132
mouse click	43	m1	1			1	7	-3	10	-20	1	4	-26	2	0	3	-1	44	36	-5	134	-16	-11	23	10.0	133
	44	m2	2			1	7	-3	10	-21	2	5	-26	1	0	3	-1	44	36	-5	134	-16	-11	21	10.8	145
	45		2	p2		1	7	-3	10	-21	2	5	-26	1	0	3	-1	44	36	-5	134	-16	-11	21		
mouse click	46	m1	1			1	7	-3	10	-21	2	5	-26	1	0	3	-1	44	36	-5	134	-16	-12	21	10.9	146
mouse click	47	m1	1			1	7	-3	10	-21	1	4	-26	1	0	3	-1	44	36	-5	134	-16	-12	20	11.2	150
	48	m2	2			1	7	-3	10	-21	2	4	-26	2	0	3	-1	44	36	-5	133	-16	-10	24	11.8	158
	49		2	p2		1	7	-3	10	-21	2	4	-26	2	0	3	-1	44	36	-5	133	-16	-10	24		
mouse click	50	m1	1			1	7	-3	10	-21	2	4	-26	2	0	3	-1	44	36	-5	133	-16	-10	24	11.8	159
mouse click	51	m1	1			1	7	-3	10	-21	2	4	-26	2	0	3	-1	44	36	-5	133	-16	-10	25	12.1	161
	52	m2	2			1	7	-4	10	-21	2	5	-26	1	0	3	-1	44	36	-5	133	-16	-10	24	12.6	169
	53		2	p2		1	7	-4	10	-21	2	5	-26	1	0	3	-1	44	36	-5	133	-16	-10	24		
mouse click	54	m1	1			1	7	-3	10	-21	1	5	-26	1	0	3	-1	44	36	-5	133	-16	-10	24	12.7	170
mouse click	55	m1	1			1	7	-4	10	-21	2	5	-26	1	0	3	-1	44	36	-5	133	-16	-10	26	13.0	174
mouse click	56	m1	1			1	7	-4	10	-20	2	5	-26	2	1	3	-1	44	36	-5	133	-16	-10	26	13.3	177
mouse click	57	m1	1			1	7	-3	10	-20	2	5	-26	2	1	3	-1	44	36	-5	133	-16	-10	26	13.6	181
	58		2		/2	1	7	-4	10	-20	2	4	-26	1	1	2	-1	44	36	-5	133	-16	-10	25	13.9	185
	59	m2	2			1	7	-3	10	-20	2	4	-26	1	0	2	-1	44	36	-5	134	-16	-11	23	14.4	192
	60		2	p2		1	7	-3	10	-20	2	4	-26	1	0	2	-1	44	36	-5	134	-16	-11	23		
mouse click	61	m1	1			1	7	-3	10	-20	2	4	-26	1	0	2	-1	44	36	-5	134	-16	-11	23	14.4	193
	62		2		/2	1	8	-3	10	-20	2	4	-26	1	0	3	-1	44	36	-5	134	-16	-11	23	14.7	197
mouse click	63	m1	1			1	8	-3	10	-20	2	4	-26	1	0	3	-1	44	36	-5	133	-16	-11	23	14.8	198
	64	m2	2			1	7	-4	10	-21	2	4	-26	1	0	3	-1	44	36	-5	134	-16	-11	22	15.1	202
	65		2	p2		1	7	-4	10	-21	2	4	-26	1	0	3	-1	44	36	-5	134	-16	-11	22		
	66		2		/2	1	7	-4	10	-21	2	4	-26	1	0	3	-1	44	36	-5	134	-16	-12	21	15.4	206
	67	m2	2			1	7	-4	10	-20	1	4	-26	1	0	2	-1	43	37	-5	132	-16	-10	24	16.2	216
	68		2	p2		1	7	-4	10	-20	1	4	-26	1	0	2	-1	43	37	-5	132	-16	-10	24		
	69		3		/3	2	8	-4	10	-20	1	4	-26	1	0	2	-1	43	37	-5	132	-16	-10	25	16.6	223
mouse click	70	m1	1			2	8	-4	10	-20	1	4	-26	1	0	2	-1	43	37	-5	132	-16	-10	25	16.8	224
mouse click	71	m1	1			2	8	-4	10	-21	1	4	-26	1	0	2	-1	43	37	-5	132	-16	-9	26	17.0	227
mouse click	72	m1	1			2	8	-4	10	-21	1	4	-26	1	-1	2	-1	43	37	-5	132	-16	-9	26	17.2	230
mouse click	73	m1	1			2	8	-4	10	-21	1	4	-26	1	-1	2	-1	43	37	-5	132	-15	-10	25	17.6	234
	74		7		/7	1	8	-4	10	-21	1	4	-26	1	-1	2	-1	43	37	-5	133	-15	-10	24	18.4	247
mouse click	75	m1	1			1	8	-4	10	-21	1	4	-27	1	-1	2	-1	43	37	-5	133	-16	-10	24	18.6	248
	76		3		/3	1	8	-4	10	-21	1	4	-27	0	-1	2	-1	44	37	-5	133	-16	-11	23	19.0	253
mouse click	77	m1	1			1	8	-4	10	-22	1	4	-27	0	-1	2	-1	44	37	-5	133	-16	-11	23	19.0	254
mouse click	78	m1	1			1	8	-4	10	-22	1	4	-27	0	-1	2	-1	44	37	-5	133	-16	-11	22	19.2	256
mouse click	79	m1	1			1	8	-4	10	-22	0	4	-27	0	-1	2	-1	44	37	-5	133	-16	-11	22	19.6	262
	80		6		/6	1	8	-4	10	-22	1	4	-27	0	-1	3	-1	44	37	-5	133	-16	-11	20	20.5	273
mouse click	81	m1	1			1	8	-4	10	-22	1	4	-27	0	-1	3	-1	44	37	-5	133	-16	-11	21	20.5	274
	82		4		/4	1	8	-4	10	-21	1	4	-27	0	-1	2	-1	44	37	-5	133	-17	-11	22	21.0	280
	83	m2	2			1	8	-4	10	-22	1	4	-27	1	-1	3	-1	45	37	-5	134	-17	-10	20	21.5	287
	84		2	p2		1	8	-4	10	-22	1	4	-27	1	-1	3	-1	45	37	-5	134	-17	-10	20		
mouse click	85	m1	1			1	8	-4	10	-22	1	4	-27	1	0	3	-1	45	37	-5	134	-17	-10	20	21.5	288
mouse click	86	m1	1			2	8	-4	10	-22	1	4	-27	1	-1	3	-1	45	37	-5	134	-17	-10	20	21.7	291
	87	m2	2			1	8	-4	10	-21	1	4	-27	0	-1	3	-1	44	36	-5	133	-17	-11	20	22.4	299
	88		2	p2		1	8	-4	10	-21	1	4	-27	0	-1	3	-1	44	36	-5	133	-17	-11	20		
mouse click	89	m1	1			1	8	-4	10	-21	1	4	-27	0	-1	3	-1	44	36	-5	133	-16	-11	20	22.6	300
	90	m2	2			2	8	-3	9	-21	1	4	-27	0	-1	3	-1	44	37	-5	132	-16	-10	21	22.8	304
	91		2	p2		2	8	-3	9	-21	1	4	-27	0	-1	3	-1	44	37	-5	132	-16	-10	21		
mouse click	92	m1	1			2	8	-4	10	-21	1	4	-27	0	-1	3	-1	44	37	-5	132	-16	-10	21	22.9	305
mouse click	93	m1	1			2	8	-4	10	-21	1	4	-27	0	-1	3	-1	43	37	-5	132	-16	-10	21	22.9	306
mouse click	94	m1	1			2	8	-4	10	-21	1	4	-27	0	-1	2	-1	43	36	-5	132	-16	-10	22	23.0	308

