Validity and inter-device reliability of dominant and non-dominant wrist worn activity trackers in suburban walking

Marten de Man (mdeman@swin.edu.au)
Skilled Performance Laboratory, Faculty of Health, Arts & Design
Swinburne University of Technology, Hawthorn VIC Australia

Elizabeth Vanderploeg
Skilled Performance Laboratory, Faculty of Health, Arts & Design
Swinburne University of Technology, Hawthorn VIC Australia

Nicole Aimers (naimers@swin.edu.au)
Centre for Design Innovation, Faculty of Health, Arts & Design
Swinburne University of Technology, Hawthorn VIC Australia

Clare MacMahon (cmacmahon@swin.edu.au)
Skilled Performance Laboratory, Faculty of Health, Arts & Design
Swinburne University of Technology, Hawthorn VIC Australia

Lisa Wise (lwise@swin.edu.au)
Skilled Performance Laboratory, Faculty of Health, Arts & Design
Swinburne University of Technology, Hawthorn VIC Australia

Lucy Parrington (lparrington@swin.edu.au)
Skilled Performance Laboratory, Faculty of Health, Arts & Design
Swinburne University of Technology, Hawthorn VIC Australia

Abstract

Wearable activity trackers have become a popular way for general and athletic populations to measure daily physical activity and rest patterns. The validity and reliability of step count is often unknown for these devices. The aims of this study were to evaluate the validity of the step count of the *Fitbit Charge HR* and the inter-device reliability between devices worn on the dominant and non-dominant wrists in an ecologically valid walking setting. A secondary aim was to compare these findings with data from an inertial measurement unit (IMU). Six participants were fitted with one Fitbit Charge HR on each wrist and an IMU positioned on the left and right hip. Data from the Fitbit Charge HRs and IMUs were compared against the participant's self-reported step count. Each participant walked the same suburban circuit whilst counting their steps. When assessed for validity, the Fitbit Charge HR was found to have a low correlation with the self-reported step count (dominant arm, $ICC_{2,1} = .19$; non-dominant arm, $ICC_{2,1} = .21$), underestimating the number of steps taken. In comparison, the inter-device reliability of the dominant and non-dominant wrist worn Fitbit Charge HRs was good ($ICC_{2,1} = .81$). Moderate validity was found between the self-reported step count and IMUs (dominant hip, $ICC_{2,1} = .74$; non-dominant hip, $ICC_{2,1} = .72$). The findings suggest that inter-device measurement from dominant and non-dominant hands is reasonably reliable, however less valid as compared to more robust research-grade devices.

Keywords: Fitbit; Wearable; Accelerometer; Step Count; IMU

Introduction

Wearable technology, such as activity trackers are defined as a category of devices that can be worn to track information about health and fitness (Dontje, de Groot, Lengton, van der Schans, & Krijnen, 2015). Activity trackers are becoming increasingly popular and more evolved. The various types of activity trackers are small in size, shaped in a way that they can be easily disguised if needed and are able to be placed on many areas of the body (Mammen, Senthinathan, McClemont, Michelle, & Faulkner, 2012). In comparison to early wearable devices such as mechanical (pendulum based) pedometers, technological advancement has progressed both the hardware and software of these devices to be both more aesthetic and more functional. Many activity trackers allow a wide array of functions and provide easy to interpret data, which can readily be synchronised and uploaded to an individual's smart device. In some populations, activity trackers are rapidly becoming a crucial element to increasing daily physical activity and are believed to play a role in maintaining a healthy lifestyle (Dontje et al., 2015).

Advancements in wearable technologies have been driven by progressions in small inertial measurement units (IMUs) that use a combination of micro electro-mechanical systems technology sensors (MEMS; e.g. combinations of accelerometer, gyroscope and magnetometer). These IMUs have been used in a number of different ways in sport and movement science, research and education (Espinosa, Lee & James, 2015; Espinosa, Lee, Keogh, Grigg & James, 2015), including assessing tasks such as front-crawl swimming (Nordsborg, Espinosa & Theil, 2014), 100m sprinting (Parrington, Phillips, Wong, Finch, Wain, & MacMahon, 2016) and gait analysis (Rueterbories, Spaich, Larson & Anderson, 2010). Investigation of the use of IMUs in gait have shown that the devices are accurate and robust regardless of lower trunk positioning (Trojaniello, Cereatti & Croce, 2014) and effective in differentiating between movements patterns (Lee, Ho, Chang, Robert & Shiang, 2015).

