

A comparison of two techniques for center of pressure measurements

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Abstract

Introduction: Force platforms and pressure-measuring insoles are the most common tools used for measuring center of pressure. Earlier studies to assess these instruments suffered from limited sample sizes or an inadequate range of participant foot sizes. The purpose of this study was to propose new methods to extract and calculate comparably accurate center of pressure for the Kistler[®] force platform and Medilogic[®] insoles.

Methods: Center of pressure data were collected from 65 participants wearing pressure-measuring insoles (six different sizes). Participants walked over consecutive force platforms for three trials while wearing pressure-measuring insoles within socks. Onset force thresholds and center of pressure segment length thresholds were used to determine accurate center of pressure path length and width. A single step for each foot and trial was extracted from both instruments.

Results: A strong correlation was observed between instruments in center of pressure length ($4.12 \pm 6.72\%$ difference, $r = 0.74$). Center of pressure width varied and was weakly correlated ($-7.04 \pm 4.48\%$ difference, $r = 0.11$).

Conclusions: The results indicate that both instruments can measure center of pressure path length consistently and with comparable accuracy (differences $< 10\%$). There were differences between instruments in measuring center of pressure path width, which were attributed to the limited number of sensors across the width of the insoles.

Keywords

Force platforms, pressure-measuring insoles, processing methods, gait analysis, center of pressure

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Introduction

Center of pressure (COP) measurements have been used as a tool to help assess balance deficits and postural instability associated with impairments, including clubfoot¹ and stroke² or diseases including Parkinson's disease³ and diabetic neuropathy.⁴ They can be also used to assess the effects of treatments such as hip osteoarthritis surgery.⁵ Other applications of COP measurements include the assessment of postural and balance control in amputees.⁶ COP parameters are also used in prosthetic design.⁷ In all of these applications, the accuracy of measurement is important, as the results have been used to diagnose or assist in treatment of patients. Currently, COP is measured using several instruments including force platforms, pressure pads, and pressure insoles.⁸

Force platforms have commonly been used to measure COP, as they have high sampling frequencies and precision; however, this instrument limits participants

to a particular environment and can only record either a single step or a few steps at a time. Another tool used for recording COP is the instrumented treadmill, which allows for the collections of multiple, consecutive steps. However, the treadmill belt has been shown to change the foot position during gait, which means they may not accurately reproduce normal, over-ground walking.^{9,10} An alternative instrument to force platforms is pressure-measuring insoles. Although insoles typically have much lower sampling

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frequencies, these frequencies are sufficient for measuring the kinetics of walking.¹¹ Pressure-measuring insoles can be used in various environments to record multiple consecutive steps.

Kadaba et al.¹² used force platforms and other instruments to assess the repeatability of gait variables. A total of 40 healthy adult participants had three-dimensional kinematics, ground reaction forces, and electromyographic data collected, while walking across a six-meter walkway instrumented with two force platforms. The protocol was performed three times on three separate test days to observe the repeatability of the variables, including COP. It was found that the COP results were very repeatable within a single day and among testing days. Roerdink et al.¹³ compared the spatial and temporal parameters determined from COP profiles of 12 healthy participants, which were collected from an instrumented treadmill, to the parameters collected from kinematic data. A good correspondence for both the spatial and temporal parameters was found between the two instruments. The work by Jamshidi et al.¹⁴ compared the COP obtained from a force platform for participants who had a normal walking gait and a steppage gait, caused by various diseases or deformities. Comparisons showed that the medial-lateral path of the COP was different between the two groups, while the COP path length was similar. Recently, Svoboda et al.¹⁵ used force platforms to examine the COP of elderly persons with and without a history of falling. Participants were asked to walk across two force platforms, with each platform having individual foot contact, at self-selected and fast walking speeds. It was found that there were no differences between fallers and non-fallers, except in the medial-lateral COP displacement at the end of stance (pre-swing or toe-off phase).

More recently, pressure-measuring insoles have been used to measure COP. Surdilovic et al.¹⁶ examined the accuracy of COP measurements between pressure sensors placed outside of a shoe and those inside it. It was found that both methods were successful in determining COP. Wang et al.¹⁷ used pressure-measuring insoles, with various numbers of sensors, to examine the COP of 10 healthy adults. It was found that an increase in the number of sensing cells lead to a better estimation of COP. Zhang et al.¹⁸ also tested the ability of an insole to measure COP, stride length, stride time, and gait velocity for both walking and running. It was found that the insoles were more accurate for walking than for running, despite having a sufficient recording frequency (500 Hz) for both activities.

Researchers have compared COP results during walking from pressure-measuring insoles and force platforms. Chesnin et al.¹⁹ compared the COP measurements of

insoles inside a pair of socks to a force platform as 35 participants walked across the force platform. To determine where the right foot of each participant contacted the force platform, the socks were dampened so that they left a footprint on the force platform. A total of two walking trials were collected for each participant. COP profiles from the two instruments showed a strong correlation ($r > 0.70$). However, larger errors in the medial-lateral direction were observed in some trials, which were attributed to the number of sensors in the medial-lateral direction. Chumanov et al.²⁰ evaluated five healthy adults who had insoles fitted into their shoes while walking or running at various speeds over a fixed force platform. The average root mean square (RMS) differences between the two instruments was found to be minimal when the insole COP trajectory was transformed into the same global position of the force platform. Cordero et al.²¹ used two force platforms and video recordings to validate in-shoe insole results. The RMS error in the medial-lateral direction was larger than the error in anterior-posterior direction, but both were relatively small. Tan et al.²² secured a pair of novel insoles designed by the researchers to the force platform. Then, 16 participants were asked to stand on the insoles and perform a rocking motion. The COP paths between the insoles and the force platform were found to be highly correlated. Similarly, Vimal et al.²³ also tested a novel insole against a force platform by securing it to the platform and having three participants stand on the insoles. The novel insoles were found to have a mean error of approximately 2%. Stoggl and Martiner²⁴ compared the COP data of two different commercial insoles to the measurements made by a force platform. The insoles were worn by 16 participants performing a variety of movements and COP measurements were made while they were balancing. It was found that while the qualitative shape was similar, the insoles-measured medial-lateral deviations were up to 75% smaller and the anterior-posterior was up to 39% smaller than the force platform.

