TECHNICAL REPORT

Validation of a portable force plate for in-field measurements of balance and postural sway

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Abstract

Objective: To determine how balance outcomes measured using a portable force platform (FP4, Biometrics Inc) compare to balance measurements from an in-floor mounted force plate (6090-15, Bertec Corp).

Methods: Twenty adult volunteers stood on the measurement platform for two trials, 10min apart, to measure bi-pedal medial-lateral and anterior-posterior balance with eyes opened and closed. We measured root mean square, range, and mean velocity of variability of center of pressure from each force plate. Pearson correlation was used to determine relationships between force plate outcomes. Intraclass correlation coefficients (ICC) were used to determine measurement reliability. Differences between eyes open and closed outcomes from each device were determined using t-tests.

Results: Correlations between portable and in-floor force plate outcomes ranged from 0.73 to 0.98. ICC values ranged from 0.07 to 0.54. Differences between eyes open and closed outcomes were observed in the anterior-posterior directions on both devices.

Keywords: Balance; Instrumentation; Validation

1. Introduction

Agricultural machinery operators are exposed to high levels of whole-body vibration (WBV) [1–3]. Low back pain, related to exposure from WBV through agricultural machinery use, is one of the most prevalent and debilitating musculoskeletal disorders in the Canadian rural workforce [4,5]. Additionally, extended periods of WBV exposes users to several potential hazards and is a contributing factor to fatal and non-fatal occupational injury [6], including equipment-related injuries such as falls and vehicle collisions [4]. Short-term effects of prolonged WBV exposure include cognitive impairment, stress, disturbances to balance and proprioception, and decrements in sensory and motor responses [7–10]. These short-term effects can lead to a high risk of near misses (slips, trips, and falls), especially during machine egress [11].

Studies evaluating the effect of WBV on balance and proprioception are typically undertaken in the laboratory environment [12–14] using an in-floor mounted force plate—the current 'gold standard' for measuring balance and postural sway. Although these in-lab studies provide certain advantages in the ability to control vibration exposure profile and duration, in-lab vibration exposure intensity and duration are not representative of typical in-field working conditions [1]. Field studies provide an environment with ecologically valid vibration intensities and duration; however, to reliably measure in-field postural sway, there is a need to validate portable force plate instrumentation.

A variety of portable force measuring devices are available, opening opportunities for in-field measurement of balance and postural sway [15–18]; however, there has been insufficient independent evaluation of the reliability of these tools to confirm the comparison of test results between in-floor 'gold standard' devices and portable devices.

The primary objective of this study was to validate and compare postural sway and balance measurements from a portable force platform (Biometrics FP4; Biometrics Inc, Newport, UK) against an in-floor 'gold standard' force plate (Bertec 6050-15; Bertec Corporation, Columbus, USA) to determine reliability of balance measurements from the portable force platform device. The secondary objective of this study was to evaluate if the portable and in-floor force plate systems are able to discern differences in balance and postural sway measurements between balanced and unbalanced positions.

2. Methods

2.1 Participants

Twenty healthy adult volunteers participated in this study (10 males, age 30.6±8.9 years; 10 females, age 31.8±6.5 years). Sample size was determined based on similar studies [15]. Participants had no current pain in back, neck, lower limbs, or upper limbs, and no history of work-limiting pain in the previous 6 months. Exclusion criteria included a history of neuromuscular and systemic inflammatory disorder that influences movement control, medical conditions or medications that may affect balance, and current or history of head injury. All participants gave informed written consent prior to engagement in the research and ethical approval was obtained by the University of Saskatchewan Ethical Review Board.

2.2 Instrumentation

The measurement device consisted of two force plate systems, one single in-floor mounted force plate (Bertec FP6090-15) and two portable force plates (Biometrics FP4). To ensure simultaneous balance measurements, portable force plates were placed directly on top of the in-floor force plate and positioned side-by-side with 105mm between the long edges of the FP4 plates, which is the equivalent distance between FP4 plates when they are placed in the accompanying portable base (Figure 1). A

24”x18”x0.093” sheet of clear polycarbonate (Lexan, Model# 1PC1824A) was positioned on top of the portable force plates to allow participants to view and confirm foot placement (Figure 1). Once all components were in place, both systems were zeroed.