FWAP		MODAPTS				FWAP POSTURE TRUNK				FWAP POSTURE HEAD						FWAP POSTURE ARM		FWAP POSTURE SHOULDER			FWAP POSTURE Forearm		FWAP POSTURE HAND			
		R	R	R	R	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19		
Right hand	No	M	T	T	Ot	SF	SS						HN	HN	HN	RS	RS	RE	RE	R	R	R	R	R	Timer1	Frame
Description		v	U	l	hr	H	H	TR	C	HF	HR	HT	F	T	R	EV	F	FS	RS	DS	FX	PR	EX	DV		No
mouse click	95	m1	1			2	8	-4	10	-21	1	4	-27	0	-1	2	-1	43	36	-5	132	-16	-10	23	23.4	312
mouse click	96	m1	1			2	8	-4	10	-21	1	4	-27	0	-1	2	-2	43	37	-5	132	-16	-10	22	24.0	320
mouse click	97	m1	1			2	8	-4	10	-21	1	4	-27	0	-1	2	-2	43	37	-5	132	-16	-10	22	24.4	325
mouse click	98	m1	1			2	8	-4	10	-21	1	4	-27	0	-1	2	-2	43	37	-5	132	-16	-10	22	24.5	327
mouse click	99	m1	1			2	8	-3	10	-21	1	4	-27	0	-1	2	-1	43	36	-5	132	-16	-10	23	24.7	330
mouse click	100	m1	1			2	8	-3	10	-21	1	4	-27	0	-1	2	-1	43	36	-4	132	-16	-10	23	24.9	333
mouse click	101	m1	1			2	8	-4	10	-21	1	4	-26	0	0	2	-1	43	36	-4	132	-16	-10	23	25.1	336
mouse click	102	m1	1			2	8	-4	10	-21	1	4	-26	0	0	2	-1	43	36	-4	132	-16	-10	23	25.3	337
mouse click	103	m1	1			2	8	-4	10	-21	1	4	-26	0	0	2	-1	43	36	-4	132	-16	-10	24	25.5	340
	104	m2	2			2	8	-4	10	-21	1	4	-26	0	-1	2	-1	44	36	-5	132	-16	-10	23	26.3	351
	105		2	p2		2	8	-4	10	-21	1	4	-26	0	-1	2	-1	44	36	-5	132	-16	-10	23		
mouse click	106	m1	1			2	8	-4	10	-21	1	4	-26	0	-1	2	-1	44	36	-4	132	-16	-10	23	26.3	352
mouse click	107	m1	1			2	8	-4	10	-21	1	4	-26	0	-1	2	-1	44	36	-4	132	-16	-10	23	26.5	354
mouse click	108	m1	1			2	8	-4	10	-21	1	4	-26	0	-1	2	-1	43	36	-4	132	-16	-10	24	26.7	357
	109		5		/5	2	8	-4	10	-21	1	4	-26	0	-1	2	-1	43	36	-4	132	-16	-10	25	27.4	365
	110	m2	2			2	8	-4	10	-21	1	4	-26	0	-1	2	-1	43	37	-4	131	-16	-9	25	27.9	372
	111		2	p2		2	8	-4	10	-21	1	4	-26	0	-1	2	-1	43	37	-4	131	-16	-9	25		
mouse click	112	m1	1			2	8	-4	10	-21	1	4	-26	0	-1	2	-1	42	37	-4	131	-16	-9	25	28.0	374
mouse click	113	m1	1			2	8	-4	10	-21	1	4	-26	0	-1	2	-2	42	37	-4	131	-16	-9	25	28.4	378
	114		3		/3	2	8	-4	9	-21	1	4	-27	0	-1	2	-2	43	37	-4	131	-16	-9	25	28.7	383
mouse click	115	m1	1			2	8	-4	10	-21	1	4	-27	0	-1	2	-2	43	37	-4	131	-16	-9	26	28.8	384
mouse click	116	m1	1			2	8	-4	10	-21	0	3	-27	0	-1	2	-2	43	37	-4	131	-16	-9	26	29.0	387
mouse click	117	m1	1			2	8	-4	10	-21	1	4	-27	0	-1	2	-2	43	37	-4	132	-16	-9	26	29.4	391
Light3 on - wait	118		6		/6	2	8	-4	10	-21	0	4	-27	0	-2	2	-2	43	37	-4	132	-16	-10	24	30.1	401
head left	119		2		e2	-1	9	-14	9	-25	-21	7	-26	8	-20	1	-1	33	41	7	130	-19	-17	22	30.7	410
head left	120		2		e2	-2	12	-30	6	-20	-49	17	-21	15	-50	3	-3	14	47	30	124	-22	-16	21	30.9	412
head left	121		2		e2	-1	14	-49	6	-25	-59	20	-24	12	-64	7	-12	-11	47	58	122	-24	-15	20	31.1	414
new focus	122		4		e4	-2	16	-54	5	-29	-58	21	-25	11	-64	9	-16	-15	48	63	124	-23	-15	20	31.2	416
new fixation	123		2		e2	-3	17	-52	6	-28	-57	20	-23	12	-62	8	-15	-11	49	60	125	-22	-15	20	31.3	417
head returns	124		2		e2	-6	17	-40	7	-13	-39	9	-9	3	-41	5	-8	11	51	38	132	-20	-16	21	31.5	419
head returns	125		2		e2	-8	16	-30	7	5	-19	-2	11	-5	-19	4	-1	28	49	19	138	-19	-18	21	31.6	421
head returns	126		2		e2	-8	15	-27	8	11	-13	-3	15	-3	-13	4	2	31	47	15	140	-20	-20	22	31.7	423
new focus	127		4		e4	-8	15	-27	8	13	-10	-4	16	-2	-10	3	2	31	47	15	140	-19	-20	22	31.8	424
new fixation	128		2		e2	-8	14	-26	7	11	-5	-3	14	-1	-6	3	1	31	47	15	139	-19	-19	22	31.9	425
head right	129		2		e2	-4	8	-8	2	-10	32	-3	-9	1	32	0	1	46	35	-3	141	-18	-20	23	32.1	428
head right	130		2		e2	1	5	18	2	-16	46	-3	-17	-3	46	4	5	57	10	-20	149	-17	-27	20	32.2	430
head right	131		2		e2	8	4	45	8	-16	56	-4	-22	-5	54	8	16	59	-13	-36	152	-18	-28	20	32.5	433
new focus	132		4		e4	9	4	47	8	-15	56	-5	-22	-5	56	8	17	58	-14	-38	152	-17	-29	21	32.6	434
new fixation	133		2		e2	10	4	46	7	-14	56	-6	-22	-4	56	8	16	57	-13	-39	151	-18	-28	23	32.6	435
head returns	134		2		e2	8	4	35	7	-18	44	-7	-24	-4	45	7	11	56	0	-37	147	-20	-25	27	32.8	437
head returns	135		2		e2	5	5	12	10	-23	19	-6	-28	-2	22	2	1	50	23	-19	138	-20	-18	24	33.0	439
head returns	136		2		e2	4	5	2	11	-27	6	-3	-32	1	9	2	-2	48	34	-12	141	-22	-16	23	33.0	441
eye refocus on screen	137		4		e4	4	3	2	8	-29	1	2	-34	5	3	5	0	63	33	-24	146	-26	-13	21	33.3	443
eye new fixation	138		2		e2	4	3	1	7	-30	1	5	-34	8	3	9	1	70	30	-33	151	-28	-13	17	33.3	444
arm up	139	m5	5			9	2	-8	4	-30	10	3	-34	5	13	12	-2	81	43	-33	156	-31	-10	17	33.8	450
place carefully	140		5	p5		9	2	-8	4	-30	10	3	-34	5	13	11	-3	80	44	-33	156	-32	-10	17	33.8	451
arm move	141	m4	4			10	4	-8	4	-27	10	4	-32	5	12	11	-2	79	45	-33	156	-30	-11	18	34.2	456
move dot	142		5	p5		10	4	-8	4	-27	11	4	-32	5	12	11	-2	79	45	-33	156	-30	-11	17	34.2	457
arm move again	143	m4	4			11	5	-9	3	-25	14	4	-27	5	14	11	-2	87	44	-40	156	-30	-12	17	35.2	470
move dot carefully	144		5	p5		11	5	-9	3	-25	14	4	-27	5	14	11	-2	87	44	-41	156	-30	-12	17	35.3	471
hold and move a bit	145	m2	2			11	5	-9	3	-25	13	4	-27	5	14	10	-3	86	45	-40	155	-29	-11	18	35.7	476
just got the dot	146		5	p5		10	5	-9	3	-25	13	3	-27	5	14	10	-3	85	45	-39	154	-28	-11	17	35.8	477
mouse click and light off	147	m1	1			8	4	-6	6	-25	8	1	-27	4	10	3	-4	49	49	-7	127	-26	-13	22	36.0	481
	148		2	p2		8	4	-6	6	-25	8	1	-27	4	10	3	-4	49	49	-7	127	-26	-13	22		
arm down	149	m5	5			6	4	-3	10	-26	2	-2	-30	0	3	2	-3	35	43	0	130	-26	-13	21	36.2	484
put mouse on mouse pad	150		2	p2		5	4	-3	11	-26	1	-1	-31	0	2	2	-3	36	42	-1	131	-25	-13	21	36.4	485
adjust hand on mouse pad	151	m2	2			5	5	-2	11	-25	1	1	-32	3	3	3	-2	37	40	-4	130	-21	-12	24	36.8	491
	152		2	p2		5	5	-2	11	-25	1	1	-32	3	3	3	-2	37	40	-4	130	-21	-12	24		
mouse click	153	m1	1			5	5	-2	11	-25	1	1	-32	3	4	3	-2	37	40	-4	130	-22	-12	25	36.9	492
mouse click	154	m1	1			5	5	-2	11	-25	1	1	-32	4	3	3	-2	37	40	-4	130	-21	-12	25	37.1	494
	155	m2	2			5	5	-2	11	-24	0	1	-32	4	2	3	-2	37	40	-4	131	-21	-13	23	37.3	498
	156		2	p2		5	5	-2	11	-24	0	1	-32	4	2	3	-2	37	40	-4	131	-21	-13	23		
mouse click	157	m1	1			5	5	-2	11	-24	0	1	-32	4	2	3	-2	37	40	-4	131	-21	-13	23	37.4	499
mouse click	158	m1	1			5	5	-2	11	-24	0	1	-31	4	2	3	-2	38	40	-4	131	-20	-13	24	37.9	505
mouse click	159	m1	1			5	5	-2	11	-24	-1	1	-31	3	1	3	-1	37	40	-4	131	-20	-14	23	38.1	508
mouse click	160	m1	1			5	5	-2	11	-24	-1	1	-31	3	1	3	-2	38	40	-4	131	-20	-14	23	38.3	510
	161		4		/4	4	5	-2	10	-24	-1	1	-30	3	1	3	-2	37	40	-4	130	-19	-13	24	38.8	518
mouse click	162	m1	1			4	5	-2	10	-24	-1	1	-30	3	1	3	-2	37	40	-4	130	-19	-14	24	38.9	519
mouse click	163	m1	1			4	5	-2	10	-24	-1	1	-30	3	1	3	-2	37	40	-4	130	-19	-14	24	39.1	521
	164	m2	2			5	5	-2	10	-24	0	1	-31	4	1	3	-2	38	40	-5	131	-19	-13	26	39.6	529
	165		2	p2		5	5	-2	10	-24	0	1	-31	4	1	3	-2	38	40	-5	131	-19	-13	26		
mouse click	166	m1	1			5	5	-2	10	-24	0	2	-31	4	2	3	-2	38	40	-5	131	-19	-13	26	39.8	530
	167	m2	2			4	5	-2	10	-24	0	2	-31	4	2	3	-2	39	40	-5	131	-20	-13	25	40.1	534
	168		2	p2		4	5	-2	10	-24	0	2	-31	4	2	3	-2	39	40	-5	131	-20	-13	25		
mouse click	169	m1	1			4	5	-2	10	-24	0	2	-30	4	2	3	-2	39	39	-6	131	-19	-13	25	40.1	535
mouse click	170	m1	1			4	5	-2	10	-24	1	2	-30	4	2	3	-2	39	39	-5	132	-20	-12	25	40.4	539
	171	m2	2			4	6	-2	10	-24	1	2	-30	3	2	3	-2	39	40	-5	131	-19	-13	24	40.8	545
	172		2	p2		4	6	-2	10	-24	1	2	-30	3	2	3	-2	39	40	-5	131	-19	-13	24		
mouse click	173	m1	1			4	6	-2	10	-24	1	2	-30	3	2	3	-2	39	39	-5	131	-19	-13	24	41.0	546
mouse click	174	m1	1			4	6	-2	10	-24	1	2	-30	3	2	3	-2	39	39	-5	131	-19	-13	25	41.2	549
mouse click	175	m1	1			4	6	-2	10	-23	0	2	-29	3	2	3	-2	39	39	-5	131	-19	-13	25	41.4	553
	176	m2	2			4	6	-2	9	-22	-1	2	-28	3	0	3	-2	38	40	-5	130	-19	-13	24	42.3	564
	177		2	p2		4	6	-2	9	-22	-1	2	-28	3	0	3	-2	38	40	-5	130	-19	-13	24		
mouse click	178	m1	1			4	6	-2	9	-22	-1	2	-29	3	0	3	-2	38	40	-5	130	-18	-13	24	42.5	567
mouse click	179	m1	1			4	6	-2	10	-22	-1	2	-28	3	0	3	-2	38	39	-5	130	-18	-13	24	42.9	573
mouse click	180	m1	1			4	6	-2	10	-22	-1	2	-28	3	0	3	-2	38	39	-5	130	-18	-13	24	43.4	578
mouse click	181	m1	1			4	6	-2	9	-22	-1	2	-28	2	0	3	-2	38	39	-5	130	-18	-14	24	43.6	581
mouse click	182	m1	1			4	6	-2	9	-23	-1	2	-28	2	0	3	-2	38	40	-5	130	-18	-14	23	44.0	587
mouse click	183	m1	1			4	6	-2	9	-23	-1	1	-28	2	0	2	-2	38	40	-5	130	-18	-14	23	44.3	590
mouse click	184	m1	1			4	6	-2	9	-23	-1	1	-28	2	0	2	-2	38	40	-5	130	-18	-14	23	44.3	591
mouse click	185	m1	1			4	6	-2	9	-22	-1	1	-28	2	0	2	-2	38	40	-5	130	-18	-14	23	44.8	597
	186	m2	2			4	6	-2	9	-22	-2	1	-28	2	-1	2	-2	39	40	-6	131	-18	-15	21	45.2	602
	187		2	p2		4	6	-2	9	-22	-2	1	-28	2	-1	2	-2	39	40	-6	131	-18	-15	21		
	188	m2	2			4	6	-2	9	-22	-1	1	-28	2	-1	2	-2	39	39	-6	131	-18	-14	23	45.4	605

FAP WA		MODAPTS				FWAP POSTURE TRUNK				FWAP POSTURE HEAD						FWAP POSTURE ARM		FWAP POSTURE SHOULDER			FWAP POSTURE Forearm		FWAP POSTURE HAND			
		R	R	R	R	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19		
Right hand	No	M	T	T	Ot	SF	SS						HN	HN	HN	RS	RS	RE	RE	R	R	R	R	R	Timer1	Frame
Description		v	U	l	hr	H	H	TR	C	HF	HR	HT	F	T	R	EV	F	FS	RS	DS	FX	PR	EX	DV		No
	189		2	p2		4	6	-2	9	-22	-1	1	-28	2	-1	2	-2	39	39	-6	131	-18	-14	23		
mouse click	190	m1	1			4	6	-2	9	-22	-1	1	-28	2	-1	3	-2	39	39	-6	131	-18	-14	22	45.5	607
mouse click	191	m1	1			4	6	-2	9	-22	-1	1	-28	2	-1	3	-2	39	39	-5	131	-18	-14	23	45.7	610
	192	m2	2			4	6	-2	9	-23	-2	2	-28	2	-1	2	-2	39	40	-5	130	-18	-15	21	46.2	615
	193		2	p2		4	6	-2	9	-23	-2	2	-28	2	-1	2	-2	39	40	-5	130	-18	-15	21		
mouse click	194	m1	1			4	6	-2	9	-23	-2	2	-28	2	-1	2	-2	39	40	-5	130	-18	-15	21	46.2	616
mouse click	195	m1	1			4	6	-2	9	-22	-2	2	-28	2	-1	2	-2	39	40	-5	130	-18	-15	22	46.4	618
mouse click	196	m1	1			4	6	-2	9	-22	-2	2	-28	2	-1	2	-2	39	40	-5	130	-18	-15	22	46.8	624
	197	m2	2			4	6	-2	9	-22	-1	2	-28	2	-1	2	-2	39	39	-5	130	-18	-14	24	47.2	630
	198		2	p2		4	6	-2	9	-22	-1	2	-28	2	-1	2	-2	39	39	-5	130	-18	-14	24		
mouse click	199	m1	1			4	6	-2	9	-22	-1	2	-28	2	-1	2	-2	39	39	-5	130	-18	-13	24	47.4	632
mouse click	200	m1	1			4	6	-2	9	-22	-1	2	-28	2	-1	2	-2	39	39	-5	131	-18	-13	23	47.7	635
mouse click	201	m1	1			4	6	-2	9	-22	-1	2	-29	3	0	2	-2	40	39	-6	131	-19	-12	22	47.8	638
mouse click	202	m1	1			4	6	-2	9	-22	-1	2	-29	3	0	3	-2	40	39	-6	132	-19	-12	22	48.0	640
mouse click	203	m1	1			4	6	-2	9	-22	0	3	-29	3	1	3	-2	40	39	-5	132	-19	-11	21	48.3	644
mouse click	204	m1	1			4	6	-2	9	-22	0	3	-29	3	1	3	-2	40	39	-6	132	-19	-11	21	48.4	645
	205	m2	2			4	7	-2	9	-22	1	3	-28	3	2	3	-2	40	39	-5	131	-19	-12	24	48.9	652
	206		2	p2		4	7	-2	9	-22	1	3	-28	3	2	3	-2	40	39	-5	131	-19	-12	24		
	207	m2	2			4	7	-2	9	-22	2	3	-28	3	2	3	-2	40	38	-5	131	-19	-11	24	49.2	657
	208		2	p2		4	7	-2	9	-22	2	3	-28	3	2	3	-2	40	38	-5	131	-19	-11	24		
mouse click	209	m1	1			4	7	-2	9	-22	2	3	-28	3	2	3	-2	40	38	-5	131	-19	-11	24	49.4	658
mouse click	210	m1	1			4	7	-2	9	-22	2	3	-28	3	2	3	-2	40	38	-5	131	-19	-11	24	49.4	659
mouse click	211	m1	1			4	7	-2	9	-22	2	4	-28	3	2	2	-2	40	38	-5	131	-19	-11	24	49.6	662
	212	m2	2			4	7	-2	9	-22	2	4	-28	3	2	2	-2	40	38	-5	131	-19	-11	25	49.8	664
	213		2	p2		4	7	-2	9	-22	2	4	-28	3	2	2	-2	40	38	-5	131	-19	-11	25		
mouse click	214	m1	1			4	7	-2	9	-22	2	4	-28	3	3	2	-2	40	38	-5	131	-20	-11	25	49.9	665
mouse click	215	m1	1			4	7	-2	9	-22	2	4	-28	3	3	3	-2	40	38	-5	131	-20	-11	25	50.0	667
mouse click	216	m1	1			4	7	-2	9	-22	3	4	-28	4	3	3	-2	40	38	-5	131	-20	-10	25	50.3	671
mouse click	217	m1	1			4	7	-2	9	-22	3	4	-28	4	3	3	-2	40	38	-5	131	-20	-9	25	50.5	674
mouse click	218	m1	1			4	7	-2	9	-22	2	4	-28	3	3	2	-2	40	38	-4	131	-20	-10	25	50.7	675
	219	m2	2			4	7	-2	9	-22	1	4	-28	3	1	2	-2	40	38	-4	131	-19	-12	24	51.1	682
	220		2	p2		4	7	-2	9	-22	1	4	-28	3	1	2	-2	40	38	-4	131	-19	-12	24		
mouse click	221	m1	1			4	7	-2	9	-22	1	4	-28	3	1	2	-2	40	38	-4	131	-19	-12	24	51.3	683
mouse click	222	m1	1			4	7	-2	9	-22	1	4	-28	3	1	2	-2	40	38	-4	130	-19	-11	25	51.4	686
	223	m2	2			4	7	-2	9	-22	1	3	-28	3	0	2	-2	39	38	-4	130	-18	-12	24	51.8	691
	224		2	p2		4	7	-2	9	-22	1	3	-28	3	0	2	-2	39	38	-4	130	-18	-12	24		
mouse click	225	m1	1			4	7	-2	9	-21	1	3	-28	2	0	2	-2	39	38	-4	130	-18	-12	24	51.9	692
mouse click	226	m1	1			4	7	-2	9	-21	1	3	-28	3	1	2	-2	40	38	-4	130	-18	-12	25	52.3	696
mouse click	227	m1	1			4	7	-2	9	-21	1	3	-28	2	0	-11	0	44	45	-13	132	-21	-13	27	52.5	700
	228	m3	3			4	7	-2	9	-21	0	3	-28	2	0	-9	0	43	44	-11	134	-18	-11	24	52.6	701
	229		2	p2		4	7	-2	9	-21	0	3	-28	2	0	-9	0	43	44	-11	134	-18	-11	24		
mouse click	230	m1	1			4	7	-2	9	-21	0	3	-28	2	0	-5	-1	42	42	-8	132	-18	-12	23	52.8	703
mouse click	231	m1	1			4	7	-2	9	-21	0	3	-28	2	0	-2	-2	41	40	-7	131	-18	-12	22	52.9	705
	232	m3	3			4	7	-2	9	-21	0	3	-27	2	0	0	-2	40	39	-5	131	-18	-12	23	53.0	708
	233		2	p2		4	7	-2	9	-21	0	3	-27	2	0	0	-2	40	39	-5	131	-18	-12	23		
mouse click	234	m1	1			4	7	-2	9	-21	1	3	-27	2	0	1	-2	40	39	-5	130	-18	-13	23	53.2	709
mouse click	235	m1	1			4	7	-2	9	-21	1	3	-27	2	0	1	-2	40	39	-4	130	-18	-12	23	53.4	712
	236	m2	2			4	7	-2	9	-21	1	4	-27	2	1	2	-2	40	38	-4	130	-18	-12	24	53.7	716
	237		2	p2		4	7	-2	9	-21	1	4	-27	2	1	2	-2	40	38	-4	130	-18	-12	24		
mouse click	238	m1	1			4	7	-2	9	-22	1	4	-28	3	1	4	-6	39	36	-5	128	-18	-12	23	54.0	719
	239	m2	2			4	7	-2	9	-22	1	4	-28	3	1	3	-4	40	37	-4	130	-19	-11	24	54.2	723
	240		2	p2		4	7	-2	9	-22	1	4	-28	3	1	3	-4	40	37	-4	130	-19	-11	24		
	241	m2	2			4	7	-3	8	-22	1	4	-28	3	1	2	-3	39	38	-4	129	-18	-12	24	54.5	726
	242		2	p2		4	7	-3	8	-22	1	4	-28	3	1	2	-3	39	38	-4	129	-18	-12	24		
	243	m2	2			4	7	-3	8	-22	1	4	-29	3	0	2	-2	40	38	-4	131	-19	-11	21	55.1	734
	244		2	p2		4	7	-3	8	-22	1	4	-29	3	0	2	-2	40	38	-4	131	-19	-11	21		
	245		3		/3	4	7	-2	9	-22	1	4	-29	3	0	2	-2	40	38	-4	131	-19	-11	22	55.4	739
mouse click	246	m1	1			4	7	-2	9	-22	1	4	-29	3	1	2	-2	40	38	-4	131	-19	-11	22	55.6	740
mouse click	247	m1	1			4	7	-2	9	-22	1	4	-29	3	1	2	-2	40	38	-4	131	-19	-11	22	55.9	744
	248	m2	2			4	7	-3	8	-23	0	3	-29	2	0	2	-2	40	39	-4	131	-19	-12	18	56.7	756
	249		2	p2		4	7	-3	8	-23	0	3	-29	2	0	2	-2	40	39	-4	131	-19	-12	18		
	250		2		/2	4	7	-3	8	-23	0	3	-29	2	0	2	-2	40	39	-4	130	-18	-12	18	56.9	758
mouse click	251	m1	1			4	7	-3	8	-23	0	3	-29	2	0	2	-2	40	39	-4	130	-18	-12	19	56.9	759
mouse click	252	m1	1			4	7	-3	8	-23	0	3	-29	2	0	2	-2	40	39	-4	131	-18	-12	19	57.2	761
	253	m2	2			4	8	-3	9	-22	0	3	-28	2	0	2	-3	40	39	-4	130	-18	-13	20	57.9	772
	254		2	p2		4	8	-3	9	-22	0	3	-28	2	0	2	-3	40	39	-4	130	-18	-13	20		
mouse click	255	m1	1			4	8	-3	8	-22	0	4	-28	2	0	2	-3	40	39	-4	130	-18	-13	20	58.1	774
mouse click	256	m1	1			4	8	-3	8	-22	0	4	-28	2	0	2	-2	40	39	-4	130	-18	-13	20	58.2	776
	257	m2	2			4	8	-2	8	-22	1	4	-28	2	0	2	-3	40	38	-4	129	-18	-11	22	58.8	783
	258		2	p2		4	8	-2	8	-22	1	4	-28	2	0	2	-3	40	38	-4	129	-18	-11	22		
	259	m2	2			4	8	-3	8	-22	0	4	-28	2	0	2	-3	40	38	-4	130	-18	-11	19	59.2	790
	260		2	p2		4	8	-3	8	-22	0	4	-28	2	0	2	-3	40	38	-4	130	-18	-11	19		
mouse click	261	m1	1			4	8	-3	8	-22	0	4	-28	2	0	2	-3	40	38	-4	130	-18	-11	19	59.4	791
	262	m2	2			4	8	-2	8	-22	1	4	-28	3	0	2	-3	40	38	-4	130	-19	-11	23	59.7	796
	263		2	p2		4	8	-2	8	-22	1	4	-28	3	0	2	-3	40	38	-4	130	-19	-11	23		
	264	m2	2			4	8	-2	9	-21	1	4	-28	3	1	2	-3	40	38	-4	130	-19	-11	21	60.0	800
	265		2	p2		4	8	-2	9	-21	1	4	-28	3	1	2	-3	40	38	-4	130	-19	-11	21		
mouse click	266	m1	1			4	8	-2	8	-21	1	4	-28	3	1	2	-3	40	38	-4	130	-18	-11	21	60.1	801
mouse click	267	m1	1			4	8	-3	8	-21	1	4	-28	3	1	2	-2	40	38	-4	130	-18	-11	21	60.3	804
mouse click	268	m1	1			4	8	-3	8	-21	1	5	-28	3	1	2	-3	40	38	-4	130	-18	-10	21	60.7	808
	269	m2	2			4	8	-3	8	-21	0	4	-28	2	0	2	-3	40	38	-4	130	-18	-12	19	61.4	819
	270		2	p2		4	8	-3	8	-21	0	4	-28	2	0	2	-3	40	38	-4	130	-18	-12	19		
mouse click	271	m1	1			4	8	-3	8	-21	0	4	-28	2	-1	2	-3	40	38	-4	130	-18	-11	19	61.8	824
	272	m2	2			4	8	-3	8	-21	0	4	-28	2	-1	2	-3	40	38	-4	130	-18	-12	19	62.4	831
	273		2	p2		4	8	-3	8	-21	0	4	-28	2	-1	2	-3	40	38	-4	130	-18	-12	19		
	274	m2	2			4	8	-3	8	-21	1	5	-28	3	0	2	-3	42	37	-3	131	-19	-7	22	63.3	844
	275		2	p2		4	8	-3	8	-21	1	5	-28	3	0	2	-3	42	37	-3	131	-19	-7	22		
mouse click	276	m1	1			4	8	-3	9	-22	1	5	-28	3	0	2	-3	42	37	-3	131	-19	-8	20	63.6	848
mouse click	277	m1	1			4	8	-3	8	-22	0	4	-28	2	-1	2	-3	42	37	-4	131	-18	-9	19	64.0	854
	278	m3	3			4	8	-2	9	-22	-1	4	-28	3	-1	-5	-2	44	41	-9	129	-24	-9	20	64.2	857
	279		2	p2		4	8	-2	9	-22	-1	4	-28	3	-1	-5	-2	44	41	-9	129	-24	-9	20		
	280	m2	2			4	8	-2	9	-21	-1	4	-28	3	-2	0	-3	42	38	-6	130	-20	-11	21	64.8	863
	281		2	p2		4	8	-2	9	-21	-1	4	-28	3	-2	0	-3	42	38	-6	130	-20	-11	21		
	282	m2	2			4	8	-2	9	-21	-1	5	-28	3	-2	1	-3	42	38	-5	130	-19	-10	21	65.1	868