Unlike the previous studies, Debbi et al.²⁵ used pressure-measuring insoles as the standard to which the force platform results were compared. This study consisted of 12 healthy male participants who wore the same shoe size, each with insoles fitted in their shoes. The study showed that force platforms produced comparable results to those measured from the insoles in the medial-lateral direction. However, the anterior-posterior direction produced a high RMS error. However, when matrix transformations were used to align the COP paths, it was found that the two instruments had very similar COP results. The results suggested that the COP from force platforms can be adjusted to match the COP as measured by insoles. In the work by Herbert-Copley et al.,²⁶ a single participant was asked to wear insoles within shoes and walk for a total of 15 trials over a force

platform. The resulting COP paths for the insoles and force platform had high correlations between walking trials in the anterior-posterior direction, with slightly lower correlations in the medial-lateral direction. Weizman et al.²⁷ tested two insole systems in comparison to a force platform. The researchers asked two participants to wear the insoles inside shoes while rocking on the force platform. The COP profiles were compared, and it was found that the insoles were more accurate in the anterior-posterior direction in comparison to the medial-lateral direction. However, the researchers determined that both the insoles and the force platform were effective at measuring COP.

The literature has shown that pressure-measuring insoles were able to accurately measure COP when compared to force platforms. Further, the reviewed research consisted of studies including only a small number of participants or groups, which were not diverse in relation to the size of insole analyzed. If multiple sizes of insoles were assessed in a study, then there was no discussion of the consistency of the measurements between or among the various sizes. This can be problematic as it has been shown that different insole sizes measure force and area differently and have different material characteristics.^{28–30}

The purpose of the current study was to evaluate new processing methods to extract relevant COP data from pressure-measuring insoles and force platforms. The researchers propose new methods to better extract relevant COP data and remove noise, which allows for the comparability and accuracy of both instruments to be established. By taking a comparative approach between the two instruments, the differences in the measurements can be found. This will allow the limitations of both instruments to be established and will enhance confidence in the accuracy of the COP measurements. In comparison to previous studies, this study had a larger number of participants consisting of a wide range of foot sizes.

Methods

Instruments

Medilogic[®] pressure-measuring insoles (Schönefeld, Germany, 60 Hz) were used in this research (Figure 1 (a)). Each pressure-measuring insole contains between 93 and 162 individual sensors, depending on the size. The sensors, 0.75 cm × 1.5 cm rectangles, are resistive and will record an 8-bit digital value in response to applied pressure. The sensors are positioned in a grid-like layout spanning the entire insole. When worn, the insoles are tethered to a data-acquisition box, fitted on a belt around the participant's waist. The data are then wirelessly transmitted to the manufacturer's program where it is



Figure 1. (a) The Medilogic pressure-measuring insole. (b) The Kistler 3 D force plate.³¹

stored. The data can then be exported to a CSV file for analysis.

Two force platforms, placed consecutively along the path of progression, were used to capture the COP of both feet (Figure 1(b)). Each Kistler[®] force platform (Winterthur, Switzerland, 1000 Hz) uses four piezoelectric load cells to determine the three components of ground reaction force as well as its location. The output of the four load cells were also used to calculate the COP location.

Data collection

A total of 65 healthy participants free from walking impairments (18 men, 47 women, 23.5 ± 5.1 years, 67.2 ± 19.3 kg, 1.64 ± 0.10 m) gave institutionally-approved written consent (Protocol #724468 of the Internal Review Board at the University of Nevada, Las Vegas) to participate. This choice was a sample of convenience. Gender, age, height, body mass, and insole size were obtained for all study volunteers. These data are presented in Table 1.

Participants were fitted with insoles that best matched their foot sizes. The insoles were in European Standard sizes. If a participant's foot was between insole sizes, the larger size was chosen to ensure full coverage of the entire plantar surface. To minimize error due to insole slippage, insoles were placed inside thin socks provided by the researchers, next to the skin, to simulate barefoot walking. Experiments were conducted with participants wearing socks to measure the natural gait pattern more accurately.²⁵ Participants were then asked to perform the following tasks:

1. Sit on a chair and lift their feet off the floor (3–5 cm) for 5 s.
2. Stand and remain stationary for 15 s.

Table 1. Participant demographic ranges (minimum–maximum) by insole size and gender.

