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Design of Low Cost Smart Insole for Real Time Measurement of Plantar Pressure

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Abstract

Real time plantar pressure provides information critical to the understanding of gait mechanics and has a wide range of applications. In this study, smart insoles were designed and developed to measure real time foot plantar pressure. Key features of the insoles included cost-effectiveness, good working pressure detection range, wireless data transfer and real-time data analysis. Calibration of the sensing material was done and the resulting accuracy of the insoles was compared to that of a Kistler force plate, achieving an r^2 value of 0.981. Real-time visualization of pressure mapping was incorporated to enable intuitive understanding of relative plantar pressure distribution.

Keywords: Smart Insole; Real-time; Plantar Pressure; Piezoresistive Sensors; Low-Cost; Wireless Data Transfer; Gait analysis

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1. Introduction

Plantar pressure measurements and analysis has important applications in medical diagnostics [1], rehabilitation [2] and sports related performances [3, 4]. There are two main types of instruments used for this analysis and measurement [5]. They are broadly categorized into platform methods and in-shoe systems. Platform methods usually involve the subject walking over a designated path with pressure sensors embedded. This method limits the study to a confined laboratory or clinical environment. Rigorous tests across varying terrains and surfaces are difficult to conduct and thus do not accurately reflect real world conditions. In-shoe systems have sensors within the base of shoes or in the insoles, and measure the pressure interaction between the foot and the shoe. This portable system enables a wider variety of research to be conducted that is not constrained to laboratory conditions.

Platform systems are generally more accurate than in-shoe systems [6, 7]. However, due to the lack of portability of these platform systems, accurate and economical in-shoe systems are highly sought after. Several commercially available in-shoe systems are designed with embedded pre-fabricated sensors in them. This restrains the density of the sensors in the insole, as they are limited by the size of individual sensors. With the miniaturization of sensors in order to achieve a higher density, the power consumption and cost of the insoles would be severely compromised.

The purpose of this report is to present a low cost plantar pressure measuring insole void of any commercially available sensors but retainig the ability to achieve a high density of sensing nodes. Some factors important to designing a pressure measuring insole such as accuracy, real-time data analysis and pressure range will also be considered [8].

2. Methodology

2.1. Hardware Development

Carbon embedded piezoresistive material (Rmat 3a, RMIT Material code 3a) was sandwiched between two layers of electrodes to form a pressure sensing insole. The horizontal electrodes had a total of 15 elements whereas the vertical electrodes had a total of 5. This formed a total of 75 sensing nodes for each insole. A sensing node was formed at the intersection of the horizontal and vertical electrodes. The assembly of the main sensing components of the insole can be seen in Fig. 1. The electrodes are wired to a microcontroller (TEENSY 3.1, 32 bit ARM Cortex-M4 72 MHz CPU, PJRC, Oregon, USA) with the horizontal electrodes as digital input and the vertical electrodes as analogue inputs. Reference resistors were connected to each analogue input and were used to measure the relative change in resistance of the piezoresistive material. The microcontroller generated a 3.3 V digital output and the change in resistance experienced by the piezoresistive material reflected a change in voltage in the reference resistors. The 2 sets of electrodes were multiplexed and the resistance across each individual sensing node could be calculated. The microcontroller was set to run at 1000 Hz which resulted in approximately 13 Hz per sensing node per insole. In this system, HC-05 Bluetooth modules were used and one was connected to the left insole. This sent the measured data to the right insole, which had 2 Bluetooth modules. On the left insole, one Bluetooth module was synced to the Bluetooth module of the right insole, whereas the other Bluetooth module was synced to a laptop. This allowed the laptop to receive data wirelessly. The hardware components were interfaced in Arduino Software (Arduino v1.0.6 IDE, Teensyduino 1.22).