		MODAPTS				FWAP POSTURE TRUNK				FWAP POSTURE HEAD						FWAP POSTURE ARM		FWAP POSTURE SHOULDER			FWAP POSTURE Forearm		FWAP POSTURE HAND			
		R	R	R	R	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19		
Right hand	No	M	T	T	Ot	SF	SS						HN	HN	HN	RS	RS	RE	RE	R	R	R	R	R	Timer1	Frame
Description		v	U	l	hr	H	H	TR	C	HF	HR	HT	F	T	R	EV	F	FS	RS	DS	FX	PR	EX	DV		No
	283		2	p2		4	8	-2	9	-21	-1	5	-28	3	-2	1	-3	42	38	-5	130	-19	-10	21		
mouse click	284	m1	1			4	8	-2	9	-21	-1	5	-28	3	-1	1	-3	42	38	-4	130	-19	-10	22	65.2	869
	285	m2	2			4	8	-2	9	-21	-1	5	-28	2	-2	2	-3	41	38	-4	131	-18	-11	19	65.8	877
	286		2	p2		4	8	-2	9	-21	-1	5	-28	2	-2	2	-3	41	38	-4	131	-18	-11	19		

APPENDIX F

THE MODIFIED TISSUE COMPLIANCE METER: RELIABILITY AND ACCURACY (CHAP 6)

F.1 INTRODUCTION

The poor inter-examiner reliability of passive spinal manual palpation (motion palpation) by manual therapists has lead to the development of objective quantitative techniques for *in vivo* musculoskeletal assessment [109]. Various mechanised stiffness measurement devices have been developed by researchers. The mechanised force application devices are fixed to rigid support frames and research has generally focused on the lumbar and thoracic spine regions. They would be limited in their ability to measure awkward body locations at varying angles.

Palpation for spinal pain has demonstrated good reliability and is advocated by some as the preferred clinical examination method [512,535,541-545]. Currently, mechanised stiffness measurement devices do not provide for objective pain measurement during assessment.

The tissue compliance meter[20] (TCM) developed by Fischer [569,608] is a hand held non-mechanised device that can be applied in the clinical setting to awkward body areas at varying application angles (see Figure F-1). This instrument was developed to provide quantitative and objective data regarding the compliance of soft tissues including muscle tone [608], where muscle tone is determined by both the passive elasticity of muscular (and fibrous) tissues (natural elasticity of the muscular and fibrous tissues) and by the active (though not continuos) contraction of muscle in response to the reaction of the nervous system [609]. Tissue compliance is defined as

[20] Pain Diagnostics and Thermography, Great Neck, NY 11021, USA

the amount of displacement produced by a given force [393]. The TCM consists of a shaft with a rubber tip that is pressed into the skin, displacing the skin surface. This displacement is measured by a disc-shaped collar (the slide collar) that surrounds the shaft and purportedly remains at the original skin surface level. The slide collar indicates depth of tip penetration visually along a ruler embedded in the shaft. An analogue force gauge at the top of the shaft measures the applied force.

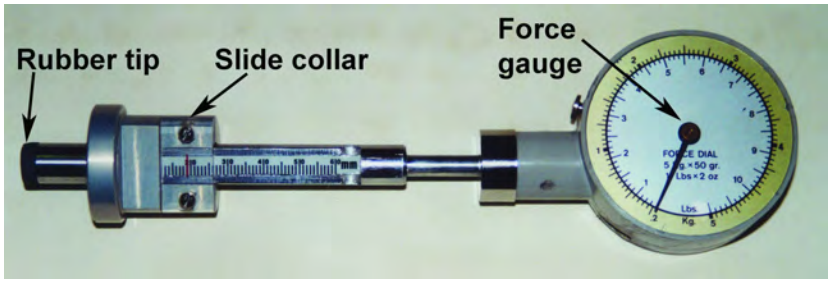


Figure F-1 – Original tissue compliance meter (TCM)

The shaft and rubber tip of the TCM are the same as the Algometer instrument (Pain Diagnostics and Thermography) that was also developed by Fischer in the late 1980's [373,374]. The Algometer is a reliable instrument [373,379,388,610] that provides a semi-objective [611] measurement method for the quantification of pain, which in clinical practice is assessed by palpation [371]. The tenderness or pressure pain sensitivity is expressed quantitatively by the pain pressure threshold (PPT), which is defined as the minimum applied force that induces pain or discomfort [371,374]. Measurements taken with a TCM may provide a PPT measurement similarly to the Algometer providing the user with an objective measurement of pain. This is discussed further in Sec. F.3.7.

The TCM has been used in several research investigations [57,579,612-615] and preliminary studies suggested the instrument had good reliability [393,616,617]. However, Kawchuk et al. [618] tested the instrument on homogeneous foam surfaces and results demonstrated that the TCM had poor reliability and accuracy. Kawchuk et al. [618] identified several shortcomings with the instrument design and instrument application. The resolution of the force and displacement scales required the examiner to make a subjective judgement between markings on these scales. The rubber tip at the end of the shaft compressed resulting in inaccurate displacement estimates. The slide collar that measured displacement was found to fall into the depression created by the application of force to the foam surfaces and therefore failed to remain at the original

surface location, thus underestimating the true displacement. Examiners reported difficulty in applying the TCM in a perpendicular orientation to the measured surface. Non-perpendicular application resulted in premature displacement of the collar causing inaccurate displacement measurements.

A modified-tissue compliance meter (M-TCM) has been developed to address some of the shortcomings of the original design and is the subject of this paper. The M-TCM was developed in order to measure musculoskeletal tissue stiffness *and pain* (similarly to the Algometer) in the posterior aspect of the cervical spine. The shaft, rubber tip and slide collar were retained whereas the analogue force and displacement transducers were replaced with a load cell and linear variable differential transducer (LVDT). An electromagnetic tracking system (ETS) was also incorporated with the M-TCM for examiner guidance assistance. The combination of a load cell and LVDT for tissue stiffness assessment is not a novel development and has been reported previously [114,116,118]. However, these measurement systems are fixed to rigid support frames that may limit their applicability to some body areas; whereas the M-TCM is a hand held device that has potential for application to awkward body areas at varying orientations. Also, objective pain measurement (expressed as PPT) has not been incorporated with mechanised tissue stiffness measurement devices. This investigation reports the reliability and accuracy of the individual components of the M-TCM and the system as a whole when tested on homogenous foam samples, wooden blocks of different depths and a control surface.

F.2 MATERIALS AND METHODS

F.2.1 MODIFIED-TISSUE COMPLIANCE METER (M-TCM)

A beam type load cell[21] and a linear variable differential transducer[22] replaced the TCM's analog force and displacement transducers respectively. An analogue to digital (A/D) computer card converted analogue voltage signals from the load cell and the

[21] LPS Single-Point $\pm 10kg$, Heastern Industries, 6/167 Whitehorse Rd, Blackburn, Vic, Australia

[22] Solartron B15 stroke $\pm$ 15mm, Davidson, 17 Roberna St, Moorabbin, Vic, Australia

LVDT to digital data at 160Hz, which was the card's default rate. Two buttons were placed on the handle of the M-TCM to provide the examiner with controls to start and stop recording. A personal computer (PC) was used to display and record data from the A/D card using the software program Visual Designer[23] v3.0. Visual Designer recorded the load cell and LVDT voltages and time (ms).

A 'Flock of Birds' electromagnetic tracking system[24] (ETS) was incorporated with the M-TCM for guidance assistance during instrument application. The ETS consists of an 'electronics card' which drives a 'transmitter' and a 'sensor'. The transmitter generates an electromagnetic field that is detected by the sensor. The signal from the sensor is processed by the electronics card and the 3-dimensional position (X, Y, Z) and orientation (elevation, roll, azimuth) of the sensor *relative* to the transmitter is determined [336] (see Figure F-2). A custom written computer program was developed using Microsoft Visual Basic v6.0 that enabled communication between the ETS and the PC.