Insole sizes (Eur)	Gender	No. of participants	Age (yrs)	Body mass (kg)	Height (m)
35–36	Male	0	–	–	–
	Female	9	20–28	40.5–68.0	1.47–1.68
37–38	Male	0	–	–	–
	Female	22	18–28	43.0–74.0	1.51–1.70
39–40	Male	1	22	73	1.58
	Female	10	19–28	51.0–110.0	1.58–1.75
41–42	Male	4	20–24	59.0–79.0	1.53–1.71
	Female	4	20–22	63.0–93.5	1.68–1.91
43–44	Male	8	22–56	66.0–132.0	1.61–1.85
	Female	1	23	58	1.70
45–46	Male	5	20–31	72.5–130.0	1.73–1.85
	Female	1	24	85	1.70

**Figure 2.** Participant walking over the force platforms while wearing the insoles in socks. Note that only one foot is placed on each platform, which allowed for a direct comparison between the insole on each foot (left and right) and the corresponding platform.

- Sit again and lift their feet off the floor (3–5 cm) for another five seconds.
- Stand and walk 5 m over two inline, consecutive force platforms at a self-selected walking speed. Participants were asked to place only one foot on each platform in order to have a direct comparison between the insole and force platform for both legs (Figure 2).

Tasks 1–3 were used to synchronize the trials and visually check the fit of the insoles between each trial. A successful trial was defined as the completion of all of the tasks (1–4) and having each foot in full contact with the corresponding force platform. A total of three successful trials were collected for each participant.

Insole data processing

Digital values of all sensors on an insole were summed at each time instant. The insole data were isolated, through a two-stage process, to match the steps that occurred on each force platform, as shown in Figure 2. First, the start and end points of each step were selected using an automated procedure (Figure 3), where the time instant

immediately preceding a steep rise of the digital values was used to identify the start of the step. Similarly, the time instant immediately following a steep drop of the digital values was used to identify the end of the step. A steep rise or drop was defined as a change of more than 600 summed digital values per second.

For each step, the digital value of each sensor was converted to pressure, using the manufacturer's conversion (64 N/cm² per 255 digital values). Pressure was then converted to force measured by the sensor, by multiplying the pressure by the sensor area (1.125 cm²). Forces of each sensor were summed at each time instant to represent the vertical component of the ground reaction force versus time (Figure 4). Following the procedures of earlier researchers,^{30,32} the onset and end of the step were then identified using a threshold value of 40 N (asterisk in Figure 4).

Additionally, it was found that there were single sensors that were isolated or had exceptionally low values, which can be attributed to the sensitivity of the sensors or the pressure from the sock. To eliminate these sensors, an adaptive threshold was used to determine the sensors that were active within the isolated step.³⁰ This threshold was defined as a percentage of the maximum summed digital value during the stance phase:

- Sizes 35–36, 37–38, 43–44, and 45–46: 0.2%
- Size 39–40 and 41–42: 0.1%

The active sensors were then used to calculate the COP location using the following equations

$$X_{Ins,t} = \frac{\sum_{i=1}^n (D_{t,i})(X_i)}{\sum_{i=1}^n D_{t,i}} \quad (1)$$

$$Y_{Ins,t} = \frac{\sum_{i=1}^n (D_{t,i})(Y_i)}{\sum_{i=1}^n D_{t,i}} \quad (2)$$

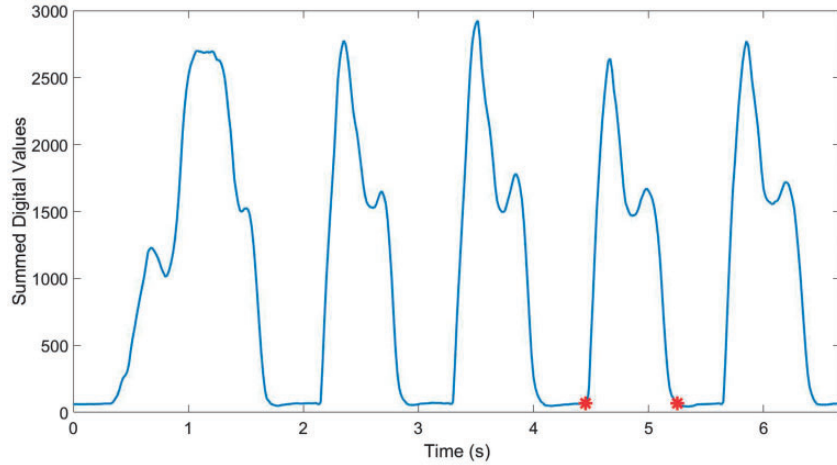


Figure 3. Summed digital values of walking protocol recorded by insoles. Please note that the first step is the first after the participant was seated. Two points on either side of a step occurring on the force platform were selected to isolate the step.