2.2. Data Analysis

The insoles were placed on a Kistler force plate (Kistler Instruments, Hampshire, UK). A cyclic force with varying peak values (between 30 and 300 N) was applied on one of the sensing nodes and the magnitude of the applied force was measured from the Kistler force plate at a sampling frequency of 1000 Hz. As the force was applied on the insole, changes in the resistance of the piezoresistive material were captured by the microcontroller. The magnitude of the measured force was then plotted against this change in resistance. Their relationship was then
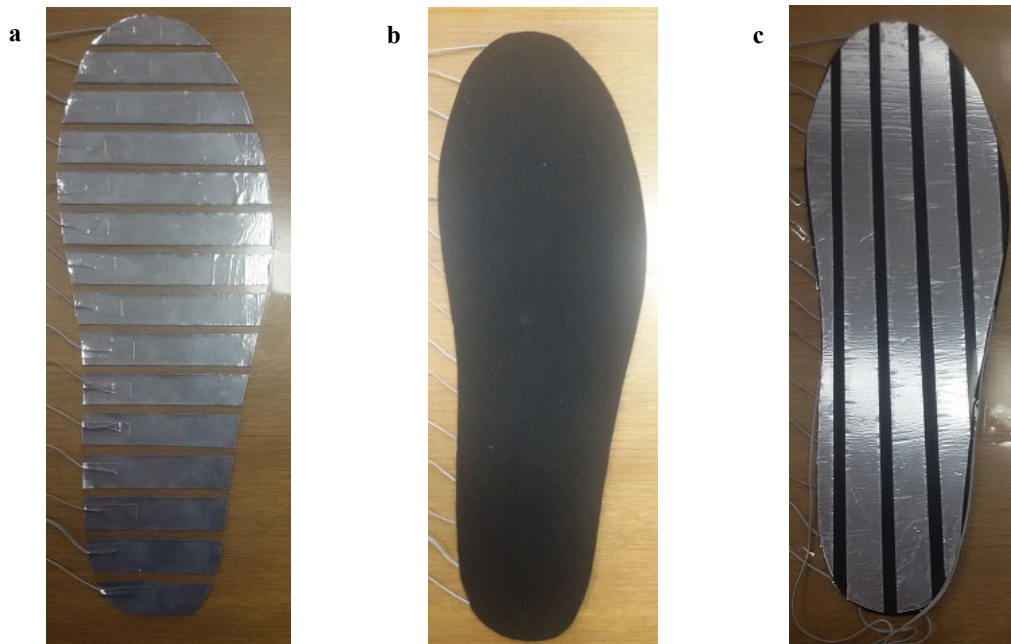
Fig. 1. (a) first layer of insole with horizontal electrodes; (b) second layer consisting of piezoresistive rubber; (c) third layer with vertical electrodes.

determined by fitting a Power function to the data and with that, we were able to correlate changes in pressure with the changes in resistance of the sensing material. With the calibration completed, a subject was asked to apply an evenly distributed force on the insole, which was placed on the force plate for 10 cycles. The experiment was repeated 3 times to ensure repeatability of results. The Power function was used to calculate the force applied to the piezoresistive material. This calculated force was then compared to the force measured by the Kistler force plate. A comparison was made with the resulting force values to determine the accuracy of the system.

2.3. Visualisation

For real-time visualization of the pressure on the insoles, the data from the microcontroller was captured by Processing Software (Processing 2.0, Massachusetts, USA). A code was written to draw the shape of the insoles. The areas of the insoles were then populated with cells of varying colors to signify the relative changes in pressure on different areas of the insole. The methods and calculations utilized are explained as follows.

Due to the way the multiplexing was programmed, the microcontroller was capable of reading only a single datum at a time. Consequently, the time at which the data of the first sensor node and the last sensor node were recorded, may have significant discrepancy. Thus a time interpolation had to be applied to all the nodes in order to obtain a more accurate depiction of the data obtained for pressure mapping.

In addition to time interpolation, a spatial interpolation will allow a more gradual visualization in contrast to the surrounding Fig. 2. shows pressure mapping of a 5x5 node sensing system with varying degrees of interpolation when a pressure was applied. In Fig. 2a. no interpolation was implemented. In Fig. 2b., there were one spatial interpolation point in x direction (x=1/2) and one in y direction (y=1/2). In Fig. 2c., there were two spatial interpolation points in x direction (x=1/3 and x=2/3) and in y direction (y=1/3 and y=2/3).
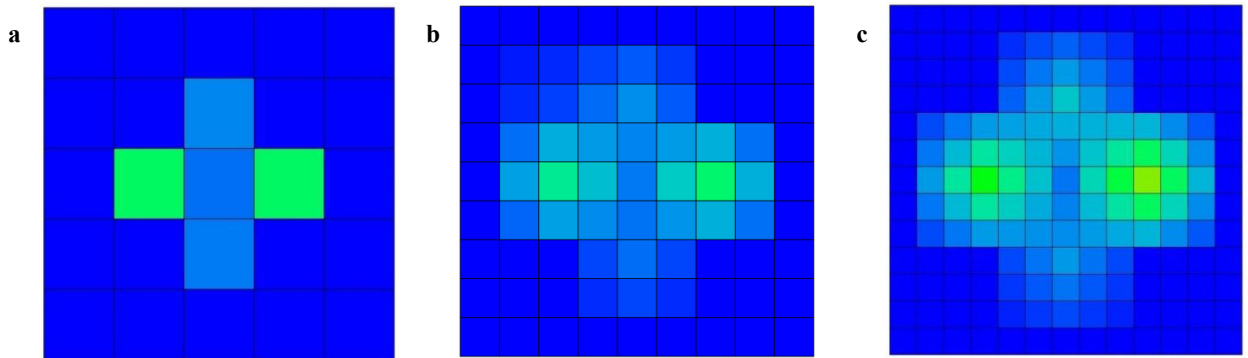
Fig. 2. (a) pressure map without interpolation; (b) pressure map with one interpolation in x and y directions; (c) pressure map with two interpolation in x and y directions.

With the values of the sensors in the corresponding visualization cells, there was a need to correlate these values with a respective colour system, representing the relative magnitude of the applied pressure. This variation in pressure is represented by colours from red with maximum pressure to blue with minimum pressure. The software Processing allows input of colours in RGB. For example, in (R,G,B) order, (255,0,0) gives red, (0,255,0) gives green and (0,0,255) gives blue. The colour in each cell is defined by a series of formulae, each representing a specific colour. By placing these values in their respective cells, we are able to achieve a whole spectrum of colours representing the amount of applied force at specific locations.