From a commercial perspective, activity trackers and their smart applications are believed to provide a useful solution to monitoring physical activity, by providing a proxy of movement data and allowing the input of other aspects of one's daily routine (i.e. number steps taken, flights of stairs climbed, total distance travelled and sleep patterns, Ferguson, Rowlands, Olds, & Maher, 2015). These data can be beneficial for individuals to access, in order to set goals, meet targets and essentially learn how to increase physical activity levels (Paul, Tiedemann, Hassett, & Sherrington, 2015). Nonetheless, there are questions over the validity and reliability of these competing commercial products.

Of the different activity tracker developers, Fitbit is one of the leading competitors (Ferguson et al., 2015). Their devices are reported to be one of the more affordable, user friendly and multifaceted devices currently available (Noah, Spierer, Gu, & Bronner, 2013). The Fitbit device range has generally been found to provide reliable and valid activity tracking. Evaluation of early Fitbit step-counters found the devices to be 95-97% accurate when measuring step count in an everyday setting (Mammen et al., 2012). More recently, Ferguson et al. (2015) found the Fitbit models (Zip and One) performed well against other consumer-level wearable trackers, a finding that was also indicated in Kooiman et al. (2015). Kooiman and colleagues assessed the accuracy of the step-count measurement in ten types of fitness trackers in both laboratory and free-living conditions. This study revealed that only seven types of trackers were reliable, with the waist or pocket worn 'Fitbit Zip' (i.e., one of the many Fitbit models) found to be most valid.

A key issue with commercial wearable technologies is how the devices are worn. Researchers have found differences in the reliability and validity of the device depending on the placement location on the body. Some Fitbit models have been shown to be effective and accurate when worn on the waist or attached to the pocket (Mammen et al., 2012), albeit with slight under reporting of the hip worn trackers (Fitbit One and Fitbit Zip) by 1.3 steps during a two minute walk test was noted by Paul et al. (2015). Nonetheless, the step count output derived from either the hip or pocket placement of the device appears to provide similar output, at least for the Fitbit One (Takacs et al., 2014). There are an increasing number of devices designed to be worn on the wrist, however, such as the Fitbit Charge HR assessed in this study. These devices have suggested advantages, including encouraging continued compliance due to ease of use and security of attachment during physical activity (Noah et al., 2013). However, previous assessments on the wrist worn 'Fitbit Flex', suggest that these devices underestimate the number of steps taken (Kooiman et al., 2015).

The increased use of wearables, particularly recently released wrist worn devices and the ability to personalise the devices have important implications. These benefits, combined with the users' ability to monitor their daily physical activity over the short and long term suggest current wearable devices such as the Fitbit Charge HR continue to play a role in maintaining a healthy lifestyle. Nonetheless, for activity trackers to be useful across the athletic or general population, it is important that these devices consistently and accurately capture activity levels whilst worn and uphold the claims made by manufactures (Ferguson et al., 2015).

To our knowledge, there have been limited studies conducted on wrist worn Fitbits and no studies looking at the validation of the Fitbit Charge HR worn on nominated dominant and non-dominant wrists, nor the validation of the devices in suburban walking. Therefore, the primary aim of this study was to explore the validity of the Fitbit Charge HR against self-reported step count and assess the inter-device reliability between preferred and non-preferred arms when walking in a suburban environment. The secondary aim was to compare the results with a third generation IMU positioned on the left and right hip.

Methods

Participants and design

A convenience sample comprised of six healthy adults, five females and one male aged between 20 and 57 years of age (*M*=35.83, *SD*=12.43) participated in the study. Participants were recruited through their involvement within a University laboratory research group conducting the current study. The University's Human Research Ethics Committee approved the study.