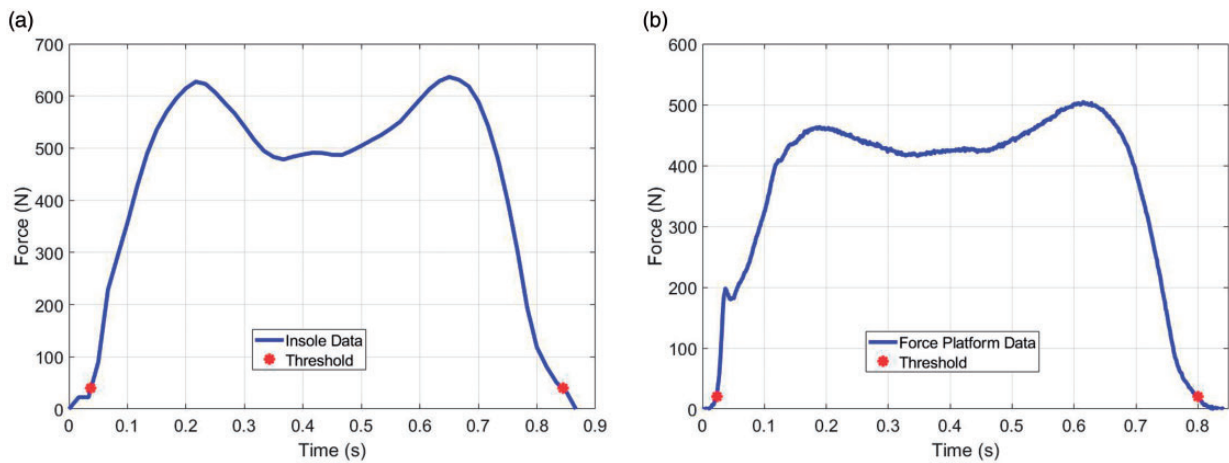


Figure 4. The solid line represents the vertical component of the ground reaction force with the onset-offset thresholds marked with asterisks. Time points of the threshold forces are the time points selected for the COP data. (a) The ground reaction forces measured by the insoles for one step. (b) Vertical component of the ground reaction forces as measured by the force platforms (FP) for one step. The methods used to isolate the step are described in the Force Platform Processing Section. COP: center of pressure.

where (X_{Ins_t}, Y_{Ins_t}) is the position of the insole COP at time instance t ; n is the number of sensors of the insole size used in the experiment; $D_{t,i}$ are the digital values of each sensor i at each time instance t ; and (X_i, Y_i) is the position of the center of sensor i , with respect to the lateral corner at the heel.

The sensors of the insole were measured from the left and right lateral corners for each respective insole (Figure 5).

Figure 6(a) shows a typical pressure-measuring insole raw COP time-history. It was observed that the first and last segment lengths of the stance were unrealistically long. This could be due to the fact that the stance thresholds were based on the ground reaction force and not on the COP measurements. Therefore, the researchers decided to examine segment lengths

during the first or last quarters of the stance. Segments that were equal to or longer than 7 mm were identified and eliminated (Figure 6(a), dotted orange). This criterion was determined through trial and error and was found to be sufficient for all insole sizes. The resulting COP path was then moved, so that it started at (0,0) (Figure 5(b)) for the purpose of comparison with the corresponding force platform COP path.

Force platform data processing

The force platform's proprietary software (BioWare® Type 2812 A, Version 4.0.1.2, Kistler) generates ground reaction force and COP data.³¹ The methods to extract the force platform COP data are similar to the methods

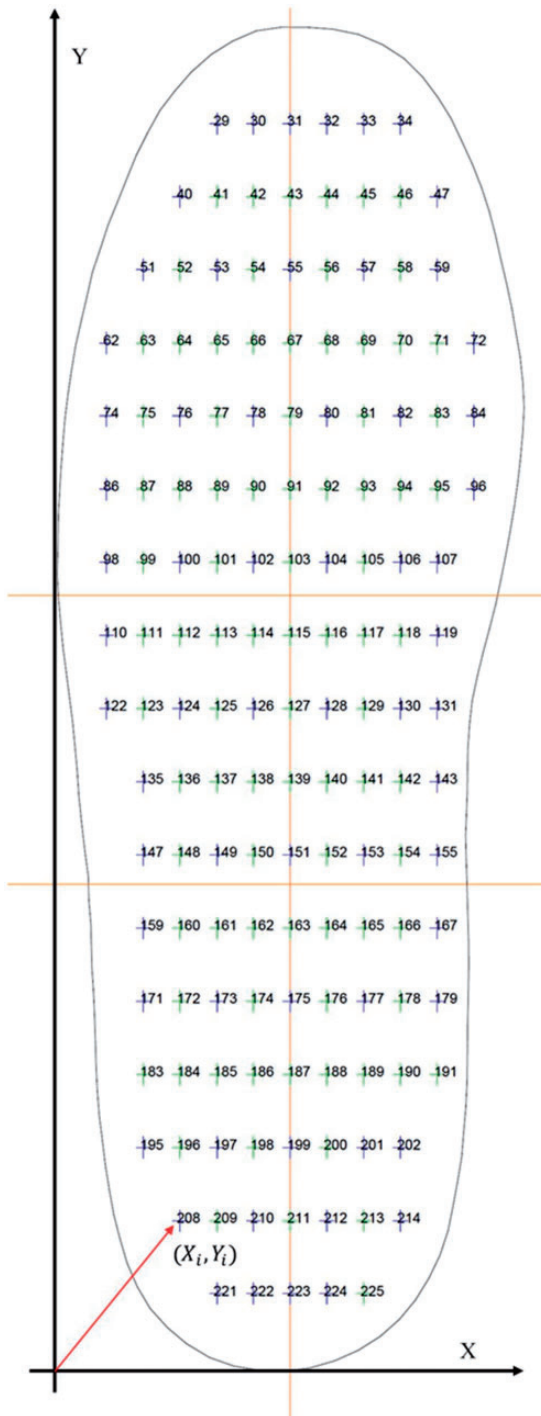


Figure 5. The axes and sensor maps (provided by the manufacturer) used to determine the location of the sensors in the left insole (Size 43–44). The red arrow and coordinates show the measurement to the center of each sensor i .

for the pressure-measuring insoles, but different values are used to achieve comparable results. The researchers used the following approach to extract the relevant COP data. First, a threshold value of 20 N, based on previous literature,³³ was used to identify the onset and

end of the stance (Figure 4(b)). The COP data based on the start and end of the stance were extracted from the BioWare data.