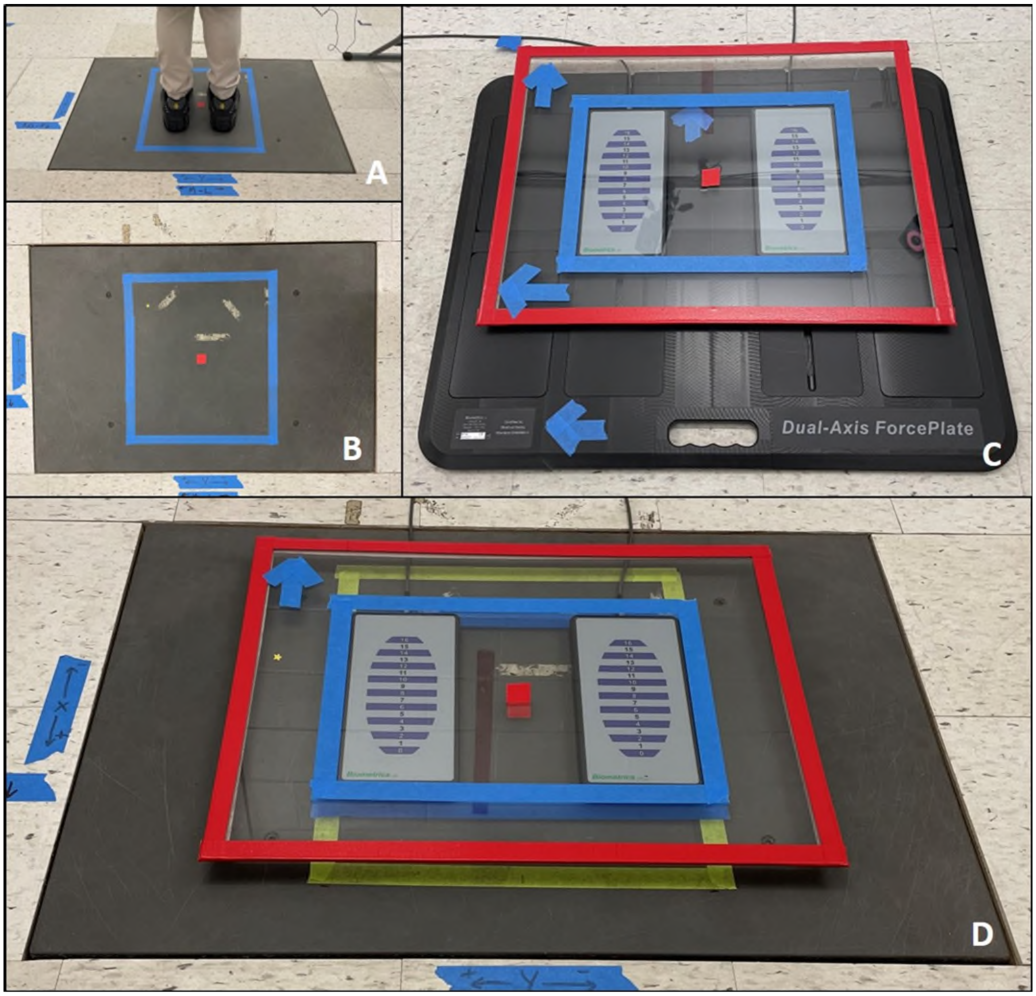

Figure 1. Force plate instrumentation set-up for simultaneous measurements. Instrumentation for this study consists of an in-floor mounted Bertec FP6090-15 force plate (A & B) and a portable force plate measurement device (C) consisting of two Biometrics FP4 force plates placed in the accompanying base with an 18” x 24” x 0.093” sheet of clear polycarbonate placed on top. For simultaneous measurements, the portable FP4 plates were removed from the base and placed in a similar position on the in-floor force plate with the clear polycarbonate place on top (D).

2.3 Procedures

Participants were asked to perform two identical standing trials on the force plate measurement system with a 10min sitting rest between trials. Before each balance trial, participants were instructed to carefully step onto the measurement device with arms at sides for a single step with the foot of the participant's choice on to one of the portable force platforms to full or almost full weight as a signal to synchronize force plate waveforms.