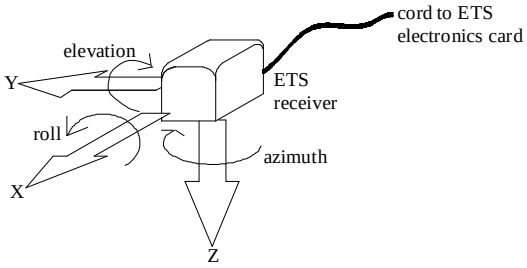


Figure F-2 – Axes of the electromagnetic tracking system

Metallic items placed near the sensor can interfere with the operation of the ETS [502]. To avoid the influence of metal components in the M-TCM the ETS sensor was mounted at one end of a wooden beam of length 190mm; the other end was attached to the M-TCM. The length of the wooden beam was determined by firstly fixing the sensor to a specific location and noting the ETS output without the M-TCM. The M-TCM was then placed near the sensor and the output notably changed. The M-TCM was then slowly moved away from the sensor until the output returned to the original unaltered state. Figure F-3 shows the M-TCM with the ETS sensor attached.

[23] Intelligent Instrumentation Inc., Tucson, Arizona, USA

[24] Ascension Technology Corp, P.O. Box 527, Burlington, VT, USA

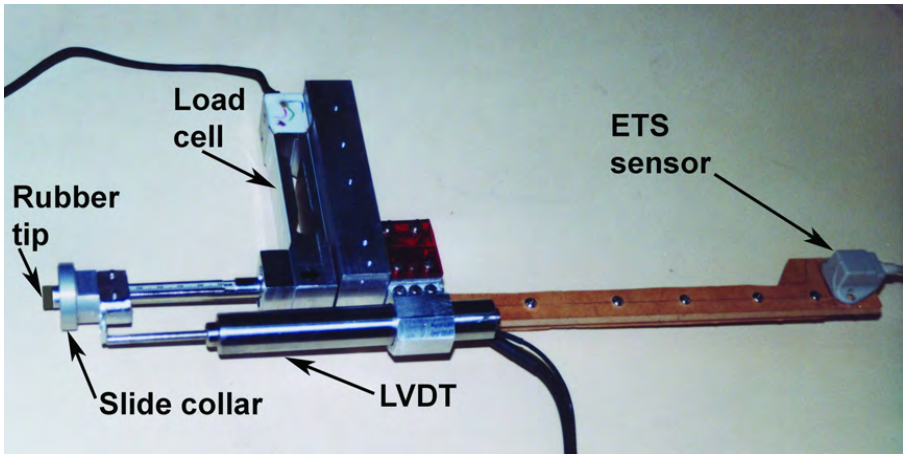


Figure F-3 – Modified-Tissue Compliance Meter (M-TCM)

F.2.2 EXAMINER INTERFACE

Before a measurement commenced, the custom VB program used the known orientation of the foam surfaces and the ETS sensor location to ascertain the distance of the sensor from that required for a perpendicular orientation of the M-TCM to the measured surface. The distance from a perpendicular orientation was graphically displayed to the examiner. A target with cross-hairs at the centre represented *'perpendicular'* and an easily visible circular *'marker'* represented the current orientation of the M-TCM with respect to the target - the closer the marker was to the centre of the target, the closer the M-TCM was to perpendicular (see Figure F-4). The marker was very sensitive to changes in the M-TCM orientation and the examiner could easily observe which direction to move the M-TCM to attain a perpendicular orientation. The examiner could be within 1-2 deg of perpendicular in a matter of seconds. The ETS transmitter generated electromagnetic fields that interfered slightly with the output of the LVDT and therefore was turned off when the 'start recording' button was pushed.

To assist the examiner maintain a continuous application rate, Visual Designer displayed a bar chart indicating the rate of change of force. The chart changed colour from green if the rate was lower or higher than the recommended application rate of 9.81N/sec. This application rate is the same used with the Algometer instrument [374], discussed below. The force and displacement were displayed and recorded as raw voltages to conceal this information from the examiner during application, to reduce distractions to the examiner during measurement.

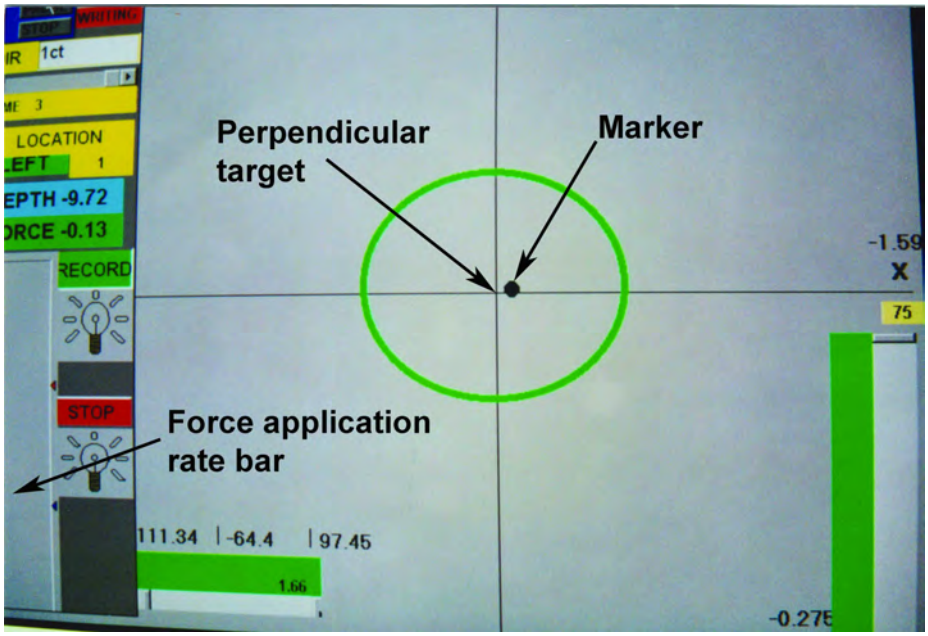


Figure F-4 – The examiner-computer interface for operating the modified tissue compliance meter

F.2.3 THE INDIVIDUAL TESTING OF COMPONENTS OF THE M-TCM

The components of the M-TCM were tested separately for reliability and accuracy and to derive calibration equations. The load cell was tested by applying known gauge weights (accuracy 0.01N). Weights were applied beginning at 0.98N, increasing in increments of 0.98N, to a maximum applied force of 49.05N. This assessment protocol was repeated ten times. Gauge blocks[25] (used for length calibration) with accuracy of 0.01 micrometers were used to calibrate the LVDT. Twelve different widths between 0 and 30mm in increments of 2 and 3mm were measured, ten times each. The load cell and LVDT calibration ranges were in accordance with future physiologic measurement ranges.

The ETS was tested in the location where M-TCM measurements were performed. This was to ensure that any unknown electromagnetic fields or metals (for example, power cables in the walls or concrete reinforcement in floor) that interfered with the ETS would be detected. The ETS determines position and orientation from the centre of the transmitter to the centre of the sensor. The outer casing protecting the inner orthogonal

[25] Mitutoyo Mfg., 33-7 Shiba 5-chome, Minato-Ku, Tokyo, Japan

coils restricts access to the centre of the sensor thus making exact position estimates difficult for accuracy testing. To overcome this, a wooden linear ruler was manufactured. The length of the ruler was determined using a digital linear vernier (accuracy 0.03mm). Wooden stoppers fitting the outer casing of the sensor were placed at each end of the ruler. The sensor was placed at one end of the ruler and its position noted. It was moved to the other end and again its position noted; the distance between the two placements was calculated.

The length of the ruler was estimated by the ETS with sensor-to-transmitter distances of 100 to 900mm, in increments of 100mm. At each sensor-to-transmitter distance, ten ruler length measurements were made. This was completed for each axis (X, Y, Z) five times giving a total of 1350 ruler length estimates. The method of measuring distance between two points in space has been utilised previously for the purpose of assessing electromagnetic tracking systems [337,588].

A similar protocol was used to evaluate the ability of the ETS to estimate the sensor's orientation (elevation, roll, azimuth). Six wooden wedges were fabricated, with angles of 15 to 90 deg in increments of 15 deg. Each wedge had two surfaces, a horizontal and an angled. Fittings for the sensor were placed on each surface. The sensor was placed on one surface, and the orientation was noted, and then on the other surface and again the orientation noted. The difference between the two angles was calculated. The sensor-to-transmitter distance was varied from 100mm to 900mm in increments of 100mm. At each sensor-to-transmitter distance roll, elevation and azimuth were measured, ten times for each wooden wedge. The actual angle of the wooden wedges was measured by an inclinometer[26] (accuracy better than 30 arc sec). A similar protocol has been used for the determination of the angular accuracy of an electromagnetic tracking system [337].

F.2.4 THE M-TCM SYSTEM

[26] Whyler WYLCL45

Two separate experiments were conducted with different groups of examiners to determine the reliability and accuracy of the M-TCM system. These experiments were conducted separately due to the availability of examiners.

Test 1: Reliability was assessed by examining FD measurement results on three homogenous foam surfaces of different densities. A testing protocol similar to that used by Kawchuk et al. [618] was used. Foam samples of 6mm thickness were measured. In this experiment, five examiners used the M-TCM to measure the three foam surfaces. Each surface was measured ten times by each examiner giving a total of 150 measurements. Measurements of the foam surfaces were made in a randomised order.

Test 2: Accuracy of the M-TCM system was assessed by measuring the depth of four wooden blocks that were placed over a homogenous foam surface of thickness 5mm. Each block had a hole in the centre to permit the shaft of the M-TCM to go through to the foam surface below. The slide collar remained at the top surface of the wooden block, thereby providing measurement of the depth of the wooden block. The hole depths were approximately 4, 7, 10 and 12mm. Depths were determined with a digital linear vernier (accuracy ± 0.03mm). These sizes were used to measure a range of depths that the M-TCM may use in future musculoskeletal stiffness measurements. Five examiners measured the foam surface through the four holes ten times each. After each measurement, the foam was moved slightly to ensure measurements were not made at the same location and therefore avoid measurement error from a damping effect (hysteresis) of the foam. The foam surface was also measured directly by each examiner ten times with no wooden blocks to provide calibration for deformation of the foam surface. Measurements were made in a randomised order and a total of 250 measurements were made.

To measure compression of the M-TCM's rubber tip, each examiner also measured a control surface that was assumed to be incompressible. Ten non-randomised measurements were recorded for each examiner, a total of 50 control surface measurements. The reliability of the M-TCM on a control surface was assessed from these results.

The foam densities for test 1 and 2 are given in Table F-1.

	Density (kg/m^3)
FOAM 1	299.4
FOAM 2	35.3
FOAM 3	82.7
FOAM 4	198.5

Table F-1 – Foam specifications

Examiner 1 (AM) was experienced in the operation of the M-TCM and participated in test 1 and 2. Four inexperienced examiners performed test 1 and another group of four inexperienced examiners performed test 2. Each inexperienced examiners received 15 minutes individual instruction and practice with the M-TCM before conducting measurements. The test surfaces were custom-built from wood and stainless steel. Wood and stainless steel do not interfere with the operation of the ETS [502]. The ETS transmitter was securely placed about head height and the test surfaces at approximately waist level. Each measurement with the M-TCM was made using the following protocol:

- The examiner assumed a stable standing stance, feet shoulder width apart, firm grasp of M-TCM handle in right hand and support with the left hand (all examiners were right handed).
- Placed M-TCM tip on surface to be measured.
- Looked at computer screen for M-TCM orientation guidance.
- Pressed record button with left hand: computer recorded angles of ETS and how many degrees away from test surface perpendicular; ETS turned off, started recording M-TCM results to computer.
- Increased applied force at approximately 9.81N/sec watching the application rate bar on computer screen.
- 50N was reached: computer stopped recording M-TCM, ETS turned back on and again recorded M-TCM position and how many degrees away from perpendicular.
- Computer visually and audibly indicated to examiner to stop measurement.

F.2.5 DATA ANALYSIS

The root mean square (RMS) error and standard deviation were used to evaluate the accuracy and reliability of the load cell and LVDT output after calibration, respectively. Pearson's r^2 value and the Standard Error of the Estimate (SEE) were used to evaluate the calibration equations. The RMS error was evaluated to describe the positional and angular accuracy of the ETS.

Results from the M-TCM were displayed as force-displacement (FD) curves and were limited to the range 5N to 50N. The computer program Mathematica[27] v3.0 was used to fit the FD curves with an exponential function ($Y = a + b.e^{c.x}$) using a non-linear least-squares fit. Slight permutations were evident in the raw data from the M-TCM possibly due to the examiners hand shaking slightly during measurement or from other sources. By modelling the data with an exponential function these permutations were removed making the FD curve smooth. Also, data analysis was made considerably easier as each FD curve was reduced to just three values (the constants in the exponential function: *c*, *b* and *a*).

The intraclass correlation coefficient ICC(2,1) [433] was used to assess the inter and intra-examiner reliability of the M-TCM from test 1 results and measurements conducted on a control surface in test 2. ICC values between 0.90 to 0.99 were interpreted as indicative of high reliability; 0.8 to 0.89 as good reliability; 0.70 to 0.79 as fair reliability and below 0.69 as poor to moderate reliability [434,435]. The average rate of change of applied force was analysed by measuring the length of time between each 2.45N increase in force. Also, the number of degrees from perpendicular at the beginning and end of each measurement was determined. This was completed for test 1 and 2 results.

The accuracy of the instrument was assessed from test 2 results. The FD curves for each examiner taken directly on the foam surface were averaged to determine deformation of the foam surface. This FD curve was subtracted from the FD curves measured on the wooden blocks, thereby providing an estimate of the depth of each hole without the confounding influence of foam deformation. The RMS error of each examiner for each hole was determined for forces 10 to 50N in increments of 10N. The maximum RMS

[27] Wolfram Research Inc., 100 Trade Center Drive, Champaign, IL 61820, USA

error for each examiner for each hole is reported. The rubber tip compression was modelled with a linear and non-linear exponential model from results on the control surface. Each model was evaluated with Pearson's r^2 and Standard Error of the Estimate (SEE).

F.3 RESULTS

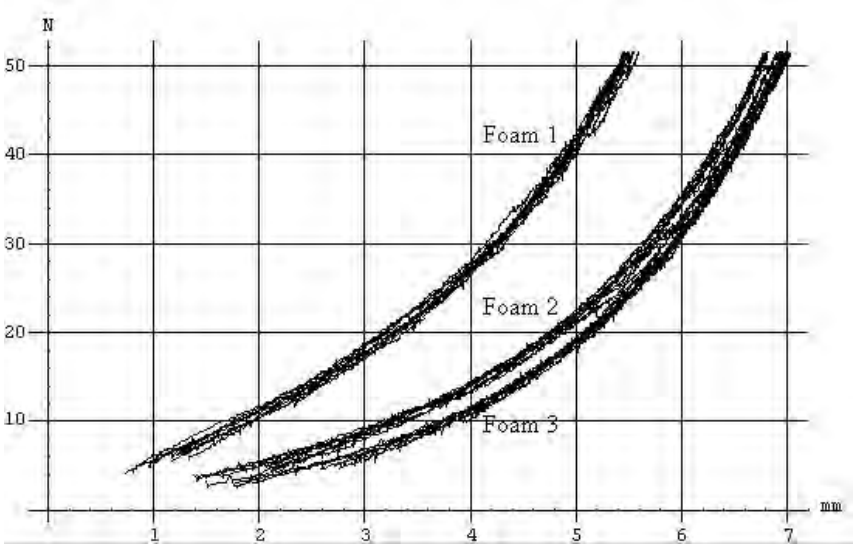


Figure F-5 – Test 1 raw FD curves (not fitted with an exponential function) for the experienced examiner on three foam samples

F.3.1 LOAD CELL AND LINEAR TRANSDUCER

The load cell and the linear variable differential transducer (LVDT) had good accuracy, expressed as low RMS error. The low standard deviation values from repeated measurements of both transducers indicate good reliability. The calibration equations modelled data closely with high r^2 values and low spread about the regression lines, expressed as low SEE. Results are given in Table F-2.