Participants walked approximately 500 meters around an identical circuit in a natural suburban environment. On each trial through the circuit participants wore two Fitbit Charge HR devices, one on each the dominant and non-dominant wrist. Specifically, each Fitbit Charge HR tested was pre-set to either dominant or non-dominant arm settings. Participants were asked to pay close attention to the number of steps taken whilst walking the circuit, so that they could report this at the conclusion of each circuit. This value was used to calculate the validity and inter-device reliability of the wearable devices.

Two research grade inertial measurement units (IMUs; IMeasureU, Auckland, New Zealand) were attached bilaterally to the anterior superior iliac spine of the hip of each participant for additional comparison against the Fitbits. The testing procedure was repeated five times such that a total of 10 Fitbit Charge HRs (five dominant and five non-dominant) were assessed.

Materials

The Fitbit Charge HR is a wrist worn wearable device that uses a MEMS three-axis accelerometer to track motion and based on proprietary algorithms the device estimates the number of steps taken (Fitbit, 2015). The physical activity data recorded and stored from each Fitbit is synchronised wirelessly to a dedicated Fitbit user account where an overview of physical activity was presented. The Fitbit user account enables individualised device configuration including the hand the device is worn on (dominant or non-dominant). This setting is designed to increase the device's accuracy by decreasing the device's sensitivity when set to dominant and increasing sensitivity when non-dominant (Fitbit, 2015).

For comparison with the Fitbits, two IMUs, composed of a tri-axially mounted accelerometer (±16 g), rate gyroscope ($\pm 2000 \text{deg.s}^{-1}$), and magnetometer (±1200μT) MEMS technology, were used for the logging of acceleration data (100Hz). The raw data from each IMU were imported into Microsoft Excel where the acceleration waveforms were then analysed. The resultant of the three-axes for each time point was calculated across each circuit trial. To calculate the step count, a peak threshold value and temporal range for each peak was determined for each participant. An algorithm was set to count each step when a threshold change in acceleration (approximately 15ms^{-2}) was reached within a minimum time period which took into account the individual's approximate step frequency.

Procedure

Ten Fitbit devices and user accounts were set up for each of the Fitbit Charge HRs. Five of the Fitbit Charge HR devices were set to be worn on the dominant wrist and five Fitbit devices were set to be worn on the non-dominant wrist. The dominant and non-dominant devices were allocated into five pairs and nominated to a circuit trial number from one to five. All individualised users' categories (i.e. the specifying of height, stride length, running stride length and weight) remained as per factory settings. Participant demographic details of gender and age were recorded. Participants indicated their dominant hand by responding to which hand they use for most day-to-day activities such as writing or throwing a ball (Fitbit, 2015).

Prior to commencing the walking circuit the participant stood stationary at the start position, which was marked on the laboratory floor. A dominant and a non-dominant Fitbit Charge HR, corresponding to the circuit trial number were attached by the participant around their wrists. The left anterior superior iliac spine and right anterior superior iliac spine were located on each participant and then the IMUs were attached with adhesive tape.

Verbal instructions were provided to each participant as to the circuit route. The circuit was to be walked at a normal walking pace, refraining from walking with hands in pockets or using any mobile devices. Each participant was requested to count the number of steps they took during each circuit.

Prior to commencing each circuit, the participant stood still as the researcher simultaneously activated the two Fitbit Charge HR devices and the IMUs. Activation of the Fitbit was indicated by a stopwatch icon appearing on the display. The IMUs were activated wirelessly via an iPad Research Application (IMeasureU, Auckland, New Zealand), which triggered both sensors to log data. The participant was then instructed to commence walking. A circuit was completed when the participant stepped back over the start position. On completion, the participant stood in a stationary position. At this time, the researcher stopped the two wearable devices and IMUs, and the self-report step count was recorded. The Fitbit Charge HR devices were removed and the next Fitbit Charge HR pair of devices attached. The participant then commenced the next circuit following the above procedure. On the final trial the Fitbit Charge HR devices were synchronised with the user accounts and the IMU data was downloaded.

