Centre of pressure detection and analysis with a high-resolution and low-cost smart insole

Adin Ming Tan\textsuperscript{a*}, Franz Konstantin Fuss\textsuperscript{a}, Yehuda Weizman\textsuperscript{a} and Michael F. Azari\textsuperscript{b,c}

\textsuperscript{a}School of Aerospace, Mechanical and Manufacturing Engineering, RMIT University, Melbourne VIC 3083, Australia
\textsuperscript{b}School of Health Sciences, RMIT University, Melbourne VIC 3083, Australia
\textsuperscript{c}Health Innovations Research Institute, RMIT University, Melbourne VIC 3083, Australia

Abstract

This study aims to compare the accuracy of a pair of novel low-cost insoles with that of the proven standard Kistler force plate. The correlation of both devices had a $r^2$ value of 0.942 and 0.946 for COPx and COPy respectively during dynamic tests conducted to measure macroscopic changes of the COP. Fractal dimension analysis was conducted to measure minute changes during quiet standing on solid surface and on foam, with both insoles and the force plate showing the same trend where the fractal values of standing on foam were significantly higher than that of standing on a solid surface. Further validation was done to compare the results with the mean velocities of the measured data that showed identical significant trends as the fractal dimension analysis.

Keywords: Smart Insole; gait analysis; centre of pressure measurement; fractal dimension analysis, balance; stability

1. Introduction

Center of pressure (COP) is the term given to the origin of a force vector, which represents the sum of all forces acting between a force applicator and its supporting surface. The COP corresponds to the single intersection point of a family of lines about which the moments of the distributed forces on either side of a line are in equilibrium.

* Corresponding author: +61-4-70714044.
E-mail address: s3514835@student.rmit.edu.au
Analysis of the center of pressure is common in studies on posture and gait of mobile living organisms. Currently, posturographic analysis of individuals is typically conducted on a force plate within a laboratory environment. This gives an indication of the current balance of the individual but cannot predict the change in balance that may occur outside of the laboratory environment. Smart insoles measuring plantar pressure distribution have the ability to overcome this shortfall.

This study aimed to compare the functionality of COP measurement of a pair of novel low-cost insoles to the proven standard Kister force plate (Kistler Instruments, Winterthur, Switzerland). This was done for distinct changes in the COP in known directions and compared between both devices. Furthermore, it is known that standing on foam versus a solid surface results in distinctly different COP patterns when measured by a force plate during quiet standing. Small changes in the COP were analyzed using fractal dimension analysis and further validated with comparison with the mean velocity of the COP.

2. Methodology

2.1. Experiment Setup

The hardware development of wireless, pressure-measuring insoles was detailed by Tan et al [1]. In this study, we used the same construction except that no Bluetooth module was attached and thus a wired version of the insoles was utilized. In the study by Tan et al. [1], Rmat3a was the piezoresistive material of choice and this material was used in the present study as well. The insoles were secured on a Kistler force plate with the x- and y-axes of the insoles aligned with the axes of the force plate. The data were recorded by the insoles and the Kistler force plate simultaneously at sampling frequencies 12 Hz respectively. For the purpose of measuring macroscopic changes in COP, a subject was asked to stand on the insoles and requested to perform a rocking motion from side to side without taking his feet off the insoles. The results of the COP in the x-direction (COPx) calculated by the insoles were then compared to that of the values of the Kistler force plate. The experiment was then repeated with a back and forth rocking motion to compare the COP values in the y-direction (COPy). Using a predetermined direction of motion ensured that the COP values measured by the insoles could be directly compared to the values derived from the force plate.

Upon completion of the macroscopic tests, two sets of experiments were conducted to measure minute changes in the COP during quiet standing on different surfaces. For the first set, the subject was asked to stand on the insoles as seen in Figure 1a, and for the second set, he was asked to stand on dense foam with a thickness of 16mm placed on the insoles as seen in Figures 1b and c. It is known that standing on foam significantly challenges the balance of an individual during quiet standing [2]. The subject was asked to close his eyes and industrial ear-plugs (Honeywell, Howard Leight, USA) were put on, to minimize environmental sound information that may influence balance [3]. Each experiment was conducted for one minute and was repeated three times to ensure reproducibility of data. Data were recorded for one minute and the first and last ten seconds were eliminated, to ensure the most reliable recordings during quiet standing.