	Max RMS Error	Max Standard Deviation	R Squared	SEE
LVDT (mm)	0.027	0.01	1.000	0.015
Load Cell (N)	0.045	0.05	1.000	0.028

Table F-2 – Linear variable differential transducer (mm) and load cell (N) accuracy and reliability

F.3.2 ELECTROMAGNETIC TRACKING SYSTEM (ETS)

Angular RMS errors were similar for each transmitter axis and for ease of analysis and dissemination results were combined. Figure F-6 to Figure F-8 show the RMS error for roll, elevation and azimuth, respectively. The ETS positional accuracy along the X, Y and Z axis is shown in Figure F-9. During M-TCM measurements, the transmitter to sensor distance was in the range 306 - 674mm (95% CI). From Figure F-6 to Figure F-8, for this range, the angular RMS error was less than 0.27 deg roll, 0.5 deg elevation and 0.75 deg azimuth, except if the sensor was oriented at 90 deg elevation. From Figure F-9, for this range, the positional RMS error was less than 1.68mm for all axes. These results corroborated the manufacturers data regarding accuracy.

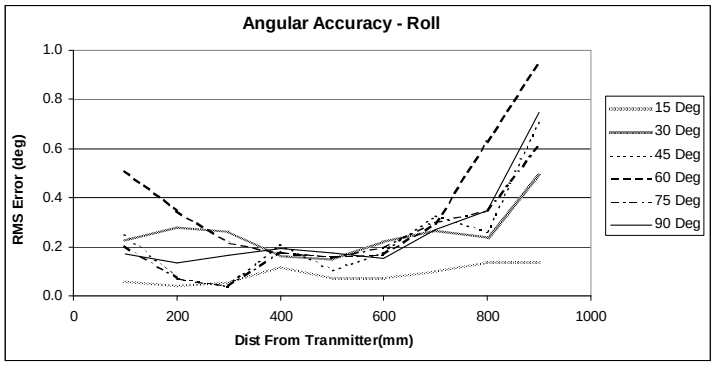


Figure F-6 – Angular accuracy of Ascension electromagnetic tracking system for roll

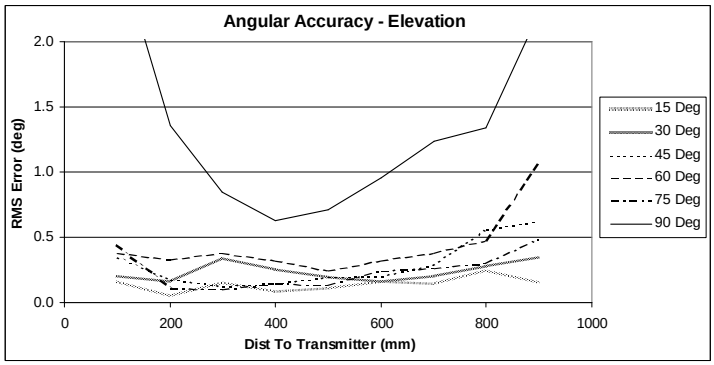


Figure F-7 – Angular accuracy of Ascension electromagnetic tracking system for elevation

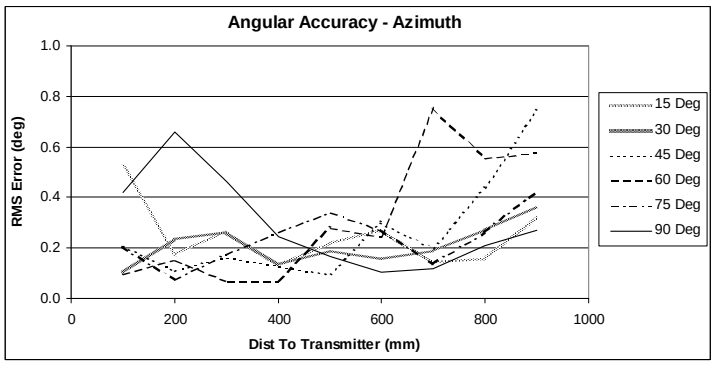


Figure F-8 – Angular accuracy of Ascension electromagnetic tracking system for azimuth

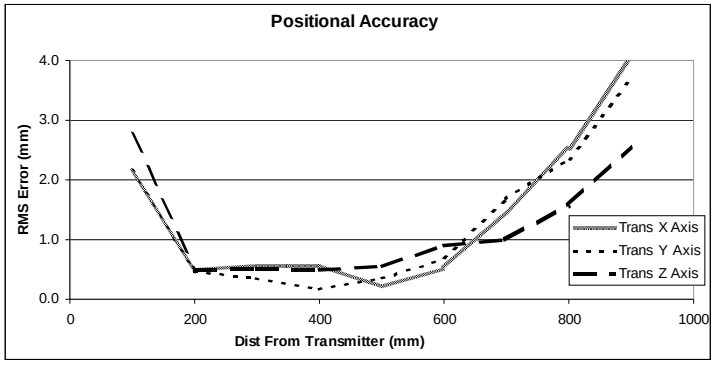


Figure F-9 – Three-dimensional positional accuracy for the Ascension electromagnetic tracking system

F.3.3 M-TCM RELIABILITY

The FD curves for all examiners on foam surfaces were fitted with an exponential function. The minimum Pearson's r^2 value for any curve fit was 0.992. The intra and inter-examiner reliability ICC's were high for test 1 foam measurements. The control surface inter-examiner ICC was good and the intra-examiner ICC's ranged from good to high. The ICC values and 95% confidence intervals are given in Table F-3 and Table F-4.

	Test 1 examiners			Test 2 examiners
Examiner	Foam 1	Foam 2	Foam 3	Control Surface
1 (AM)	0.998 (0.996-0.999)	0.997(0.992-0.998)	0.998(0.997-0.999)	0.975(0.946-0.987)
2	0.995 (0.987-0.997)	0.994(0.991-0.996)	0.994(0.986-0.997)	0.907(0.832-0.945)
3	0.993 (0.986-0.996)	0.992(0.984-0.996)	0.996(0.992-0.998)	0.835(0.639-0.914)
4	0.984 (0.976-0.989)	0.990(0.985-0.993)	0.996(0.995-0.998)	0.961(0.918-0.979)
5	0.993 (0.985-0.996)	0.994(0.988-0.996)	0.996(0.993-0.997)	0.955(0.917-0.974)

Table F-3 – Intra-examiner reliability (ICC) and 95% confidence interval

Test 1 examiners			Test 2 examiners
Foam 1	Foam 2	Foam 3	Control Surface
0.991 (0.988-0.994)	0.986 (0.980-0.990)	0.994 (0.992-0.996)	0.894 (0.848-0.927)

Table F-4 – Inter-examiner reliability (ICC) and 95% confidence interval

F.3.4 M-TCM ACCURACY

The accuracy of the M-TCM in measuring the depth of holes in four wooden blocks is given in Table F-5.

Examiner	Hole 1	Hole 2	Hole 3	Hole 4
1 (AM)	0.060	0.099	0.090	0.101
2	0.204	0.259	0.202	0.252
3	0.333	0.226	0.243	0.329
4	0.108	0.144	0.085	0.132
5	0.140	0.147	0.161	0.126

Table F-5 – Accuracy of the M-TCM: maximum RMS error (mm) of each hole for all applied forces

Rubber tip compression was analysed by averaging the control surface FD curves for all examiners. Two models were used to fit the averaged FD curve: a linear model and an exponential function ($Y = a + b.e^{c.x}$) using a non-linear least-squares fit. The exponential function was a better fit of the FD curve with a higher Pearson's r^2 value and a lower SEE and was therefore selected to model compression of the rubber tip. The r^2 value was 1.00, SEE was 0.50 and the model constants were c= -43.17, b= 34.03 and a= 0.57. The exponential function crossed the X axis (mm) at 0.418mm.

F.3.5 FORCE APPLICATION RATE

The rate of force increase during instrument application closely approximated the recommended rate of 9.81N/sec [374] for both the experienced and inexperienced examiners. The experienced and inexperienced examiners average rate of force application was 9.7 ± 2.9N/sec($\pm sd$) and 10.1 ± 4.9N/sec respectively.

F.3.6 START AND FINISH POSITION

The ETS driven target system assisted examiners attain a close to perpendicular orientation of the M-TCM to the measured surface in test 1 and 2. Results for test 1 and 2 were similar and were therefore combined. The average deviation from perpendicular at the start of each measurement was 0.14 ± 0.10 deg($\pm sd$) and 0.23 ± 0.16 deg for the experienced and inexperienced examiners respectively. At the conclusion of each measurement the experienced examiner had deviated the orientation of the M-TCM from the start position by 0.84 ± 0.49 deg and the inexperienced examiners by 1.22 ± 0.82 deg. Examiner 3 in test 2 appeared to have difficulty in maintaining a perpendicular orientation during instrument application. Results indicated that this

examiner's orientation difference from start to end of measurements was almost double of the other examiners.

F.3.7 DISCUSSION

Modifications made to an original TCM were designed to overcome some of the shortcomings identified by Kawchuk et al. [618] with the instrument's design and application. The M-TCM, like its predecessor the TCM, was designed to objectively assess the compliance of a tested surface. Unlike the TCM, M-TCM results can also produce FD curves of assessed surfaces from which a stiffness estimate of the measurement can be derived. The computer interface guided the examiner throughout the process and limited their subjective involvement in measurements. Results from this investigation indicate that the alterations made to the TCM significantly improved the reliability and accuracy of the instrument, when compared with previously reported data regarding the TCM [618].

The M-TCM was repeatedly applied to homogenous foam surfaces in test 1 and a control surface in test 2 to determine the reliability of the instrument. The high ICC values for test 1 indicate high inter and intra-examiner reliability by experienced and inexperienced examiners on foam surfaces. The M-TCM had good to high intra and good inter-examiner reliability when applied to a control surface. Examiner 3 in test 2 on the control surface had good intra-examiner reliability compared with high for other examiners. This examiners result likely influenced the good inter-examiner reliability ICC value on the control surface.

The M-TCM had good accuracy in measuring the depth of holes in wooden blocks. The experienced examiner had the lowest RMS error. Examiner 3 had poorer accuracy than other examiners. The lower reliability and accuracy suggest that examiner 3 in test 2 experienced some difficulty in applying the instrument in a consistent manner. This is likely explained by the orientation control during measurement. Examiner 3 moved the orientation of the M-TCM between the start and finish of measurements almost more than double all other examiners. Non-perpendicular orientation causes erroneous

movement of the slide collar that may explain the poorer accuracy and reliability results for this examiner.

The reliability and accuracy of the M-TCM compared reasonably well with automated stiffness measurement devices tested on foam surfaces. Kawchuk et al. [118] reported high instrument reliability with ICC's above 0.99 for repeated foam surface measurements. The accuracy of this automated tissue stiffness measurement device was 0.008 ± 0.013mm and was determined using a different measurement protocol. This accuracy was higher than the M-TCM, which is an expected result for an automated measurement device compared with a hand held device. Owens [114] tested a stiffness measurement device on foam samples and reported 1.3 to 2.7% error of the probe position at the point of deepest penetration. For reasons of comparison this was done also with M-TCM test 1 results using a slightly modified formula reported by Markolf et al. [619] which was *%diff = (max stiffness – min stiffness) / higher of the two stiffness values*. The M-TCM results have an error of between 1.2 and 5.3% at 50N for the three measured foam surfaces. The load cell and LVDT compared well with similar R squared values [114,118] and RMS Error values [118].

The rubber tip of the M-TCM compressed during measurement and was identified as a source of error for the original TCM [618]. When designing the M-TCM, careful consideration was given to replacing the rubber tip with a non-deforming blunt probe to remove this error, however for several reasons the rubber tip was retained. Firstly, fitting an exponential model to results from the control surface predicted the tip compression error. The exponential curve modelled the compression of the rubber tip and, for a given force, could estimate the amount of compression. The exponential curve did not pass through the origin (0,0) of the FD axes indicating that there was some displacement of the slide collar at zero force. There was a small gap between the end of the rubber tip and the face of the slide collar that accounted for this. The small gap moved the curve from the origin to the right by 0.418mm.

Secondly, comfort of participants is an important consideration and several mechanised spinal tissue stiffness devices use rubber or foam indentation probes to decrease discomfort for participants during measurement [115,116,558,559,564]. Similarly, the rubber tip of the M-TCM prevents unnecessary early pain sensation during measurement from the sharp edge of the tip [388].

Thirdly and most importantly, the rubber tip and shaft of the M-TCM are the same as the Algometer instrument. The Algometer is a hand held force gauge similar in design to the M-TCM except the Algometer does not have a slide collar to measure penetration. Measurement with an Algometer involves applying force to the skin at a rate of 9.81N/sec and stopping when the participant indicates that the applied force has induced discomfort or pain [374]. The maximum applied force is recorded as the pressure pain threshold (PPT) [371,374]. Pressure algometry and PPT was discussed in Ch. 4, Sec. 4.3.5.1. The M-TCM may provide a PPT measurement in the same way as the Algometer due to the identical design features of the shaft and *rubber tip*. The force application rate of the Algometer was adopted for use with the M-TCM to ensure PPT measurements were completed in a similar manner. Use of PPT measurement during stiffness assessment is advantageous as this measure provides a semi-objective quantification of pain that in clinical practice is assessed by palpation [371]. Manual palpation for tenderness has good reliability [535,542-544] and PPT provides a quantitative value of this clinical measure. A disadvantage of using the M-TCM to measure PPT is limitation of the applied force. The FD curve upper force limit would stop at the PPT force value. It is possible that each curve may have a different upper end point making analysis challenging.

Currently, PPT measurements have not been included with spinal stiffness measurements completed by mechanised tissue stiffness devices. Instead other methods have been used to account for pain in participants: the McGill pain questionnaire [102,566], visual analogue scale [566], excluding participants if they report pain on application of force [113] or simply requesting participants to report pain during stiffness measurement [558].