Similar to the insole COP path data, the force platform was visually determined to be oversensitive, producing noisy data when the foot was lifted, which made it difficult to distinguish the actual force platform COP path (Figure 7(a)). Segment path lengths during the first or last quarters of stance that were equal or longer than 10 mm were identified and excluded from the COP path (Figure 7(a)). The resulting COP path was then moved to a common origin (0,0) (Figure 7(b)). Next, the path was rotated to be in the same orientation as the insole data (Figure 7(c)). The angle of rotation was determined from the first and last points of the force platform data. The force platform COP path was then down-sampled to 60 Hz to match the frequency of the pressure-measuring insole (Figure 7(d)).

Data analysis

The length and width of the COP paths of each instrument were calculated for all trials, as shown in Figure 8. To compare the two instruments, the differences in COP path length and width were normalized using these equations

$$\Delta L = \left(\frac{L_{Ins} - L_{FP}}{L} \right) 100 \quad (3)$$

$$\Delta W = \left(\frac{W_{Ins} - W_{FP}}{W} \right) 100 \quad (4)$$

where L_{Ins} and L_{FP} are the length of the insole and force platform COP path, respectively; W_{Ins} and W_{FP} are the width of the insole and force platform COP path, respectively; L and W are the length and width of the insoles, respectively (Table 2); and the percent differences are ΔL and ΔW , which describe the differences in COP path length and width, respectively.

The data from both limbs and all three trials were averaged for each participant. Paired t -tests ($p \leq 0.05$) were conducted between the insole and force platform data path lengths and widths. Pearson product-moment correlations were also computed between the path width and length between the two instruments. Additionally, correlations were calculated between the path width and length for each instrument, and the insole size and mass of each participant. Further, the difference between the variables, ΔL and ΔW , were correlated to the body mass, height, and insole size worn by each participant. Bland-Altman plots were created to examine the agreement between the two

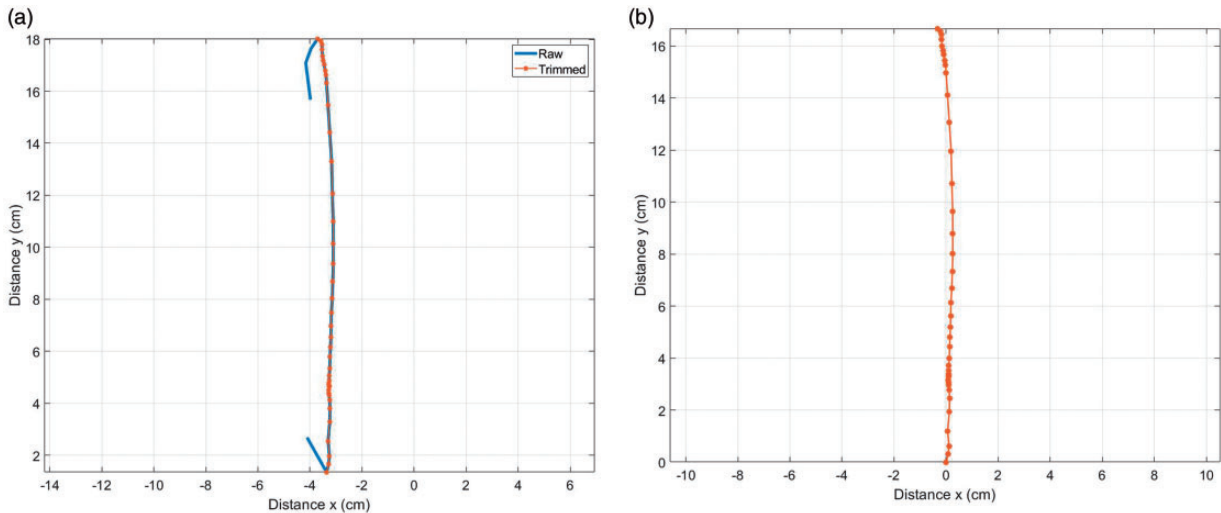


Figure 6. Processing of pressure-measuring insole COP: (a) trimming segments greater than 7 mm in the first and last quarter of the path; (b) moving the start of trimmed COP path to the origin (0, 0) for comparison with the corresponding force platform. COP: center of pressure.

instruments. All statistical analyses were conducted using Microsoft Excel 2016.

Results

Table 3 presents the average and standard deviation values for the COP path length and width by instrument and insole size. The table also presents the percentage difference in COP path length and width.

The results in Table 3 show that the COP path lengths of the pressure-measuring insoles were comparable to the corresponding force platform results. However, the COP path widths of the insoles consistently produced shorter COP path widths than the force platform COP paths. The magnitude of the difference of the normalized COP width difference measure, ΔW , was approximately double the normalized COP length measure, ΔL . However, both measures exhibited less than a 10% difference.

The paired t -test results between the COP path length and width between the instruments showed significant differences ($p < 0.05$): $t_{(64)} = -4.95$, $p = 5.65 \times 10^{-5}$ for COP path length; and $t_{(64)} = 12.81$, $p = 2.53 \times 10^{-19}$ for COP path width. The correlation of the COP path lengths between the two instruments showed the instruments to be highly correlated ($r = 0.74$). Further, the Bland-Altman plot shows that most of the path length data have excellent agreement between the FP and insole (Figure 9). In contrast, the correlation of the COP path widths between the instruments was weak ($r = 0.11$). The Bland-Altman plot reinforces this observation by showing that the differences were grouped, for a good agreement, but shifted where the force platform consistently measured a larger path width (Figure 10).