2.2. Data analysis

For the macroscopic tests, the COPx and COPy values from the insoles were plotted with respect to time on separate graphs. The same values from the force plate were then superimposed. The $r^2$ values were calculated to measure the degree of correlation between the two devices. With the correlation of the two devices during distinct movements established, we then compared the COP data during quiet standing. As the experiments only involved quiet standing, COPy versus COPx plots were expected, and did, amount to just a tight cloud of points. Separating the plots into COPx and COPy with respect to time did not manage to generate any meaningful information either. Hence, in agreement with Doyle et al [2], we examined the fractal dimension of COP movements to distinguish minute changes in COP between the instruments and experimental conditions. However, unlike Doyle et al, who had used Higuch’s algorithm to calculate the fractal values, we used the method recently developed by Fuss [4]. Fuss’ method is a more robust method of fractal dimension analysis which can distinctly separate different physical phenomena as explained in his paper.
The Hausdorff-Besicovitch dimension, $D_H$, measures the size of a space by taking into consideration the distance between two points, and this would be used to quantify the degree of chaos in a signal. In Fuss’ approach, an amplitude multiplier, $m$, is introduced to $D_H$ and the new fractal dimension is labeled $D_{Hm}$. The multiplier for the signal had to be determined, and this was done for both the insoles and the force plate. A sliding window of twenty data points was selected which represented approximately 1.67s of the data. The multiplier $m$ was chosen such that the average fractal values between two known extreme conditions are a maximum. This was determined by plotting $D_{Hm}$ of both conditions, with the logarithm of varying multiplier, $m$, from 0.001 to 1000, and subsequently to calculate the differential. The multiplier is unique for individual systems and thus two values had to be determined for the insole and the force plate. Upon derivation of the $m$ values, fractal dimension analysis was applied to all the experimental data and their average values were calculated. Student’s t-test was used across all paired sets of data with different experimental conditions to determine if the fractal dimensions were significantly different.

Mean velocity of COP is also considered a reliable measure of stability [5]. For the purpose of validation, the mean velocities of all tests were calculated. These were then compared with the results of the fractal dimension analysis.

3. Results and Discussion

3.1. Macroscopic measurements of COPx and COPy

The graph of COPx and COPy were plotted in Figure 2a and 2b for both the insole and Kistler force plate readings. The COP values matched relatively well although there was a greater variance in the values obtained from the insoles, in particular, the COPx values. The correlation between the two systems was calculated and $r^2$ values of 0.942 and 0.946 were obtained for COPx and COPy respectively. The residual standard deviations normalized to the insole data followed a power function with a negative exponent; the residual standard deviations amounted to 4% and 8.5%, respectively, at COP positions of 60-70 mm. These results demonstrated that the insoles system was capable of measuring COP changes with acceptable accuracy.
In order to proceed with Fuss’ method of fractal dimension analysis, the amplitude multiplier, $m$, had to be determined. Figure 3 shows an example of the method of deriving the multiplier value. $D_{lim}$ was calculated for both COP values on solid surface and on foam. The maximum difference occurred when $m = 0.116$ for the insole and $m = 0.126$ for the force plate. It was noticed that in Figure 3, $D_{lim}$ crossed over at a value of approximately $m = 10$. This is important as the selection process in obtaining a correct $m$-value is paramount to the explanation of corresponding physical events. If an $m$-value of 10 or more had been selected, it would have meant that standing on a solid surface would have generated a higher fractal value than standing on foam. Interestingly, Higuchi’s method of calculating fractals would be equivalent to Fuss’ method when the $m$-value is at infinity (or sufficiently large) as only the magnitude of the signal is taken into consideration. That would have meant that Higuchi’s algorithm would have had a different conclusion and this phenomenon was elaborated by Fuss [4] in his studies on wheelchair activity patterns. This is consistent when compared to the study by Doyle et al. [2] when using Higuchi’s method, in which a lower fractal value was derived when standing on foam compared to solid surface. However, the authors did not question whether the derivation of a lower fractal dimension when standing on foam makes practical sense.