The required force application rate of 9.81N/sec could be closely approximated during measurement by observing the application rate bar, although some variability was noted. Experience did not appear to be a factor, with the inexperienced examiners achieving basically the same application rate of the experienced examiner. It is reasonable to assume that the application rate and the variability of application rate is more controlled than that attained by manual palpation, as the M-TCM examiner is guided by the computer generated application rate bar, unlike the manual therapist. From the high reliability and accuracy results it appears that force application rate variability does not significantly affect measurement of foam surfaces. The effect of this

variability if the M-TCM were applied to the human musculoskeletal system may be a source of error in tissue stiffness results. The mechanical behaviour of connective tissues to applied force reflects a viscoelastic response [620-623], which is characterised by the combined properties of a an elastic solid and a viscous fluid [620]. In-vitro tests of connective tissues demonstrate a non-linear deformation behaviour to load that is dependant not only on the magnitude of the applied load but also the duration of its application (time-dependant) [620,621,624,625]. In-vivo spinal stiffness measurements are consistent with in-vitro biomechanical studies. In-vivo lumbar spine measurements from posterior anterior force application with a mechanised tissue stiffness device demonstrate a time-dependant response. Slow quasistatic loading (20-30sec) of the lumbar spine increased the resulting lumbar spine displacement [116,562] and lowered the measured stiffness [626] when compared with a fast (0.5-2sec) force loading time. However, for similar force loading times of 1 and 2sec the differences in observed responses were small [562]. In other areas of the human musculoskeletal system, stiffness measurements of similar force loading times do not appear to affect stiffness measurements. Measurements of the forearm FD response with an ultrasonic indentation probe demonstrated that observed responses were relatively rate-insensitive to probe indentation rate [555]. In stiffness assessment of the knee with a hand-held testing device, the rate of load application did not appear to affect the shape of the test curves for [619]. Based on the low variation in force application rate for the M-TCM it is possible that this variability will not significantly alter M-TCM tissue stiffness results if applied to the musculoskeletal system.

Kawchuk et al. [618] questioned the slide collar design in the original TCM. They discovered that the slide collar fell into the depression caused by the tip of the TCM underestimating the tip penetration. Foam of 30mm thickness was used by Kawchuk et al. [618]. In this investigation, a brief examination with 20mm thickness produced the same problem. Therefore foam of 6mm thickness was used to ensure that this did not occur. If the M-TCM were applied to the human musculoskeletal system, the examiner may have confidence in results to low deformation values. The limitation of 6mm deformation restricts the applicability of the M-TCM to less compliant areas of the human musculoskeletal system. Kawchuk et al. [618] also discussed that if the TCM was not applied perpendicular to the measured surface the slide collar was prematurely moved giving a false reading. This source of error may be limited by the target guidance

system driven by the ETS to attain a perpendicular orientation to the measured surface at the start of the measurement.

The slide collar of the M-TCM measured surface displacement *relative* to the instrument tip. This is similar to some mechanised spinal tissue stiffness devices [116,118]. Other mechanised stiffness devices measure displacement from a fixed position and record the *absolute* displacement of the indentation probe [102,114,115,117,119]. Absolute measurements may include displacement of structures remote to the site of force application such as movement from rotation of the pelvis [559,562], deformation of the rib cage [564] and abdominal contents [546,559], compression of padding under participants [627] and general movement of the whole spine [562]. The slide collar was retained in the M-TCM to measure relative displacement and avoid possible contribution from these external structures.

Accuracy of the ETS's elevation angular measurement was notably affected when the sensor was aligned at ± 90 deg (see Figure F-7). This is an operational limitation of the ETS [502]. The test bench was designed such that the elevation angle would not approach this value. The ETS guided the examiners of the M-TCM to an orientation that was approximately perpendicular to the measured surface before each measurement. At the conclusion of each test the M-TCM orientation deviated not more than approximately one degree from a perpendicular orientation to the test surface. If the M-TCM were applied in the clinical setting an operational requirement would be maintenance of approximately 200 to 800mm distance between the sensor and transmitter. For this sensor-to-transmitter range the ETS has acceptably low angular and positional RMS error.

F.4 CONCLUSION

The newly developed M-TCM is a computer-interfaced objective system for the evaluation of stiffness and PPT. The M-TCM was applied to foam surfaces, wooden blocks and a control surface and analysis of the FD curves produced indicate that it has good to high intra and inter-examiner reliability and good accuracy for experienced and inexperienced examiners. Examiners were guided by a computer screen image during

measurement minimising their involvement during recording. It has potential as a hand held measurement device for reliable and reasonably accurate stiffness evaluation and objective pain measurement (expressed as PPT) in the clinical or research setting. The M-TCM can be applied at varying angles and may be applicable to measurement of awkward areas of the human musculoskeletal system. The applicability of the M-TCM to the human musculoskeletal system has yet to be established.

APPENDIX G

ADDITIONAL RESULTS (CHAP 6)

G.1 LITERATURE REVIEW ADDITIONAL MATERIAL - MECHANISED – SPINAL STIFFNESS ASSESSMENT INFORMATION

G.1.1 SOURCES OF VARIATION IN SPINAL STIFFNESS MEASUREMENTS

There are many documented sources of variation affecting stiffness measurement with mechanised devices. Kawchuk et al. [560] categorised these as subject and process based variables.

Subject based variables that may impact on spinal stiffness measurements include gender of participants [580], respiratory status at time of measurement [113,558,560,562,580,626] and age of participants [558,559]. Extraspinal elements that influence stiffness measurements include the thoracic cage and contents [564], intrathoracic pressure, skin and subcutaneous tissue, sagging of the spine due to applied force [559], rotation of the pelvic girdle [559,562,626] and the posture of the participant at the time of testing [115,560]. The underlying state of muscular activation has been shown to alter spine stiffness measurements [565]. Little is known about the extent to which these variables individually contribute to stiffness measurement [546,566].

The spine comprises many tissues and measurements obtained from mechanised stiffness measurement devices are a summation of each components contribution to the overall measurement [551,628]. Spinal elements which may contribute to the measured stiffness might include zygapophysial joints, intervertebral discs, attached muscles and ligaments, both locally and at adjacent spinal levels [546,566]. However, there is little evidence to identify which anatomical elements contribute most to the displacements that occur during spinal stiffness measurement [546,565,566].

There is a high degree of variability among participants at a particular segmental level, for posterior-anterior stiffness measurements [113,546,558,559,562,565]. Based on the

high degree of variability, a defined range of 'normal' posterior-anterior stiffness values would have to encompass a large range of values and moderate differences from average may not indicate abnormality [562]. Spine stiffness measurements have also been observed to vary considerably and significantly between spinal segmental levels in the lumbar [116,558,559,580,626], thoracic [546,559,564] and sacral [558] regions. A large proportion of this variation in stiffness between levels can be attributed to variability within individuals [546]. Viner et al. [558] found variation between levels accounted for approximately one fifth of variation between individuals. They [558] concluded that by far the greatest component of stiffness variation occurred because individuals differed.

Process based variables include indentation angle, absolute or relative indentation movement measurement, presence or not of plinth padding during testing [627], padding on the end of the indentation probe [115,116,559,564], maximum applied force and stiffness estimation methods from FD data. Different angles of application of the indentation probe have been used with mechanised stiffness measurement devices for spinal stiffness measurement. Predominantly, a vertical orientation has been used. Orientation angles not of vertical orientation have been applied in the lumbar and sacral spine regions [102,558,559,583,626]. A 'T' square has been used to align the indentor perpendicular to the measurement location [580]. There were minor differences in stiffness values from a vertical or perpendicular orientation.

Extra-spinal elements can contribute to spinal stiffness measurement. Some mechanised spinal tissue stiffness devices measure surface displacement *relative* to the indentation probe [116,118]. Other mechanised stiffness devices measure displacement from a fixed position and record the *absolute* displacement of the indentation probe [102,114,115,117,119]. Absolute measurements may include displacement of structures remote to the site of force application. Movement from rotation of the pelvis [559,562], deformation of the rib cage [546,559,564,583,626] and abdominal contents [546,559,583], compression of padding under participants [627] and general movement of the whole spine due to loading [562] may be included in absolute measurements.

The force application rate may affect the FD response of spinal tissues from indentation testing. The mechanical behaviour of connective tissues to applied force reflects a viscoelastic response [620-622]. Spinal stiffness measurements also display a

viscoelastic response that is characterised by a time-dependant response to applied force [116]. Different stiffness responses have been observed for quasi-static loading [564].

G.1.2 STIFFNESS ESTIMATION FROM FORCE-DISPLACEMENT (FD) DATA

The force-displacement (FD) curve properties of the spinal musculoskeletal system demonstrate a non-linear response to applied force. Similar to other areas of the human musculoskeletal system, the stiffness of spinal measurement increases with increases in the applied force [113]. This makes stiffness estimation a challenging task and several mathematical representations have been used to estimate stiffness from FD data. Several methods are available and decision is based partly on accuracy and smoothing needs and other requirements of the investigation [560]. There is no evidence that one form of data analysis is superior or more relevant than another [510].

Single point selection involves selecting one point from the FD curve. This method is appealing due to its simplicity. It is problematic due to the arbitrary selection process and ignores the shape of the FD curve and therefore the mechanical properties of the measurement [510].

Predominantly, linear approximations have been used to estimate stiffness from spinal FD data. Traditionally, linear approximations for spinal FD data ignore initial non-linear parts of the curve, the 'toe-in' region, and determine the gradient (stiffness) for the remainder and more linear appearing part of the curve [102,113,115,546,558,559,563-566,580,626]. Generally 30N has been used as the value indicative of the end of the non-linear 'toe-in' region. The 'toe-in' region of a spinal FD curve has been attributed to compression of the skin and superficial tissues lying over spinous processes. Hypothetically, nearly all of the soft tissue compression likely occurs at relatively low levels of force, in the toe in region [562,565]. Linear approximations are useful because they produce a single figure outcome (stiffness) for the entire FD curve. Linear approximations of FD data are stable at the terminal ends and beyond, and can be used for regression (extrapolation) for missing values [559]. However, rarely are FD curves entirely linear and therefore the user must decide (usually arbitrarily) sections of the curve that are expendable [510]. Linear approximations cannot determine variations in FD data and stiffness [510]. It is unclear how therapists interpret FD data and make decisions about stiffness and therefore it is not known which parts of a FD curve are

clinically relevant [102,510]. Employing linear approximations will determine an average stiffness value which may miss important information at various points of the test [510]. Latimer et al. [113] demonstrated that linear approximations of different force ranges significantly altered the derived stiffness values [113]. Kawchuk and Fauvel [560] advised against using linear approximations for estimating stiffness due to potential significant error.

Polynomial and spline approximations of FD data are advantageous in that they can allow for the quantification of curvilinear aspects of the data. The first derivative of a polynomial approximation can be used to describe stiffness. Derivatives of polynomials are more likely to be representative of actual tissue properties [510]. Maitland and Kawchuk [510] supported use of the second derivative (the rate of change of stiffness), which may be indicative of the onset of constraints and the sharpness with which restraints come into play. They [510] believed that the second derivative may contain important clinical information. However, the second derivative of a polynomial model has not been employed to characterise spinal FD data. A disadvantage of polynomial approximation is that polynomials are prone to error in estimating the stiffness of the terminal ends of FD curves [510,560]. This problem has been termed 'endpoint error' in biomechanical literature [584] and describes the erratic behaviour at the beginning and end of computed acceleration data after smoothing and differentiating raw displacement data. In addition, polynomials do not summarise the entire curve with a single figure and the user must select a specific aspect of the curve and use a representative value [510]. Normally, 75% of the maximum applied force is selected for a representative value for the stiffness of the FD data [560]. Polynomials have been used to estimate stiffness from spinal FD data [560,562,563]. Splines have also been used to estimate stiffness of spinal FD data [560]. Splines model data with several polynomial functions linked together and can model raw data more closely than polynomials, however they require more user decisions regarding their parameters [510].

Exponential approximation of FD data characterises a curve where the rate of stiffness increase is proportional to the applied force. Similarly to polynomials they do not summarise the entire curve with a single figure and the user must select a specific aspect of the curve and use a representative value. Unlike polynomials, exponentials are stable at the terminal ends and beyond of FD curves. There is potential for regression of

exponential approximations outside the FD curve range for missing data. Exponential approximations have been used to model FD data [117,393,608].

G.2 CERVICAL MUSCULOSKELETAL STIFFNESS RESULTS

G.2.1 STIFFNESS ESTIMATES FROM FORCE-DISPLACEMENT (FD) CURVES

The stiffness data for each individual cervical location is given in Table G-1 for each participant classification. This data is also shown above in Ch. 5 in Figure 6-10 to Figure 6-13. There was large variability within and between measurement locations. This indicated that there were no systematic musculoskeletal stiffness differences between the participant groups at any of the cervical locations. As well, the sites demonstrated large differences in musculoskeletal stiffness.

		FM			NP			NORM			Average		
Loc	Force	Mean	SD	No	Mean	SD	No	Mean	SD	No	Mean	SD	No
L1	12.5	7.72	2.13	52	8.45	2.52	50	8.13	2.63	67	8.10	2.46	169
	25	13.83	3.96	28	16.64	5.48	32	13.58	4.90	47	14.56	5.00	107
	37.5	21.73	6.25	7	27.60	10.23	15	19.69	6.99	15	23.28	8.93	37
	50			0	46.50	15.55	5	26.91	11.65	8	34.44	16.07	13
L2	12.5	6.17	2.19	49	6.89	2.34	54	5.84	1.76	66	6.27	2.12	169
	25	10.86	3.69	27	10.90	2.37	34	10.04	3.46	48	10.51	3.22	109
	37.5	13.43	6.01	9	14.77	2.87	14	12.26	4.66	13	13.53	4.47	36
	50			0	19.95	3.06	8	19.15	6.44	7	19.58	4.75	15
L3	12.5	7.26	2.62	50	7.20	2.72	52	6.93	2.36	62	7.12	2.55	164
	25	11.36	3.46	24	10.42	4.81	28	10.92	4.05	47	10.89	4.13	99
	37.5	20.94	8.13	3	14.59	6.84	10	12.92	4.90	12	14.55	6.37	25
	50			0	19.39	8.49	3	16.50	2.26	3	17.94	5.78	6
L4	12.5	6.00	1.74	50	5.69	1.70	48	5.58	1.67	64	5.74	1.70	162
	25	9.64	3.29	30	8.88	2.69	27	8.50	2.59	42	8.95	2.86	99
	37.5	14.81	6.86	8	12.67	3.97	13	12.74	2.60	11	13.23	4.45	32
	50	32.08		1	16.40	4.79	2	17.16	3.53	6	18.65	6.01	9
L5	12.5	6.05	2.09	55	5.76	1.89	53	5.82	1.99	64	5.88	1.98	172
	25	10.09	3.30	35	7.73	2.38	35	8.05	2.52	47	8.56	2.90	117
	37.5	13.26	4.32	13	10.95	4.90	16	10.52	3.34	26	11.29	4.15	55
	50	13.63	6.37	2	11.88	5.66	9	12.86	4.99	13	12.56	5.12	24
R1	12.5	8.40	2.91	49	8.00	2.62	50	8.18	2.14	66	8.19	2.52	165
	25	15.37	4.83	30	14.65	5.88	24	14.23	4.47	45	14.68	4.93	99
	37.5	21.42	6.37	10	24.75	8.05	7	19.54	4.88	14	21.32	6.30	31
	50	40.33		1	44.86	9.77	3	26.38	8.17	8	32.16	11.59	12
R2	12.5	6.48	1.84	50	6.93	2.38	52	6.18	2.34	66	6.50	2.23	168
	25	11.47	2.83	32	10.60	2.78	25	10.95	3.28	44	11.03	3.01	101
	37.5	14.50	3.92	12	14.32	3.22	7	13.97	3.41	14	14.24	3.47	33
	50	14.36	4.00	2	20.06		1	15.49	3.76	3	15.88	3.66	6
R3	12.5	6.42	1.98	56	7.98	3.29	47	7.91	2.70	62	7.42	2.76	165
	25	10.10	3.24	24	11.97	4.88	24	11.55	4.86	42	11.28	4.51	90
	37.5	14.70	5.71	7	20.61	9.47	5	16.29	6.35	9	16.79	7.01	21
	50			0			0	23.71	11.02	3	23.71	11.02	3
R4	12.5	6.33	2.02	47	6.54	4.02	50	6.80	2.68	65	6.58	3.00	162
	25	9.99	4.04	22	10.03	7.36	21	10.04	3.47	43	10.03	4.77	86
	37.5	16.57	9.16	8	19.79	19.68	4	12.96	3.45	12	15.30	9.42	24
	50	12.01	0.11	2			0	14.81	5.46	4	13.87	4.47	6
R5	12.5	6.07	2.27	59	5.29	2.09	51	5.50	1.88	68	5.63	2.09	178
	25	10.15	3.03	32	7.62	2.55	30	7.13	2.11	53	8.10	2.80	115
	37.5	14.04	5.00	21	8.95	3.87	13	9.25	2.17	30	10.76	4.28	64
	50	19.36	7.03	5	12.56	6.91	5	9.82	2.31	14	12.38	5.88	24

Table G-1 – Stiffness averages and SD for each measurement location for each participant classification.