3. Results and Discussion

The calibration curve from the above experiment was plotted and the equation below shows the relationship between the applied force, F and the instantaneous resistance, R of the piezoresistive material.

$$F = 19066528 \times R^{-1.108}$$

(1)

The coefficient of determination obtained for the above data was $r^2 = 0.974$. The applied force ranged from 30 to 300 N. The size of each sensing node is 2.25×10^{-4} m^2, which amounted to a pressure of between 0.13 and 1.33 MPa applied on the node. This is sufficient for plantar pressure analysis in rigorous sports activities where peak pressure measured was approximately 0.6 MPa [9].

The entire insole was loaded on a Kistler force plate and the calculated force from the insole, utilizing equation (1), was compared to the measured force from the force plate. Fig. 3. was obtained and reproduced with permission from Tan et al. [10] and it showed the comparison between forces measured by the Kistler force plate and the calculated forces from the insoles. The forces do match up relatively well with an r^2 value of 0.981 and the residual standard deviation achieved was 70.35 N for forces larger than 700 N.

In addition to determining the pressure sensing range and the accuracy of the pressure measuring insoles, there was a need to represent these data in a visually attractive and functional manner. The calculated data was converted to corresponding colours as described above. Fig. 4. shows the result of the visualization exercise where there were one spatial interpolation point in x and y directions. The areas where colour changes were detected corresponded well to areas where pressure was applied. In addition, the changes in the colours were in the order that we had programmed from blue to cyan to green to yellow to red in increasing pressure application.
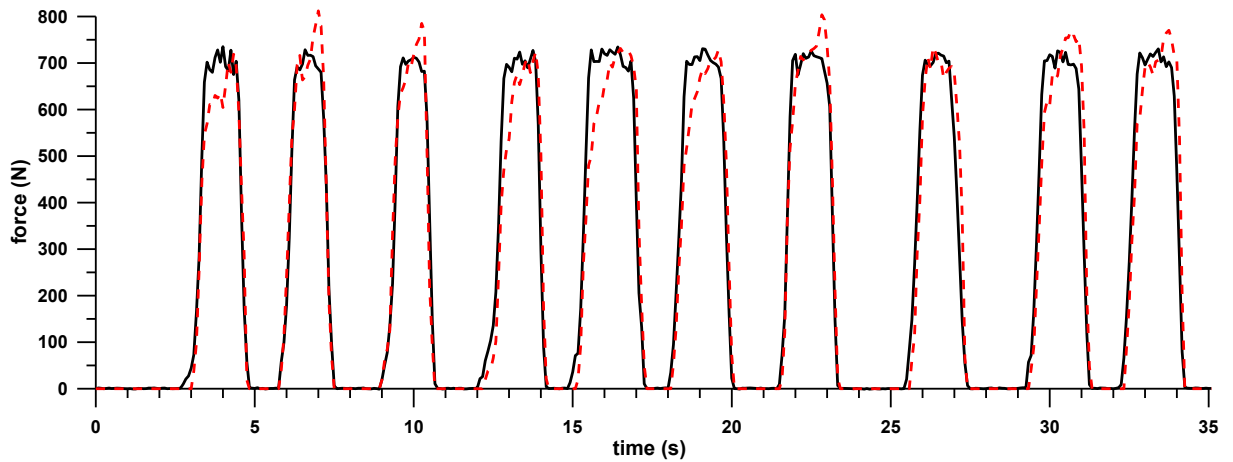
Fig. 3. Forces measured by the insoles (dashed line) as compared to the Kistler force plate (solid line). Image reproduced with permission from Tan et al. [10]

4. Conclusion

In this paper, the design and development of a plantar pressure measuring insole was presented. The key features of this insole are cost-effectiveness, good working pressure detection range, portable, wireless data transfer, real-time data analysis and relative accuracy. Some preliminary results were presented to show feasibility of calibration and accuracy of the insoles. Real-time visualization of pressure mapping of the foot sole offers the end-user and clinicians comprehensive and convenient way of understanding what the feet experience under different environmental conditions. Some of the potential applications of this device include foot ulcer prevention, balance analysis, rehabilitation and sports performance analysis.
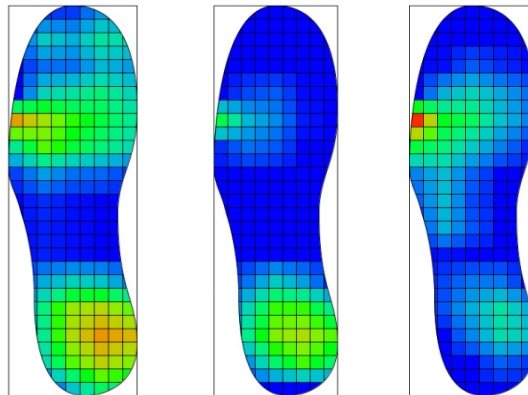

Fig. 4. changes in colours on the insoles depicting plantar pressure distributions.

Acknowledgements

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