Correlations were also calculated between ΔL and ΔW , and the participants' insole sizes, body masses, and heights. Correlations of participants' foot size and the two variables showed weak correlations (ΔL : $r = -0.158$ and ΔW : $r = 0.379$). The results showed there was little to no correlation between ΔL and ΔW and body masses of the participants (ΔL : $r = -0.288$ and ΔW : $r = 0.296$). Finally, there was also little to no correlation between the variables and the heights of the participants (ΔL : $r = -0.210$ and ΔW : $r = 0.261$).

Discussion

The goal of this study was to establish new methods to better extract relevant COP data from pressure-measuring insoles and force platforms, which would allow for the reliability of both instruments to be effectively established. Simultaneously, measuring COP with both force platforms and pressure-measuring insoles allows the results to be compared, and the accuracy of the instruments to be assessed. Unlike other studies, where one measurement system is considered the "gold-standard", the accuracy of both instruments was assessed equally. The similarities between the two instruments were examined, and the accuracy was based on how the two COP trajectories compared to one another. Both the COP path length in the anterior-posterior direction and the COP path width in the medial-lateral direction were measured during walking. Similar to previous studies, which showed that pressure-measuring insoles can be valid tools to measure COP,^{20,25,27} this study verified the accuracy of using pressure-measuring insoles in comparison to a force platform, as all differences in COP length and

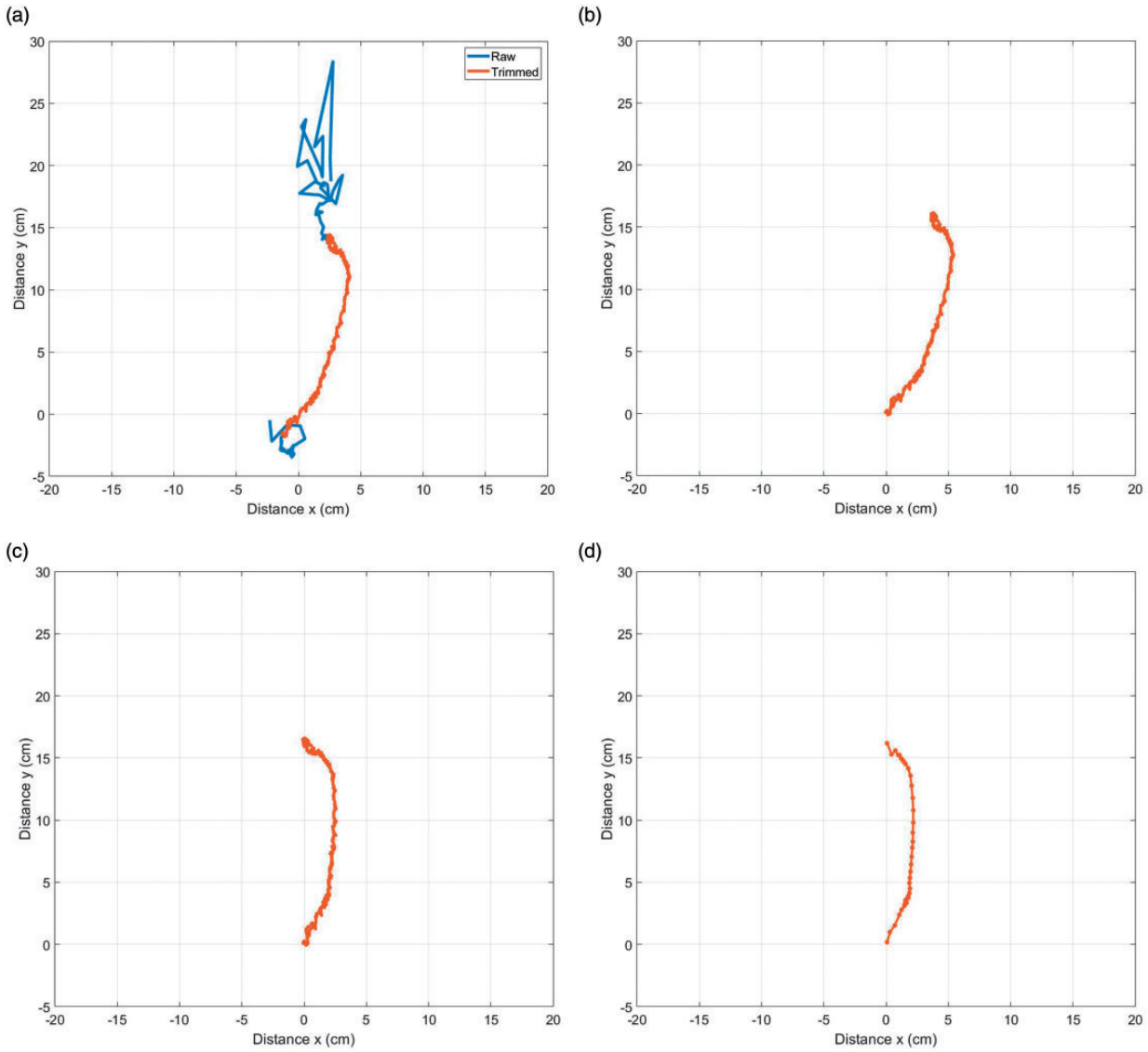


Figure 7. Processing of the force platform COP data: (a) trimming of segments greater than 10 mm in first and last quarters of path; (b) moving start of trimmed COP path to the origin (0, 0); (c) path rotated to align it with corresponding insole path; (d) COP curve downsampled to 60 Hz to match corresponding insole path. COP: center of pressure.