Table 1 shows the fractal dimensions $D_{lim}$ calculated for the measurement derived from the insoles. The fractal dimensions $D_{lim}$ calculated for COPx and COPy are both higher when standing on foam than on solid surface at averages of 1.431 and 1.449 as compared to 1.373 and 1.351 respectively. This was consistent with the results obtained from the Kistler force plate as shown in Table 1. Fractal dimensions $D_{lim}$ of COPx and COPy when standing on foam were higher than on solid surface at averages of 1.101 and 1.162 as compared to 1.038 and 1.113 respectively. The differences were small but significant as Student’s t-test was conducted for all the data across the two sets of experiments. The p-values obtained ranged between $p = 0.0013$ and $p < 0.0001$. These values confirmed the significant differences between the averages of the fractal dimensions.
Fig. 3. Method of determining the multiplier for fractal analysis.

Table 1. Fractal dimension analysis comparison of data.

|              | Insole, average ± SD | Force plate, average ± SD |
|--------------|-----------------------|---------------------------|
| $D_{hm}$ of COPx |                       |                           |
| Standing on solid surface | 1.373±0.0142  | 1.038±0.0106  |
| Standing on foam     | 1.431±0.0435  | 1.101±0.0091  |
| $D_{hm}$ of COPy |                       |                           |
| Standing on solid surface | 1.351±0.0431  | 1.113±0.0240  |
| Standing on foam     | 1.449±0.0332  | 1.162±0.0170  |

3.3. Mean velocity comparison

To further validate the results obtained from the fractal dimension analysis above, we compared the results with absolute mean velocities of COPx and COPy for both devices. The results are shown in Table 2. As with the fractal dimension, the mean velocities of COPx and COPy are both significantly higher when standing on foam than standing on solid surface for both insoles and force plate measurements ($p < 0.0001$). Interestingly, the mean velocities of COPx and COPy are both significantly higher when standing on the insole than on the force plate ($p < 0.001$).

Table 2. Mean velocity comparison of data (in mm s⁻¹).

|              | Insole, average ± SD | Force plate, average ± SD |
|--------------|-----------------------|---------------------------|
| Mean velocity of COPx |                       |                           |
| Standing on solid surface | 11.603±0.3766  | 5.583±1.9425  |
| Standing on foam     | 13.759±1.5849  | 11.237±1.5616  |
| Mean velocity of COPy |                       |                           |
| Standing on solid surface | 10.969±1.3408  | 7.925±0.6367  |
| Standing on foam     | 14.668±1.2883  | 13.296±1.5736  |
4. Conclusions

The insoles have the ability to detect macroscopic changes to the COP and this showed a high degree of correlation with the force plate with $r^2$ values of 0.942 and 0.946 for COPx and COPy respectively. For the investigation of minute changes in the COP during quiet standing on different surfaces, Fuss' fractal dimension analysis proved capable of differentiating the two scenarios and the trend was similar in both insoles and force plate measurements. Student’s t-test showed that the average fractal values calculated had significant differences. This was further validated with the results compared to mean velocity of the COP and once again, the results obtained had the same trend as that of the fractal dimension analysis. The insoles therefore, have the capability to measure COP changes to an acceptable standard. However, more tests need to be conducted outside of the laboratory environment in order to investigate whether they are able to fulfill their purpose of real-time COP measurements.

References

[1] A.M. Tan, F.K. Fuss, Y. Weizman, Y. Woudstra, O. Troynikov, Design of low cost smart insole for real time measurement of plantar pressure, Procedia Technology (2015) in print.

[2] T.L. Doyle, R.U. Newton, A.F. Burnett, Reliability of traditional and fractal dimension measures of quiet stance center of pressure in young, healthy people, Arch. Phys. Med. Rehabil. 86 (2005) 2034-2040.

[3] V. Cornilleau-Peres, N. Shabana, J. Droulez, J.C.H. Goh, G.S.M. Lee, P.T.K. Chew, Measurement of the visual contribution to postural steadiness from the COP movement: methodology and reliability, Gait & Posture 22 (2005) 96-106.

[4] F. K. Fuss, A robust algorithm for optimisation and customisation of fractal dimensions of time series modified by nonlinearly scaling their time derivatives: Mathematical theory and practical applications, Comp. and Math. Meth. in Med. 2013 (2013) 1-19, Article ID 178476.

[5] A. Ruhe, R. Fejer, B. Walker, The test-retest reliability of centre of pressure measures in bidedal static task conditions – A systematic review of the literature, Gait & Posture 32 (2010) 436-445.