Balance trials consisted of two sections: first evaluating ML sway and then AP sway. To evaluate ML sway, participants stood with a foot on each individual portable force plate (visible through the clear polycarbonate sheet, Figure 2A). To place their feet on the polycarbonate sheet, participants were asked to carefully step on to the measurement device, with arms at sides for a single step on to one of the individual FP4 force plates visible through the polycarbonate sheet with the foot of their choice as described above. After single-foot full weight transfer, participants were then asked to step on to the FP4 plate visible through the polycarbonate sheet in the same manner (carefully and with arms at sides) with the other foot. To determine exaggerated signal values, participants were asked to lean or shift their weight to the left and right as much as comfortable. They were then asked to stand with arms at their sides, looking ahead at a visual target placed at eye level at a distance of 1m in front of them [19,20]. Participants were instructed to stand as still as possible for 30s with their eyes open, then 30s with eyes closed [15,21,22].

Participants were then asked to rotate by 90 degrees, to evaluate AP sway. Participants could either carefully rotate on top of the force plate measurement device or step off then step back on after rotating 90 degrees, depending on their comfort and mobility. Participants were then asked to carefully move forward or backward to ensure their center of mass (CoM) was as close to the marked center of the force plates as possible, verified by live datalogger output. To evaluate AP sway, participants stood with both feet bridging the portable force plates (Figure 2B). To determine exaggerated signal values, participants were asked to lean or shift their weight forward and rearward as much as comfortable. They were then asked to stand with arms at their sides, looking ahead at a point placed at 1m in front of them. Again, participants were instructed to stand as still as possible for 30s with eyes open, then 30s with eyes closed.

