Development of a smart insole for medical and sports purposes

Adin Ming Tan\textsuperscript{a,c,*}, Franz Konstantin Fuss\textsuperscript{a,c}, Yehuda Weizman\textsuperscript{a,c}, Olga Troynikov\textsuperscript{b,c}

\textsuperscript{a}School of Aerospace, Mechanical and Manufacturing Engineering, RMIT University, Melbourne VIC 3083, Australia
\textsuperscript{b}School of Fashion and Textiles, RMIT University, Melbourne VIC 3056, Australia
\textsuperscript{c}Wound Management Innovation Cooperative Research Centre, Brisbane QLD 4101, Australia

Abstract

A study was conducted to determine the performance of a low cost plantar measuring device. The aim of the device was to establish an in-shoe measurement system with high resolution and to take relatively accurate measurements. The calibration method for the smart material was established with the use of a Kistler force plate. The coefficient of determination $r^2$ of the force against resistance calibration curve was 0.974. The residual standard deviation amounted to 13.91 N. The $r^2$ value of the repetitive loading experiments amounted to 0.981. The residual standard deviation was 70.35 N for forces larger than 700 N. From the data obtained, the insole is deemed to be sufficiently accurate for quantitative analysis.

1. Introduction

Plantar pressure measurements provide an indication of foot functions during gait and other activities. This is recognized to have a significant relevance in gait analysis, medical applications such as diagnostics [1] and rehabilitation [2], as well as in sports [3]. The use of force platforms is the most common method in analyzing plantar pressure measurement. They are highly accurate but lack the versatility of in-shoe systems. There are an increasing number of in-shoe systems and some of these commercially available ones, such as F-Scan [4] and Pedar Sense System [5], have high resolutions, but they can be rather costly and used mainly in clinical diagnostics and research purposes. Relatively cheaper ones such as Moticon [6] and Orpyx [7] have low resolution due to low

* Corresponding author. Tel.: +61-4-70714044.
E-mail address: s3514835@student.rmit.edu.au
number of sensors. This limits the accuracy of plantar pressure mapping and may not be able to capture important details. Although these insoles are relatively cheaper than those with high resolutions, they are not necessarily affordable to the masses as well. The development of a low cost and high-resolution smart insole system is highly desirable for medical and sports applications, as well as research which involve mass participation.

In this paper, we present a study on the performance of these insoles that utilized smart materials enabling the development of a low cost plantar pressure measuring device void of any commercially available sensors and still having the ability to achieve a high density of sensing nodes. Low cost carbon embedded piezoresistive materials are potential candidates for this application.

2. Methodology

The hardware developments of a wireless, pressure measuring insoles were detailed by Tan et al [8]. In this study, we used the same construction described except that no Bluetooth module was attached and thus a wired version of the insoles was utilized. A piezoresistive material, Rmat3a (RMIT material code), was investigated to explore their feasibility to be used as plantar pressure measuring sensors. When a force was applied on these insoles, there would be a drop in the resistance of that material and this change in resistance was measured by the voltage drop across the reference resistor. The microcontroller generates a 3.3 V input electrical signal and resistance change in each pressure sensing node was calculated in equation (1).

\[
R_{\text{node}} = \frac{V_{\text{in}} \cdot R_{\text{ref}} - V_{\text{ref}} \cdot R_{\text{ref}}}{V_{\text{ref}}}
\] 

(1)

where \(R_{\text{node}}\) is the resistance across the piezoresistive material, \(V_{\text{in}}\) is the input voltage generated by the microcontroller, \(R_{\text{ref}}\) is the reference resistor and \(V_{\text{ref}}\) is the voltage drop across the reference resistor.

The insoles were placed on a Kistler force plate (Kistler Instruments, Winterthur, Switzerland) as can be seen in Figure 1. A cyclic force with varying magnitudes was applied to a single node on the insole. This force was recorded by the Kistler force plate at a frequency of 1000 Hz. The change in resistance of the sensing node was recorded by the microcontroller at a frequency of 12 Hz for the entire insole. The data from the force plate were then matched to that of the insoles due to the difference in sampling frequency. The logarithm of the measured force data were then plotted against the logarithm of the calculated resistance data. It was noticed during preliminary tests the presence of hysteresis in the data recorded. To minimize the effects of hysteresis in the data, only the peak forces of each cycle was used in the calibration curve. Although the presence of hysteresis is inherent in viscoelastic sensors, there is a need to diminish its influence on the calibration process so as to achieve relatively accurate results. A linear fit was applied to the log-log plot and the coefficient of determination was calculated.