Data Analysis

The validity of the Fitbit Charge HR was measured against the self-reported step count. A paired sample *t*-test was first conducted to evaluate the differences in step count collected by the Fitbit devices and the self-reported step count. The level of agreement between Fitbit Charge HR and the self-report step count was then assessed using a two-way random intra-class correlation coefficient (ICC), with absolute agreement assessed. The ICC analysis estimates the proportion of variance attributable to the objects of measurement (McGraw & Wong, 1996). This study followed cut-off points for interpretation that have been previously used in this area > .90 (excellent), .75-.90 (good), .60-.75 (moderate) and <.60 (low) were used (Kooiman et al., 2015). To evaluate the differences in step count collected by the Fitbit Charge HR devices when worn on the dominant and non-dominant wrist, a paired sample *t*-test was first conducted. Inter-device reliability of the step-count measure was then analysed using a two-way random intra-class correlation coefficient ($ICC_{2,1}$), with absolute agreement assessed. Mean absolute percentage errors of step count were calculated between the dominant and non-dominant worn Fitbit Charge HRs and self-reported step count.

For comparison, these processes were repeated to calculate the validity of the step count from the hip worn IMUs against the self-reported step count. Inter-device reliability of the IMUs was also assessed using the same procedures. Finally, for additional comparison, the level of agreement between the dominant and non-dominant wrist worn Fitbit Charge HR devices and hip worn IMUs were calculated. Mean absolute percentage errors of step count were also calculated between the dominant and non-dominant worn IMUs.

In line with Kooiman et al. (2015) mean absolute percentage errors were calculated between the devices and self-report step counts. Tudor-Locke, Sisson, Lee Craig, Plotnikoff and Bauman (2006) posited that less than a 10% error margin in step count between research grade pedometers and a gold standard device in free-living conditions is desired.

Data Screening

Self-report data of step count were missing from two trials of one participant, and non-dominant hip IMU data from one trial of another participant were missing and excluded from the analysis. One self-report step count was observed as an outlier when compared within the subject and between other participants. While the self-report step count is a subjective measure and some error is expected the value was found to be an extreme outlier (> 4 *SD*) and was removed from the data set.

Results

A total of six participants completed five walking trials. The Fitbit Charge HR devices for each participant recorded a lower mean step count than IMU devices and self-report measures. The mean and standard deviations of step counts recorded across each device is provided in Table 1 and mean absolute percentage errors are displayed in Table 2.

Table 1

Descriptive data for each step counter apparatus, displayed as mean (standard deviation)

Participant	Fitbit (D)	Fitbit (ND)	IMU (D)	IMU (ND)	Self-Report
01	419.20 (25.79)	415.20 (28.89)	662.40 (4.88)	663.25 (3.59)	665.0 (20.6)
02	664.20 (17.40)	633.60 (31.80)	786.80 (9.01)	789.20 (4.32)	782.67 (7.02)
03	562.20 (27.38)	526.20 (30.15)	691.20 (11.90)	693.20 (13.77)	680.00 (52.88)
04	661.00 (13.64)	666.40 (6.35)	783.40 (4.04)	783.40 (4.72)	780.80 (10.26)
05	546.20 (62.86)	575.80 (14.32)	723.20 (9.20)	719.40 (5.03)	723.50 (4.12)
06	412.20 (65.90)	494.00 (46.58)	653.60 (12.44)	661.20 (5.81)	662.40 (4.98)

Note. D = dominant hand, ND = non dominant hand

Table 2

Mean absolute percentage errors of step count between recording devices, displayed as mean difference (percentage difference)

Device	Fitbit (D)	Fitbit (ND)	Self-Report	IMU (D)
Fitbit (ND)	-9.4 (1.7%)	-	-	-
Self-Report	173.7 (24.2%)	164.3 (23%)	-	-
IMU (D)	172.6 (24.1%)	163.24 (22.77%)	1.05 (<1%)	-
IMU (ND)	176.00 (24.4%)	166.64 (23.1%)	2.35 (<1%)	3.4 (<1%)

Note. D = dominant hand, ND = non dominant hand

A significant difference was found between the self-reported step count and the Fitbit Charge HR device step count for dominant wrist worn *t*(27)= 11.62, *p*<.001 and non-dominant wrist worn devices *t*(27)= 13.19, *p*<.001. A low level of agreement was found between the Fitbit Charge HR and self-report step count for both the dominant hand Fitbit ($ICC_{2,1}$ = .19, 95% CI -.07 to .53) and non-dominant ($ICC_{2,1}$ =.21, 95% CI -.06 to .57), with both devices underestimating the step-count for each participant.