G.2.2 PENETRATION OF THE M-TCM TIP

The average amount of M-TCM tip penetration between each force category and the total amount is shown in Table G-2. The minimum to maximum penetration range was 0.29-13.46mm. In Ch. 5, Figure 6-15 shows that as the force increased, the tip penetration significantly reduced. The amount of tip penetration was **not large** and it was possible that the results **characterised the superficial tissues**, rather than the deeper tissues, particularly at the lower force categories.

	L1		L2		L3		L4		L5	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Start-12.5N	1.50	1.16	1.82	1.31	1.54	1.21	1.65	1.02	1.46	1.05
12.5-25N	1.26	0.49	1.62	0.46	1.58	0.61	1.86	0.61	1.98	0.89
12.5-37.5N	1.88	0.52	2.94	0.97	2.43	0.85	2.96	0.74	3.23	1.21
12.5-50N	2.10	0.70	3.10	0.59	2.80	0.78	3.66	0.77	4.70	1.58
25-37.5N	0.68	0.27	1.22	0.48	1.12	0.45	1.22	0.47	1.49	0.75
25-50N	1.04	0.49	1.70	0.41	1.68	0.44	1.88	0.43	2.87	1.19
37.5-50N	0.43	0.24	0.70	0.19	0.76	0.23	0.86	0.23	1.32	0.67
Total	2.90	1.57	3.77	1.67	3.36	1.64	3.86	1.51	4.23	2.00

	R1		R2		R3		R4		R5		Average	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Start-12.5N	1.34	1.03	2.00	1.33	1.20	1.05	1.22	1.01	1.43	1.02	1.51	1.15
12.5-25N	1.20	0.38	1.48	0.42	1.46	0.58	1.69	0.63	2.03	0.85	1.62	0.68
12.5-37.5N	1.86	0.37	2.52	0.61	2.30	0.62	2.98	1.30	3.35	1.07	2.74	1.05
12.5-50N	2.20	0.33	3.43	1.16	3.02	0.76	4.20	1.28	4.60	1.23	3.62	1.45
25-37.5N	0.73	0.17	1.09	0.30	1.02	0.39	1.25	0.74	1.51	0.58	1.18	0.58
25-50N	1.13	0.33	2.22	0.89	1.67	0.65	2.36	0.70	2.72	0.84	2.08	1.01
37.5-50N	0.46	0.22	1.07	0.46	0.67	0.29	1.07	0.29	1.21	0.39	0.93	0.51
Total	2.63	1.22	3.74	1.49	2.76	1.29	3.12	1.44	4.19	1.79	3.45	1.67

Table G-2 – Average penetration of the M-TCM tip between each force category and average total tip penetration

G.2.3 CERVICAL STIFFNESS ANALYSIS OF VARIANCE

The post-hoc analysis of significant outcomes from the cervical musculoskeletal stiffness data ANOVA (see Ch. 5 Table 6-5) is reported below. There was as significant outcome for time and this is shown in Table G-3 and Table G-4. These tables show that the stiffness varied significantly between the three measurement times.

In Table G-5, the post-hoc analysis shows that the upper cervical spine locations (L1 and R1) were significantly more stiff than almost all other locations.

	Time3	time1	time2
time3	--	0.23	0.34+
time1		--	0.12
time2			--

Table G-3 – Post-hoc analysis of measurement times at force 12.5N.

	Time2	Time3	Time1
Time2	--	0.12	1.64*
Time3		--	1.51*
Time1			--

Table G-4 – Post-hoc analysis of measurement times at force 37.5N.

	R5	L4	L5	L2	R2	R4	L3	R3	L1	R1
R5	--	0.11	0.25	0.64	0.87	0.96*	1.49+	1.80+	2.47+	2.56+
L4		--	0.14	0.53	0.76	0.84	1.38+	1.68+	2.36+	2.45+
L5			--	0.39	0.63	0.71	1.24+	1.55+	2.22+	2.32+
L2				--	0.23	0.31	0.85*	1.15+	1.83+	1.92+
R2					--	0.08	0.62	0.92*	1.60+	1.69+
R4						--	0.54	0.84*	1.52+	1.61+
L3							--	0.30	0.98+	1.07+
R3								--	0.68	0.77
L1									--	0.09
R1										--

Table G-5 – Post-hoc analysis of measurement location at force 12.5N.

G.2.4 TREND ANALYSIS OF CERVICAL STIFFNESS

The analysis of trend results are shown in Table G-6. There was insufficient data to complete a trend analysis at forces 37.5 and 50N. The cervical spine displayed a **significant linear trend** in musculoskeletal stiffness, with higher stiffness in the upper cervical spine, decreasing in the lower cervical spine measurement locations. The trend analysis confirmed the post-hoc analysis shown above in Table G-5.

			polynomial degree			
Force	Measurement Time	Measurement Side	linear	quadratic	cubic	quartic
12.5N	time1	left	+ [1]			+ [2]
		right	+ [3]			
	time 2	left	+ [4]			
		right	+ [5]			
	time 3	left	+ [6]			+ [7]
		right	+ [8]			
25N	time1	left	+ [9]			
		right	+ [10]			
	time 2	left	+ [11]			
		right	+ [12]			
	time 3	left	+ [13]			
		right				

Table G-6 – Analysis of trend of the left and right cervical measurement sides.

1: ($F_{(1,33)} = 15.22$, $p < 0.01$), 2: ($F_{(1,33)} = 4.58$, $p < 0.01$), 3: ($F_{(1,27)} = 15.35$, $p < 0.01$), 4: ($F_{(1,33)} = 28.31$, $p < 0.01$), 5: ($F_{(1,33)} = 13.16$, $p < 0.01$), 6: ($F_{(1,33)} = 22.46$, $p < 0.01$), 7: ($F_{(1,33)} = 10.96$, $p < 0.01$), 8: ($F_{(1,33)} = 11.78$, $p < 0.01$), 9: ($F_{(1,6)} = 27.80$, $p < 0.01$), 10: ($F_{(1,6)} = 16.52$, $p < 0.01$), 11: ($F_{(1,12)} = 23.75$, $p < 0.01$), 12: ($F_{(1,6)} = 13.52$, $p < 0.01$), 13: ($F_{(1,9)} = 48.89$, $p < 0.01$).

G.2.5 FD CURVES REMOVED FROM ANALYSIS

186 measurements were removed from the analysis mostly because some FM participants indicated a painful response before the lowest force category of 12.5N was reached.

- 91 measurements (89 FM and 2 NP) or 4.9% of total number of measurements were removed from the analysis because the PPT value, and therefore the upper limit of the FD curve, did not exceed a force value of 12.5N.
- 62 measurements (17 FM, 21 NP and 24 NORM) or 3.3% of total number of measurements were removed from analysis due to r^2 values below 0.97 for the exponential model fit to the FD data.
- 33 measurements (7 FM, 10 NP, 16 NORM) or 1.7% of total number of measurements were removed from analysis due to irregular shaped FD curves. Irregular shaped FD curves included backward sloping and unexplained spikes in the data. This was likely due to the measurers hand shaking during recording and affecting the measurement.

G.2.6 FD EXPONENTIAL AND POLYNOMIAL MODEL ANALYSIS

All FD curves displayed non-linear behaviour and therefore the data was not fit with a linear model. FD curves were fit with exponential and polynomial models and Table G-7 shows that both models fit the experimental data very well and that there was virtually no difference between them.

	Mean	SD	No
Exponential	0.994	0.005	1674
Polynomial	0.997	0.003	1674
Difference	0.003		

Table G-7 – Average Pearson correlation values for exponential and polynomial models fit to each FD curve

Most FD curves had a small amount of data truncated from the start and end of the curve as shown in Table G-8.

	Average	SD
Truncated at start	4.6%	6.58%
Truncated at end	0.68%	2.87%

Table G-8 – Average percentage of force-displacement curves truncated at start and end of curve

G.2.7 LEFT VS RIGHT COMPARISON RESULTS

Paired *t*-tests compared left and right side stiffness estimates data for each participant classification and force category. There was only one significant outcome: NORM participants at 12.5N [$_{(}\alpha_{2=0.01)}t_{(306)} = -2.928$].

Ninety paired *t*-tests of stiffness values were conducted between each bilateral measurement location for force values (12.5N and 25N). There was insufficient data to complete analysis at higher force values. Five *t*-test results were significant. These are shown in Table G-9. There was **no systematic difference in stiffness between the left and right side** at any location for the three participant groups.

		L1 - R1			L2 - R2			L3 - R3			L4 - R4			L5 - R5		
	Force	F	H/N	A	F	H/N	A	F	H/N	A	F	H/N	A	F	H/N	A
time 1	12.5												* [2]			* [4]
	25															* [5]
time 2	12.5															
	25							* [1]					* [3]			
Time 3	12.5															
	25															

Table G-9 – Paired *t*-test results for comparison of stiffness values between left and right sides at each segmental level

1: $({\alpha}_{2=0.05})t_{(7)} = 3.016$, 2: $({\alpha}_{2=0.05})t_{(17)} = -2.341$, 3: $({\alpha}_{2=0.05})t_{(12)} = -2.364$, 4: $({\alpha}_{2=0.05})t_{(20)} = 2.762$, 5: $({\alpha}_{2=0.05})t_{(13)} = 2.460$.

G.2.8 ESTIMATION OF STIFFNESS AND DISPLACEMENT DATA

Differences between extrapolated FD curves and actual FD data are given in Table G-10. There were **large differences** in the actual FD data and the extrapolated FD data using the exponential model. Therefore, the use of the exponential model to estimate FD data was not feasible.

Force range	12.5-25	12.5-37.5	12.5-50	25-37.5	25-50	37.5-50
Average difference in stiffness between extrapolated and actual (N/mm)	-0.81± 6.05	-0.66± 10.56	-3.11± 14.38	-0.55± 5.94	-2.27± 9.45	-1.29± 7.29
Average absolute difference in stiffness between extrapolated and actual (N/mm)	4.38± 4.25	7.65 ± 7.29	10.78± 9.96	4.03± 4.40	6.58± 7.13	3.99± 6.23
Average difference in distance between extrapolated and actual (mm)	0.21± 0.71	0.42 ± 1.39	0.69± 1.99	0.09± 0.48	0.35± 0.84	0.11± 0.41
Average absolute difference in distance between extrapolated and actual (mm)	0.54± 0.50	1.09 ± 0.96	1.66± 1.29	0.34± 0.34	0.64± 0.64	0.29± 0.32

Table G-10 – Average, absolute and SD for differences between actual data and estimated data from extrapolated exponential models

G.2.9 FORCE APPLICATION RATE

The average rate of force application was $10.4 \pm 5.6(SD)$ (N/sec). This was very close to the required rate of 10 N/Sec.

G.2.10 ANGLE OF APPLICATION OF THE M-TCM

The difference between the M-TCM initial estimate of a perpendicular orientation determined by the unaided eye and the orientation advised by data from the neck profiler, purportedly at an actual perpendicular orientation, is shown in Table G-11. The use of the neck profiler changed the orientation of the M-TCM by 7.5 deg and was therefore useful in attaining a perpendicular orientation to the skin surface of the neck.

Move between estimate orientation to actual (deg)	
Average	SD
7.46	6.24

Table G-11 – Difference in M-TCM orientation between initial estimate orientation and actual orientation used

The change in orientation of the M-TCM from the start of a measurement was very minimal. Table G-12 shows that the examiner moved the orientation by 1.7 deg during the measurements.

Move between start and finish (deg)	
Average	SD
1.71	1.19

Table G-12 – M-TCM orientation movement between start and finish of a measurement

The examiner could also very closely attain a similar orientation of the M-TCM at the second and third measurement times, compared with the first. Table G-13 shows that the orientation difference was 0.7 deg between each measurement time.

Move between measure time 2 & 3 compared with time 1 (deg)	
Average	SD
0.74	1.82

Table G-13 – Difference in M-TCM orientation between initial time 1 orientation and orientation for measurements at times 2 and 3

G.3 CERVICAL PRESSURE PAIN THRESHOLD (PPT) RESULTS

G.3.1 CERVICAL PPT ANALYSIS OF VARIANCE

The post-hoc analyses of significant outcomes from the PPT data from Ch. 5 in Table 6-7, are shown in Table G-14 and Table G-15.

There was a significant outcome for time of measurement (Table G-14), indicating that the PPT was significantly different at the two hour measurement time, compared with the time 1 and 2. This confirmed the small variability in the data over time.

Table G-15 showed that the lower **cervical measurement locations** were significantly less tender than the other measurement locations. The lower cervical spine was less sensitive to mechanical pressure than the middle and upper cervical spine.

	time3	time1	time2
time3	--	1.47^{+}	1.70^{+}
time1		--	0.23
time2			--

Table G-14 – Post-hoc analysis of PPT for measurement time.

	R3	R4	L3	R1	R2	L4	L1	L2	L5	R5
R3	--	0.49	0.99	1.50	1.62	1.74	2.22*	2.3*	5.3^{+}	5.4^{+}
R4		--	0.50	1.01	1.13	1.25	1.73	1.8	4.8^{+}	4.9^{+}
L3			--	0.51	0.63	0.75	1.23	1.31	4.3^{+}	4.4^{+}
R1				--	0.13	0.25	0.72	0.80	3.8^{+}	3.9^{+}
R2					--	0.12	0.60	0.68	3.7^{+}	3.8^{+}
L4						--	0.48	0.56	3.6^{+}	3.7^{+}
L1							--	0.08	3.1^{+}	3.2^{+}
L2								--	3.0^{+}	3.1^{+}
L5									--	0.1
R5										--

Table G-15 – Post-hoc analysis of PPT for measurement location.