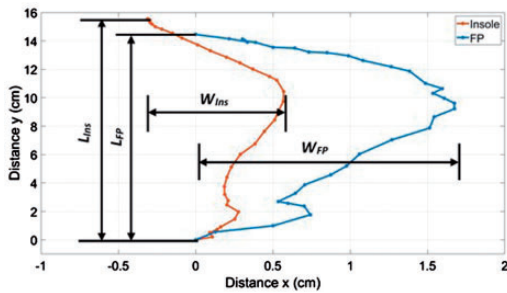


Figure 8. An exemplar COP path with length (L) and width (W) shown for pressure-measuring insoles and force platform. Please note that the axes are not square so that the COP path width could be accentuated. COP: center of pressure.

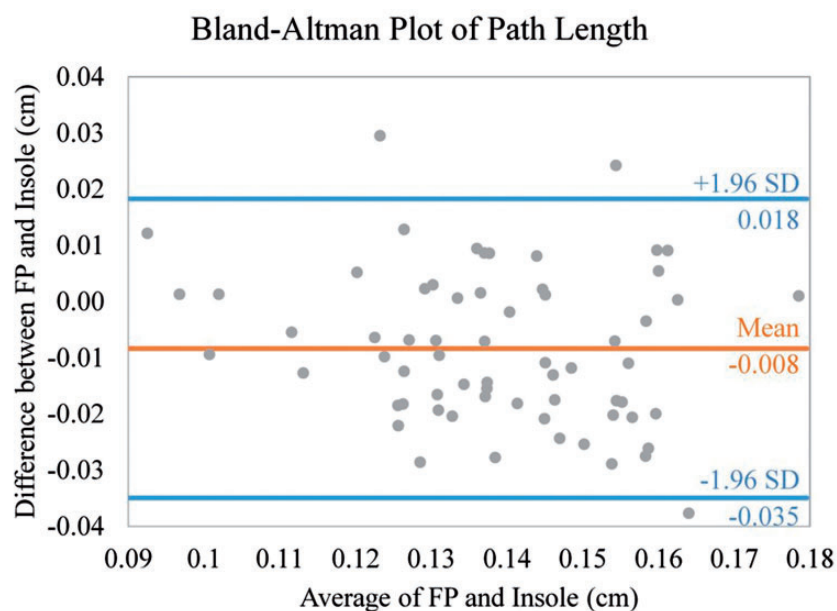
Table 2. Pressure-measuring insole length and width for various sizes used in experiment.

Insole size	Length (cm)	Width (cm)
35–36	22.13	7.12
37–38	23.90	7.77
39–40	25.00	8.32
41–42	26.17	8.55
43–44	27.43	9.38
45–46	28.33	9.73

Table 3. The average and standard deviation values for the COP path length and width, and normalized differences in COP path length and width for all participants (N = 65).

Insole Size	COP length (cm)		COP width (cm)		ΔL (%)	ΔW (%)
	FP	Ins	FP	Ins		
35–36	12.76 (1.35)	13.73 (1.71)	1.26 (0.20)	0.58 (0.21)	4.37 (3.49)	–9.64 (3.92)
37–38	13.05 (1.97)	13.77 (1.85)	1.33 (0.25)	0.72 (0.28)	5.20 (8.51)	–7.91 (3.75)
39–40	13.75 (1.28)	15.10 (1.65)	1.28 (0.25)	0.74 (0.26)	5.40 (5.45)	–6.51 (5.27)
41–42	13.85 (1.80)	14.78 (2.09)	1.41 (0.24)	0.62 (0.22)	3.55 (7.33)	–9.27 (2.95)
43–44	14.01 (1.74)	14.12 (2.35)	1.21 (0.23)	0.97 (0.31)	0.42 (4.52)	–2.55 (2.92)
45–46	14.02 (0.71)	15.08 (1.47)	1.31 (0.18)	0.85 (0.26)	3.73 (4.54)	–4.69 (3.45)
All	13.45 (1.72)	14.28 (1.97)	1.31 (0.24)	0.74 (0.29)	4.12 (6.72)	–7.04 (4.48)

COP: center of pressure; FP: force platform; Ins: insoles.

**Figure 9.** The Bland-Altman plot of the path lengths from the force platform and insoles. A comparison of these measurements shows an excellent agreement and small differences in the instruments.

width were less than 10%. Unlike previous studies that used small numbers of participants,^{20,25,27} the current study used a larger sample size of diverse participants in order to improve accuracy and achieve consistent results. While some studies had participants wear in-shoe insoles,^{19,25,27} this choice was deliberately avoided in order to avoid the possible confounding factor of footwear. To more accurately compare and assess the accuracy of both instruments, new methods specific to each instrument were also introduced in order to best extract and remove noise in the COP data.