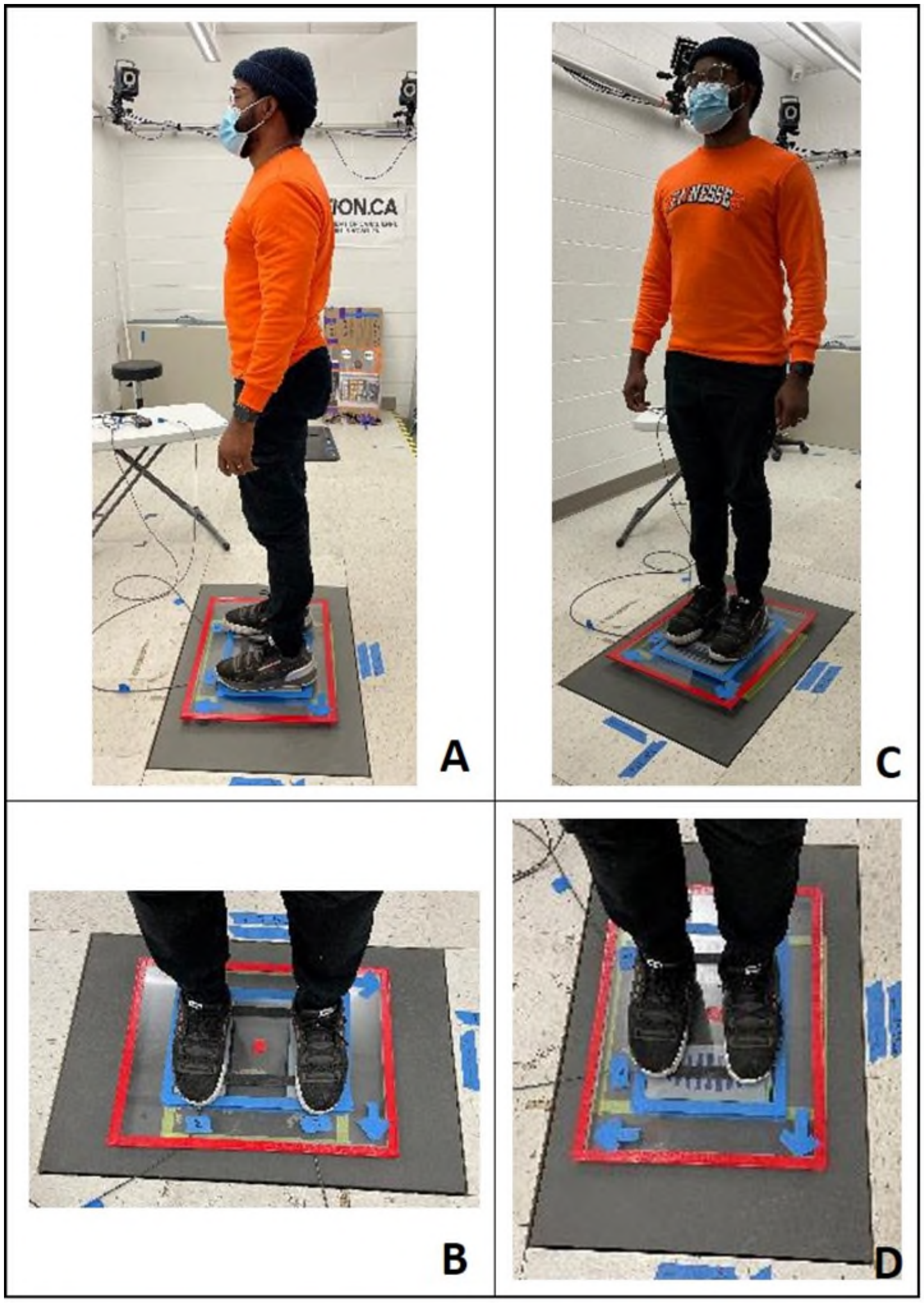

Figure 2. Participant stance on force plate instrumentation. To measure balance and postural sway in the medial-lateral (ML) direction, participant stand with arms at side with one foot on each of the Biometrics FP4 force plates, visible through the clear polycarbonate sheet (A & B). To measure balance and postural sway in the anterior-posterior (AP) direction, participant stands with arms at side and both feet bridging across both FP4 force plates visible through the clear polycarbonate (C &D).

2.4 Data Analysis and Conditioning

Center of pressure (CoP) data from the in-floor force plate was collected with Vicon software (Vicon Nexus v2.12.1, Oxford, UK). Percent-difference in force (%-Diff-F) in Newtons (N) between left and right, or anterior and posterior, data from the portable force plates was collected via MWX8 DataLOG (Biometrics Ltd, Newport, UK), and accompanying Biometrics Datalog software (v9.01, Biometrics Ltd). All data from both force plate devices were collected at a sampling rate of 1000Hz. We used default settings for all force plate devices and exported raw data from each for analysis using a custom Matlab script (Matlab Mathworks vR2021a) for all post-processing and output calculations.

All raw CoP and %-Diff-F data were passed through a 4^{th} order, 10Hz, low-pass Butterworth filter [12,23–25] and detrended prior to calculating any balance metrics. Cross-correlations between force plate waveforms were computed to isolate appropriate matching time-dependent sections for analysis. The middle 5 second interval from each 30s measurement event was used for analysis to ensure that participants had time to adopt a stable position after stepping up on to the force plate system and to account for any abrupt changes in balance between test conditions e.g., eyes open to eyes closed [18]. Preliminary results showed no differences between 10s and 5s intervals, so a 5s analysis interval was chosen. Computed balance measurements for each of ML and AP directions include: range of sway (Range), root mean square measure of variability (RMS), and mean velocity (MeanV) [25] of each 5s interval of both CoP and %-Diff-F waveforms.

2.5 Statistical Analysis

To determine measurement reliability, we report intraclass correlation coefficients (ICC) for all four balance conditions: medial-lateral eyes open, medial-lateral eyes closed, anterior-posterior eyes open, anterior-posterior eyes closed. We used Pearson correlation to determine relationships between portable force plate %-Diff-F and in-floor force plate CoP for pooled outcomes over each of 4 balance conditions, i.e., both trial 1 and trial 2 outcomes from each participant were included in the sample for determining correlation coefficients between portable and in-floor force plates for a sample size of n=40. Additionally, we used paired t-tests using the outcomes from the first trial for each participant (n=20) to determine differences in balance outcomes from each force plate between trials with eyes open (to simulate a balanced position) and eyes closed (to simulate an unbalanced position) [21]. Level of statistical significance for all tests was set at $p<0.05$ with a Bonferroni correction for multiple comparisons.