G.3.2 TREND ANALYSIS OF CERVICAL PPT

The trend analysis of the PPT results indicated that there was a quadratic trend between the measurement locations (see Table G-16). This confirmed the quadratic appearance of the PPT results from Ch. 5 in Figure 6-16.

		polynomial degree			
Measurement Time	Measurement Side	linear	quadratic	cubic	quartic
time1	left		+ [1]		
	right		+ [2]	+ [3]	
time 2	left	+ [4]			
	right		+ [5]		
time 3	left	+ [6]	+ [7]		
	right	+ [8]	+ [9]	+ [10]	

Table G-16 – Analysis of trend PPT on the left and right sides of the neck

1: ($F_{(1,51)}$ = 11.85, p< 0.01), 2: ($F_{(1,51)}$ = 14.55, p< 0.01), 3: ($F_{(1,51)}$ = 18.54, p< 0.01), 4: ($F_{(1,51)}$ = 8.49, p< 0.01), 5: ($F_{(1,51)}$ = 15.92, p< 0.01), 6: ($F_{(1,51)}$ = 7.53, p< 0.01), 7: ($F_{(1,51)}$ = 12.99, p< 0.01), 8: ($F_{(1,51)}$ = 9.72, p< 0.01), 9: ($F_{(1,51)}$ = 18.57, p< 0.01), 10: ($F_{(1,51)}$ = 9.21, p< 0.01).

G.3.3 LEFT VS RIGHT COMPARISON RESULTS

Paired *t*-tests compared the average left and right side PPT data for each participant classification. There was as significant difference in PPT between left and right sides in the NP and FM participants (see Table G-17).

Figure G-1 shows that in the NP participants, there were **clearly lower PPT values in the right cervical measurement locations, compared with the left side**. This may have indicated that in the NP participants there was some form of spinal dysfunction that contributed to this clear difference in pain sensitivity between the left and right sides. A side to side difference in PPT was not observed in the other participant groups.

Class	*t*-test
FM	$(\alpha_{2=0.05})t_{(314)} = -1.99^{*}$
NP	$(\alpha_{2=0.01})t_{(269)} = 7.48^{+}$
NORM	$(\alpha_{2=0.05})t_{(344)} = 0.25$ns

Table G-17 – Paired *t*-test of left vs right PPT data

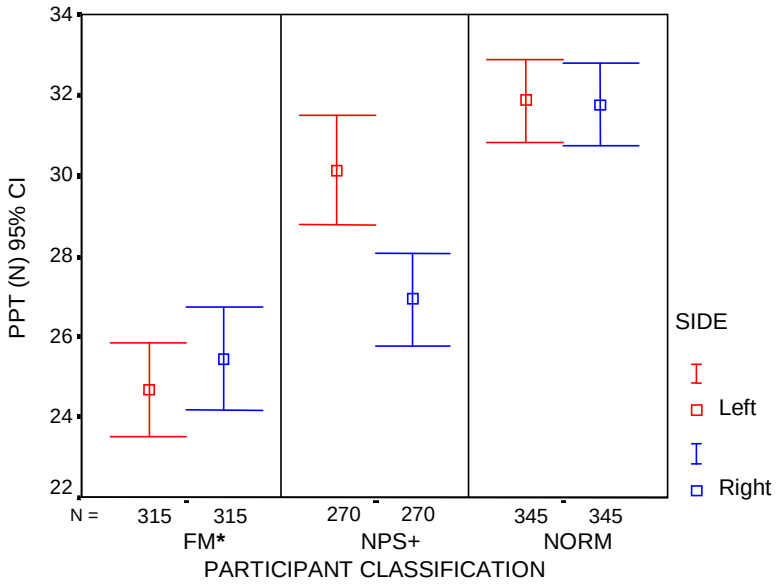


Figure G-1 – Average PPT for left and right sides of the cervical spine for each participant classification. + *t*<0.01, * *t*<0.05

G.4 CERVICAL RANGE-OF-MOTION (ROM) RESULTS

G.4.1 SUMMARY OF ROM RESULTS

The conjunct motion ROM (motions in planes other than the primary movement plane) is reported in Table G-18. The ROM data from a neutral position to an extreme position in a plane indicated that all movement planes there was **not unequal bi-lateral motions** in the any of the participant groups. Instead, the NP and FM participants demonstrated a **gross deficit in ROM in all movement planes** compared with the NORM participants, and it was relatively consistent bi-laterally.

		FM						NP					
		Rot		LF		FE		Rot		LF		FE	
		Avg	SD	Avg	SD	Avg	SD	Avg	SD	Avg	SD	Avg	SD
primary movement	Right Rot	**65.4**	**11.5**	4.8	4.4	0.2	2.8	**74.3**	**10.4**	6.7	3.7	2.0	4.2
	Left Rot	**-66.3**	**13.8**	-4.9	5.1	-0.4	4.7	**-76.8**	**9.9**	-4.5	5.6	1.7	4.9
	Right LF	12.8	5.3	**35.1**	**9.2**	0.2	5.3	7.6	6.5	**40.0**	**7.6**	-1.6	5.3
	Left LF	-12.0	7.0	**-35.9**	**7.6**	2.4	6.8	-5.4	6.2	**-41.8**	**7.4**	3.0	6.8
	Flexion	-1.2	5.0	3.3	4.9	**48.0**	**13.4**	-2.4	6.3	4.8	5.6	**59.0**	**12.1**
	Extension	-1.3	7.2	-2.4	6.9	**-53.9**	**15.2**	-2.3	8.0	-2.8	7.7	**-62.0**	**11.1**

		NORM						Average					
		Rot		LF		FE		Rot		LF		FE	
		Avg	SD	Avg	SD	Avg	SD	Avg	SD	Avg	SD	Avg	SD
primary movement	Right Rot	**80.7**	**11.2**	7.8	4.5	2.7	5.3	**73.6**	**12.8**	6.5	4.4	1.6	4.4
	Left Rot	**-85.0**	**14.1**	-6.0	5.8	3.0	5.0	**-76.2**	**15.0**	-5.2	5.5	1.4	5.0
	Right LF	13.1	9.2	**45.5**	**9.3**	4.4	8.9	11.4	7.6	**40.3**	**9.8**	1.2	7.2
	Left LF	-13.4	9.1	**-45.9**	**8.2**	10.1	8.4	-10.5	8.3	**-41.2**	**8.8**	5.4	8.2
	Flexion	-2.5	5.5	4.8	7.9	**66.6**	**9.1**	-2.0	5.6	4.3	6.3	**58.0**	**14.0**
	Extension	-0.9	5.5	-1.6	5.1	**-66.0**	**12.9**	-1.5	6.8	-2.3	6.5	**-60.7**	**14.1**

Table G-18[28] – Average ROM and standard deviation (SD) of primary movement from the neutral position and conjunct motion in planes other than the primary movement plane.

Bold text indicates ROM values in the primary movement plane. [Rotation (Rot: +right, -left), Lateral Flexion (LF: +right, -left), Flexion/Extension (FE: +flexion, -extension)]

G.5 MEASURES COMPARISON RESULTS

G.5.1 CORRELATION RESULTS

Correlation analysis of the cervical range of motion, total PPT data, self-reports of neck and headache pain on the visual analog scale, Neck Disability Index (NDI) scores and the total region count are shown in Table G-19. There were good correlations between the NDI and the self-reported neck pain (from the neck pain VAS), the total region count and the NDI, and between the self-reported neck pain and the total region count.

[28] During the extension ROM movement, on 33 (4.5%) occasions the ETS sensor Yaxis approached 90^{o}. This caused error in the conjunct rotation (Zaxis) and lateral flexion (Xaxis) data. This problem was not realised until after all measurement were completed. The erroneous conjunct data of rotation and lateral flexion was modified to the neutral values for these measurements.

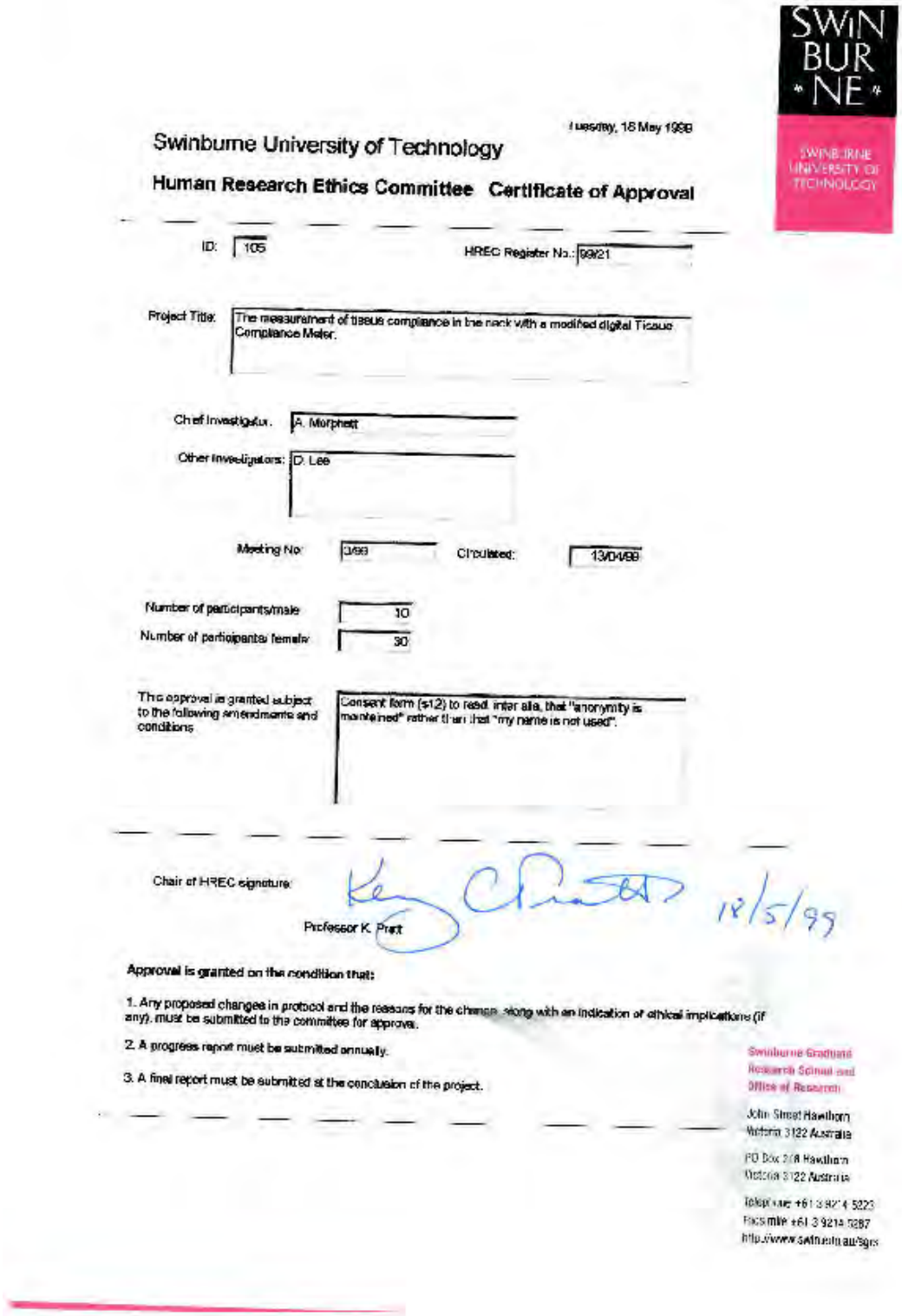
	Lat Flex	Flex/Ext	Rotation	total ROM	total PPT	Headache VAS	Neck pain VAS	Total Region No
Flex/Ext	0.77+	--						
Rotation	0.83+	0.77+	--					
total ROM	0.92+	0.91+	0.95+	--				
total PPT	0.42+	0.27*	0.39+	0.39+	--			
Head VAS	-0.26*	-0.34+	-0.26*	-0.31*	-0.11ns	--		
Neck VAS	-0.37+	-0.41+	-0.44+	-0.44+	-0.27*	0.52+	--	
Total Region No	-0.52+	-0.52+	-0.51+	-0.56+	-0.26*	0.45+	0.76+	--
NDI	-0.42+	-0.42+	-0.40+	-0.44+	-0.33+	0.52+	0.71+	0.78+

Table G-19[29] – Pearson's R correlations between cervical range of motion (ROM), neck pain and headache visual analog scale (VAS) pain, and pressure pain threshold (PPT). * $p<0.05$, + $p<0.01$, ns – not significant.

[29] Time 1 total PPT data was used for the correlation analysis.

APPENDIX H

ETHICS APPROVALS



Tuesday, 18 May 1999

Swinburne University of Technology

Human Research Ethics Committee Certificate of Approval

ID: 105 HREC Register No.: 99/21

Project Title: The measurement of tissue compliance in the neck with a modified digital Tissue Compliance Meter.

Chief Investigator: A. Morphett

Other Investigators: D. Lee

Meeting No: 3/99 Circulated: 13/04/99

Number of participants/male: 10

Number of participants/ female: 30

This approval is granted subject to the following amendments and conditions: Consent form (s1.2) to read, inter alia, that "anonymity is maintained" rather than that "my name is not used".

Chair of HREC signature: Professor K. Pratt 18/5/99

Approval is granted on the condition that:

1. Any proposed changes in protocol and the reasons for the change, along with an indication of ethical implications (if any), must be submitted to the committee for approval.
2. A progress report must be submitted annually.
3. A final report must be submitted at the conclusion of the project.

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SWINBURNE UNIVERSITY OF TECHNOLOGY

16 August, 2001

Mr Adrian Morphett
30 Cambridge Street
Belgrave South VIC 3160

Dear Adrian,

RE: Application for Ethics Approval of a Research Protocol

The Human Research Ethics Sub-Committee of the School of Engineering and Science has considered and approved your application for ethics approval entitled 'Measurement and Outcomes of Poor Working Posture'.

Please find the Committee's comments attached and adjust your application as appropriate. Please contact your supervisor Mr Don Lee or myself if you need further clarification.

Yours sincerely,

Mr Kerry McManus, AM
Chair, Ethics Sub-Committee
Deputy Head - School of Engineering and Science

cc. D. Lee

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APPENDIX I

LIST OF PUBLICATIONS

1. Morphett A, Lee D. Upper Extremity Posture and Chronic Pain. In: Ergonomics Society of Australia National Conference. Melbourne, Australia: Jamison Printing; 1998. p. 290-9.

2. Morphett A. The FWAP-Link system: linking motion capture data, 3D computer animation and MODAPTs analysis with FWAP for Windows. In: Farrell J, Swann I, editors. Successful management of repetitive work. The way of the future. Proceedings of the 6th ANZMA Biennial Seminar. Melbourne, Australia: ANZMA; 2002. p. 16-30.

3. Morphett A, Crawford C, Lee D. The use of electromagnetic tracking technology for measurement of passive cervical range of motion: a pilot study. J Manipulative Physiol Ther 2003;26:152-9.