No significant difference in step count was found between Fibit Charge HR devices worn on the dominant or non-dominant wrists (*p*>.05). No exact agreement across any pair of devices worn on the dominant and non-dominant wrist was found. The estimated inter-device agreement between the paired Fitbit devices was good, $ICC_{2,1}$ = .81 with a 95% confidence interval from .63 to .90.

No significant difference was found between the self-reported step count and step count of the IMUs worn on the dominant or non-dominant hips (*p*>.05). Moderate agreement was found between the IMUs and the self-reported step count for the dominant hip worn IMU ($ICC_{2,1}$ = .74 95% CI .51 to .87) and non-dominant hip worn IMU ($ICC_{2,1}$ = .72 95% CI .49 to .86).

There was no significant difference in step count between the two IMUs (*p* > .05), and excellent inter-device agreement was found between the IMUs worn on the dominant hip and non-dominant hip ($ICC_{2,1}$ = .99 95% CI .98 to .99).

A significant difference was found between the dominant side worn Fitbit Charge HR and IMU *t*(29)= 14.66, *p*<.001. Similarly, a significant difference was found between the non-dominant side worn Fitbit Charge HR and IMU *t*(28)= 19.17, *p*<.001. Low agreement was found between the Fitbit Charge HR and IMUs (dominant side worn $ICC_{2,1}$ = .24 95% CI -.06 to .76, non-dominant side $ICC_{2,1}$ = .24 95% CI -.04 to .62).

Discussion

Constant advancements in wearable technology require product developers and researchers to remain current in evaluating the accuracy of these devices. This study is novel because of the exploration of the validity of the Fitbit Charge HR step count while walking in a natural suburban environment, as well as the effect of hand dominance on the inter-device reliability.

To date, findings within the literature on wearable devices have consistently found a margin of error in step counts. Tudor-Locke et al. (2006) previously suggested that an error margin of no more than 10% is desirable for a wearable step counter. In this study, when compared to the self-reported step count the error margin for both dominant and non-dominant worn Fibit Charge HR devices exceeded 10%. The error for the dominant worn Fibit (24%) and non-dominant worn Fitbit (23%) combined with low ICC suggest the Fitbit Charge HR has low validity in counting steps when used in a natural suburban setting. Specifically, our findings indicated the Fibit Charge HR undercounted steps, which is consistent with the results of Kooiman et al. (2015) and Paul et al. (2015).

The Fitbit Charge HR devices were found to have good inter-device reliability in counting steps, indicated by a small margin of error (1.7%) paired with a good ICC agreement between the dominant and non-dominant worn devices. This supports the findings of Dontje et al. (2015). This finding suggests that each device will collect approximately the same data, and supports the use of the preferred hand setting within Fitbit user accounts.

The research grade IMUs worn on the hip performed better than the Fitbit Charge HRs. The devices provided a better representation of the self-reported step count, demonstrating error margins less than 1% and were also found to have excellent inter-device reliability with less than 1% error margin between IMUs. These devices may provide a useful proxy step-count measure for comparison in future investigation of activity trackers in complex and dynamic environments.

The current study extends upon the wearables research on a number of important factors. First the study is novel in that the protocol involved suburban walking trials, a key setting where the devices may be used. We believe this increased ecological validity over previous studies where a treadmill task has been used (e.g. Mammen et al., 2012; Noah et al., 2013; Takacs et al., 2013). In addition, while increasing ecological validity, this study retained experimental control over how the wearables were attached and over the physical activity performed.