3. Results

Mean balance outcomes from all balance conditions across both measurement devices are presented in Table 1. ICC values for each of the portable and in-floor force plate devices across all balance conditions ranged from 0.07 to 0.52 (Table 2). Pearson correlation coefficients for relationships between in-floor and portable force plate balance outcomes ranged from 0.73 to 0.98 ($p<0.001$) (Figure 3). Differences in balance and postural sway outcomes of the first trial from each participant between eyes open (balanced) and eyes closed (unbalanced) in each of the ML and AP are presented in Figure 4. Differences between balanced and unbalanced positions were observed with both the in-floor and the portable force plates in both AP range and mean velocity. There were no differences between balanced and unbalanced positions on either the portable or in-floor force plate during any ML measurements. RMS outcomes from either force plate were not able to discern any differences between balanced and unbalanced positions.

Table 1. Mean and standard deviations of balance and postural sway outcomes from both in-floor and portable force plates for the first trial from each participant and pooled samples including both trials from each participant.

		In-Floor Force Plate			Portable Force Plate		
		RMS (mm)	Range (mm)	Mean Velocity (mm/s)	RMS (% difference)	Range (% difference)	Mean Velocity (% difference/s)
n=20 (first trial from each participant)	Medial-Lateral, Eyes Open	1.00 (0.47)	4.68 (2.94)	4.87 (1.89)	0.67 (0.32)	3.07 (1.90)	2.75 (1.30)
	Medial-Lateral, Eyes Closed	1.24 (0.69)	4.98 (2.61)	5.35 (2.13)	0.88 (0.53)	3.43 (1.86)	3.27 (1.78)
	Anterior-Posterior, Eyes Open	2.48 (1.07)	11.42 (8.65)	8.30 (2.87)	3.20 (1.39)	14.62 (10.545)	10.11 (3.52)
	Anterior-Posterior, Eyes Closed	3.68 (2.58)	17.23 (12.98)	12.18 (5.25)	4.83 (3.75)	22.24 (17.04)	15.10 (6.94)
n=40 (pooled outcomes, both trials from each participant)	Medial-Lateral, Eyes Open	1.08 (0.59)	4.62 (2.64)	4.71 (1.68)	0.76 (0.45)	3.21 (1.87)	2.92 (1.66)
	Medial-Lateral, Eyes Closed	1.17 (0.62)	4.83 (2.49)	5.05 (1.79)	0.834 (0.47)	3.32 (1.78)	2.97 (1.42)
	Anterior-Posterior, Eyes Open	2.37 (1.05)	10.36 (6.73)	8.01 (2.58)	3.03 (1.30)	13.13 (8.14)	9.57 (3.27)
	Anterior-Posterior, Eyes Closed	3.60 (2.10)	15.56 (9.91)	11.86 (4.78)	4.67 (3.01)	19.89 (12.99)	14.65 (6.49)

Table 2. ICC values of balance and postural sway outcomes from both the in-floor and portable force plates. *P*-values are noted in brackets with significant values in bold text.

	In-Floor Force Plate			Portable Force Plate		
	RMS	Range	Mean Velocity	RMS	Range	Mean Velocity
Medial-Lateral, Eyes Open	**0.46 (0.019)**	**0.38 (0.044)**	**0.54 (0.006)**	**0.41 (0.032)**	**0.52 (0.008)**	**0.54 (0.007)**
Medial-Lateral, Eyes Closed	0.36 (0.056)	0.33 (0.073)	**0.48 (0.014)**	**0.37 (0.050)**	0.34 (0.065)	**0.53 (0.007)**
Anterior-Posterior, Eyes Open	0.14 (0.269)	0.07 (0.386)	0.36 (0.063)	0.05 (0.419)	0.04 (0.432)	**0.39 (0.039)**
Anterior-Posterior, Eyes Closed	**0.45 (0.020)**	**0.42 (0.029)**	**0.46 (0.019)**	**0.38 (0.046)**	**0.45 (0.021)**	**0.39 (0.042)**