With the calibration of a single node completed, the fit function determined during the calibration exercise was used to calculate the force applied to the entire insole with a total of 75 nodes. A subject was asked to apply an evenly distributed force on the insole for ten cycles over a period of 40s while the applied force was simultaneously measured by the Kistler force plate for validation. The force calculated from each individual node was summed up for all 75 sensing nodes and this would be the total force applied onto the insole. This calculated force was compared with the force recorded by the Kistler force plate to determine the accuracy of the system. The above experiment was repeated three times to ensure repeatability of the results. The calculated force from the insole was superimposed on the recorded data from the force plate and their coefficient of determination, \(r^2\), was calculated, together with the standard deviation and residual standard deviation. The results in each set of experiments were then combined to calculate the overall \(r^2\) value and the residual standard deviation.
3. Results

Fig. 2. shows the calibration curve for Rmat3a. The data had a linear fit when logF was plotted against logR with a coefficient of determination $r^2$ of 0.974. The fit function derived can be seen in equation (2). The residual standard deviation was subsequently calculated and amounted to 13.91 N. The residual standard deviation when normalized to the measured force ranged from 15.4% at 90 N to 5.46% at 230 N and this range followed a Power law. The peak force applied to the sensor with an area of 225 mm$^2$ was 250 N which amounted to approximately 1 MPa.

$$\log F = 1.11 * \log R + 7.28$$

Equation (2) was used to calculate forces from the insole output. Fig. 3. shows the data comparison between the calculated force from the insole and the measured force from the Kistler force plate during experiment 1. It could be seen that the data matched up relatively well. The data of all 3 experiments were combined and the coefficient of determination $r^2$ was calculated and amounted to 0.981. The peak forces calculated are of great importance and consequently, a more detailed analysis was required. A range of peak forces measured from the force plate, between 700 N and 750 N, was taken for comparison to the calculated output of the insole. The residual standard deviation was 70.35 N for forces larger than 700 N which corresponded to an average relative residual standard deviation of 9.94% between 700 and 750 N.

4. Discussion

There is a clear need for an in-shoe device that can measure real time plantar pressure in order to do gait analysis away from a gait laboratory. The paper presented a novel method of using off-the-shelf common material to be used as pressure sensors for this purpose. This may potentially pave the way for design of low cost tactile sensors to be used in a wide variety of applications. Most commercially available pressure measuring insoles utilize the integration of pre-manufactured pressure sensors. These designs are therefore limited by the sizes and costs of these sensors. The results obtained in these experiments measure the feasibility and accuracy of these sensors as compared to a force plate commonly used in research laboratories and clinics.
The selection of this piezoresistive material is critical to the appropriate application of this system as the material may have different working ranges. In the event that the required working range is not commercially available, it is possible to produce carbon embedded rubber with correct carbon concentration and spatial distribution as described by Wang et al. [9].

Fig. 3. shows the results of experiment 1 for the loading of the insole. It can be seen that the sensors in the insoles responded in sync with that of the Kistler force plate and the results were repeatable. The data from the output of the insole had a very good correlation with that of the force plate data with an $r^2$ value of 0.981. This was in comparison with the work done by Sawacha [10] and Ferber et al. [11] on the SurroSenseRx™ Insole (Orpyx Medical Technologies Inc., Calgary, Canada) which only managed a maximum correlation, $r$ value of 0.86, corresponding to an $r^2$ value of 0.74. A point to note was that the comparison they made was to Pedar X® (Novel, St. Paul, Minnesota). Although the basis of comparison was different, the Kistler force plate was the basis of comparison when determining if the Pedar system was accurate [12]. Thus the Kistler force plate was still deemed to be the most accurate device amongst the systems discussed. Moreover, the pressure range at which the SurroSense Rx™ Insole functions seemed exceedingly low at up to 75 mmHg [10,11], equivalent to only 10 kPa. This is significantly lower than the plantar pressure for walking, between 0.4 and 0.8 MPa on average, with maxima just under 1 MPa [13].

4. Conclusion

The main endeavour of this investigation was to develop a relatively accurate Smart insole with high resolution. The calibration method was established with the use of a Kistler force plate. The coefficient of determination achieved an $r^2$ value of 0.974 for the calibration process. Validation was further conducted with the use of the Kistler force plate. The output data from the insole had a very good correlation with that of the force plate data with an $r^2$ value of 0.981. This performance was relatively better than the results obtained for the SurroSense Rx™ Insole. The peak forces were further analysed and the residual standard deviation achieved was 70.35 N for forces larger than 700 N. From the above results, the insole is deemed to be sufficiently accurate for quantitative analysis.

Acknowledgements

The authors would like to acknowledge the support of the Australian Government’s Cooperative Research Centres Program.
References