Second, there has been limited investigation on wrist worn wearables and to our knowledge no study has assessed the Fitbit Charge HR along with the preferred hand setting. This study addresses this key absence. The findings of the current study indicate some support for the results of Kooiman et al. (2015), in that this study found good reliability between Fitbit devices. In comparison, however, the excellent reliability and low error percentage (3.7%) identified by Kooiman et al. when the device was worn in the free-living condition was not supported by our results. This discrepancy may be explained by methodological factors, such as the free living condition in Koomiman and colleagues being assessed over a greater time period (a period of one day), and assessment of more participants (*n* = 33).

Wearable devices can play a role in maintaining a healthy lifestyle, by assisting the monitoring of daily physical activity over the short and long term.

Wrist worn devices such as the Fitbit Charge HR are believed to encourage continued compliance due to ease of use and security of attachment during physical activity (Noah et al., 2013). Nonetheless, inaccuracies such as the underreporting found in this study have implications for the user, as well as health care professionals who may advocate their use. The under reporting of physical activity may not be as problematic as over-reporting, as it may help increase activity to reach a desired goal. Nonetheless, underreporting may have negative consequences on motivation, and cause frustration to the user if he or she has the perception that more physical activity has been performed than what has been recorded. Consumers should be made aware of the margin for error inherent in wearable devices, in order to allow users to have an informed outlook on the data attained. Development of wearable devices requires on going work to increase the validity of their products.

This study has some limitations. One limitation that is acknowledged includes the trade-off between an ecologically valid walking setting and the loss of control during the trial when compared with studies that have required participants to walk on a treadmill. This study is unique in using an ecologically valid walking setting, but this environment may have caused potential interruptions to the participant, which may have reduced the accuracy of the step count by the participant.

A second limitation is that in increasing ecological validity, there were challenges faced with obtaining an externally measured step count to compare with the Fitbit devices. Where other studies have involved a researcher verified step count, this study's protocol required the participant to count his or her own steps. The rationale behind this decision was that it was perceived to be a harder dual-task for the researcher to shadow the participant, whilst counting steps and navigating through the environment safely, than for the participant themselves to complete this. We also attempted to tackle this problem by having participants wear research grade IMUs on their dominant and non-dominant hip whilst performing the trials. These devices demonstrated low error margins and we believe they provided a helpful cross-check with the self-report step count.

Finally, this study collected samples from a relatively small set of walking conditions, limiting the generalizability of the results to standard suburban walking. Future research should include trials over a wider range of walking terrain (e.g. walking on sand, grass, inclines), and include both closed and open environments (e.g. busy city streets), in order to assess how changes in the walking environment effect the accuracy of the devices. Whilst there is no standardised method for assessing the validity and reliability of activity monitor wearables, a follow-up study could assess the ability of the devices to track other non-walking activity.

Conclusion

Advances in technology have allowed personal wearable devices such as activity trackers, and the data they collect to be more accessible to the general population. This study assessed the validity and inter-device reliability of dominant and non-dominant arm worn Fitbit Charge HR devices. The Fitbit Charge HRs were found to have low validity for counting steps taken over a 500m outdoor circuit and underestimated the number of steps, regardless of preferred or non-preferred arm settings. Whilst validity was low, good inter-device reliability was found for step count between dominant and non-dominant wrist worn devices. The findings from this study suggest there is a need for further improvements to be made to the accuracy of these devices. Consumers and any health care practitioners (e.g., General practitioners, personal trainers) who incorporate the device into their professional practice should be adequately informed about the potential miscalculations of the devices.

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Correspondence

Marten de Man
Swinburne University of Technology
John St, Hawthorn VIC 3122, Australia
mdeman@swin.edu.au

Research Profile

Marten de Man recently completed his Bachelor of Arts (Honours) in psychology at Swinburne University of Technology. He is currently a member of a laboratory research group that is interested Skilled Performance, particularly within a sporting context. The current study was conceived and completed within this Skilled Performance laboratory group. His research interests are focused on the functional and cognitive components of Tool-use within a perception-action context. Under the supervision of Dr Wise and Dr Parrington he has been exploring the differences in monitoring and adjusting tool use while in action across individuals along the novice-expert continuum.