Both instruments produced comparable results (less than 10% difference between instruments) and exhibited similar COP paths during the gait cycle. Further, the results indicated that the difference between the instruments was not related to the participant's mass, height, or insole size. Similar to Debbi et al.,²⁵ the COP

paths were re-oriented to closely match each other. Both instruments produced very similar COP path lengths; however, similar to Chumanov et al.,²⁰ the greatest differences between the insole and force platform trajectories occurred at heel strike and toe off. This observation was based on the figures of the COP path, such as the one shown in the exemplar curves in Figure 8. This was likely due to the naturally increased signal-to-noise ratio at these instances during the support phase, when less than body weight is being applied to the support surface. These differences were addressed using filtering and trimming methods. This resulted in both COP paths exhibiting similar patterns, as seen in the Bland-Altman plot where the mean was close to zero and most of the data was within 1.96 standard deviation (Figure 9). The similarity in COP path length measurements were found to be consistent

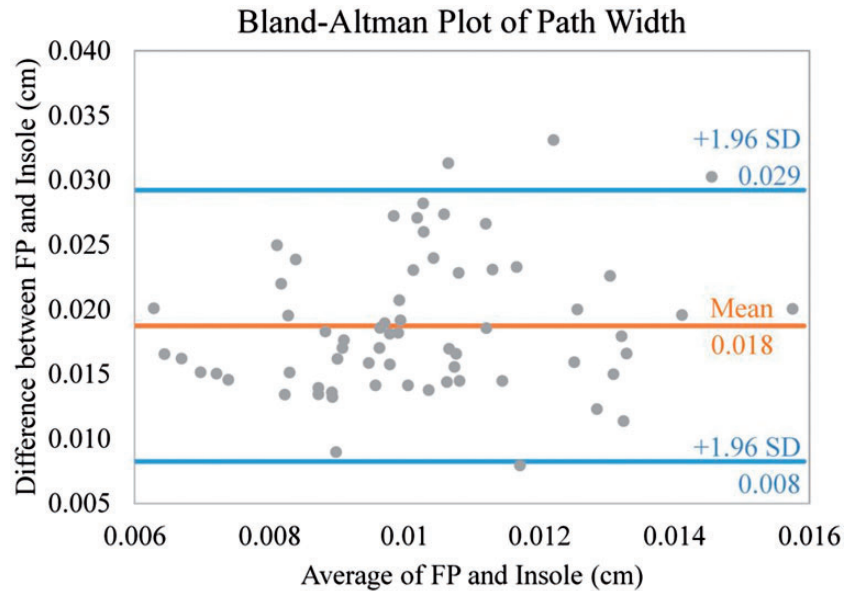


Figure 10. The Bland-Altman plot of the path widths from the force platform and insoles. A comparison of these measurements shows a good agreement but the force platform measuring larger widths (positive deviation from the mean).

among the six various insole sizes, with the three larger insoles (41–42, 43–44, 45–46) having smaller normalized COP path length differences, when compared to the force platform. The three smaller insoles (35–36, 37–38, 39–40) exhibited larger normalized COP path length differences when compared to the force platform. Therefore, it can be deduced that the larger insoles produce results more similar to the force platform, which could be due to the larger number of sensors in the insoles.

Similar to Weizman et al.,²⁷ the difference in COP path width was much larger compared to the difference in COP path length, but this is as expected, as the differences are amplified due to the short-measured distance and small number of sensors in the medial-lateral direction. It was observed that the insoles measured a significantly different COP path width in comparison to the force platform as seen in the Bland-Altman plot where the mean was positive, which indicated the force platform measured a greater path width (Figure 10). However, through size-specific analysis, it can be seen that the two largest insoles (43–44 and 45–46) measured a COP path width more comparable to the force platform. This can be attributed to the higher number of sensors in the medial-lateral direction in the larger insole sizes. Therefore, it can be surmised that a minimum number of sensors may be required to accurately measure COP path width. This supposition is supported by the work of Wang et al.,¹⁷ who found that an increase in the number of sensors led to a more accurate measurement of COP. Researchers should be aware of this limitation when using smaller

sized pressure measuring insoles, as they may lack the number of sensors required to produce accurate COP results.

Overall, the results suggest that both Medilogic[®] pressure-measuring insoles and Kistler[®] force platforms can be used to measure COP, based upon the purpose and accuracy required. Although the instruments do not produce identical results, the similarity and consistency between the two methods is promising and confirms they both provide an acceptable measure of COP. The larger-sized insoles may provide results that are more similar to a force platform due to the higher number of sensors. This study also provides assurance and confidence in using both insoles and force platforms in future research endeavors. Considering a clinical setting and dealing with patients, the insoles may be a more suitable choice due to portability, versatility, and the fact that they are not burdened with a distance constraint. Knowing the accuracy of the measurements from these instruments will allow professionals to confidently use them to aid in the diagnosis of physical impairments, diseases, and other medical applications.

Future work has multiple directions that can be assessed. First, the minimum number of sensors that are required for an accurate COP measurement must be determined. This would inform researchers on their purchases of commercial insoles or how to appropriately develop their own pressure-measuring insoles. Second, other commercial insole brands should be assessed, using the methods discussed above, to determine their accuracy in measuring COP. Third,

comparing the COP measurements of the insoles to the measurements from an instrumented treadmill would allow for the assessment of the accuracy in measuring multiple, consecutive steps. This would also allow the validation of the insoles at multiple speeds in order to determine if there are any limitations in the movements that the insoles can record. Finally, the insoles could be used to assess the COP during various movements in both a sports science and clinical environments.

Conclusions

New methods were introduced to better extract relevant COP data, which allows for the comparable accuracy of both instruments to be effectively established. The results showed that both instruments provided comparable and correlated results in measuring COP path length. However, the COP path width results were much different. Statistical comparisons between measures and instruments showed significant differences ($p < 0.01$) in measuring both COP path length and width. Regarding COP path width, a larger difference was expected due to the low number of insole sensors and short measured distance in the medial-lateral direction. The differences in the smaller-sized insoles can be attributed to the lower number of sensors in the insoles. Therefore, it can be assumed that a threshold for a minimum number of sensors may be required to accurately measure COP. Results suggest either instrument is sufficient to measure COP, based upon the purpose and accuracy required.

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