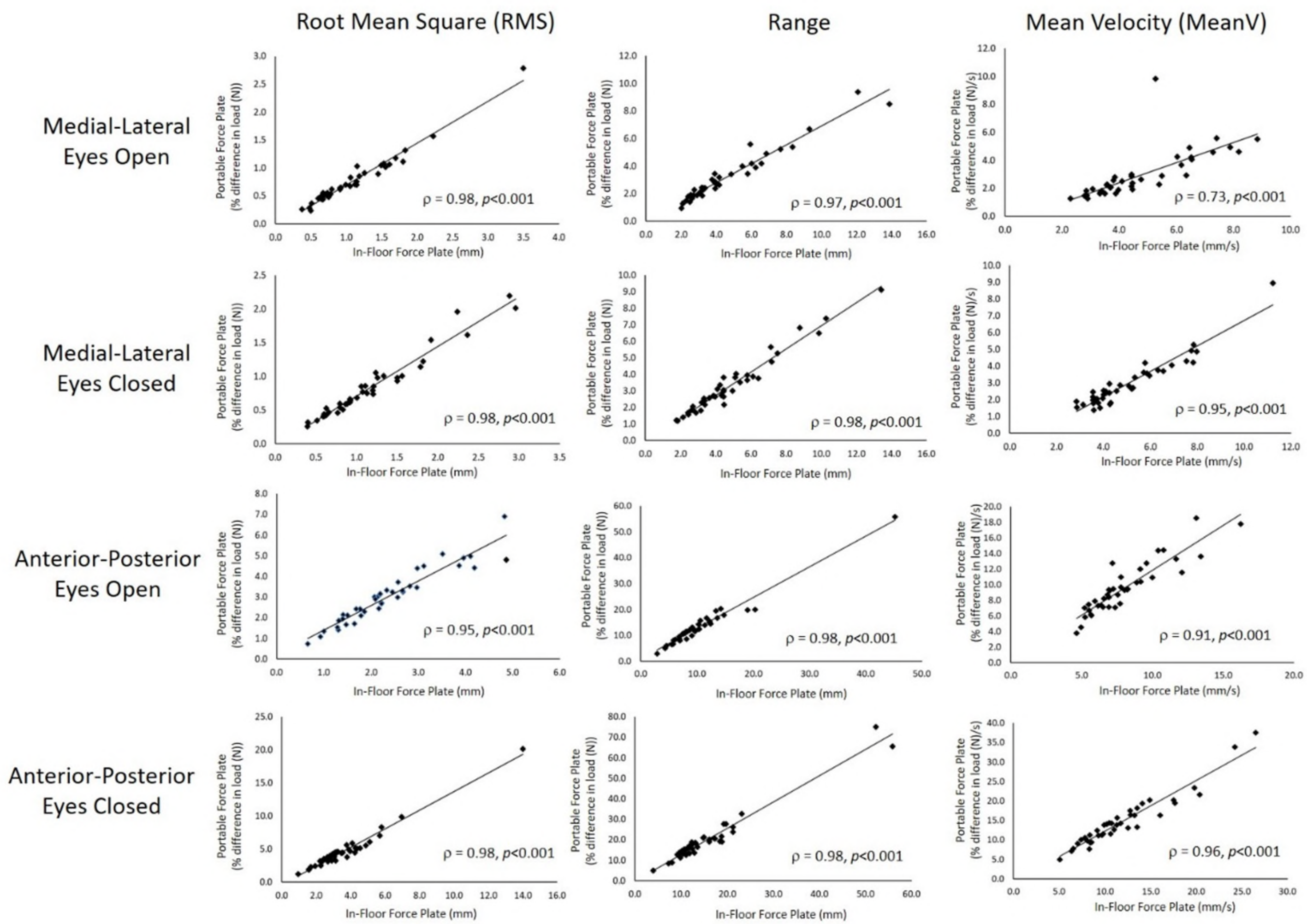

Figure 3. Scatter plots of relationships of root mean square (RMS), range, and mean velocity (MeanV) outcomes between in-floor Bertec force plate and portable Biometrics force plates of each balance position: medial-lateral with eyes open, medial-lateral with eyes closed, anterior-posterior with eyes open, and anterior-posterior with eyes closed. Pearson correlation coefficients and levels of significance for each relationship are displayed within the respective scatter plot.

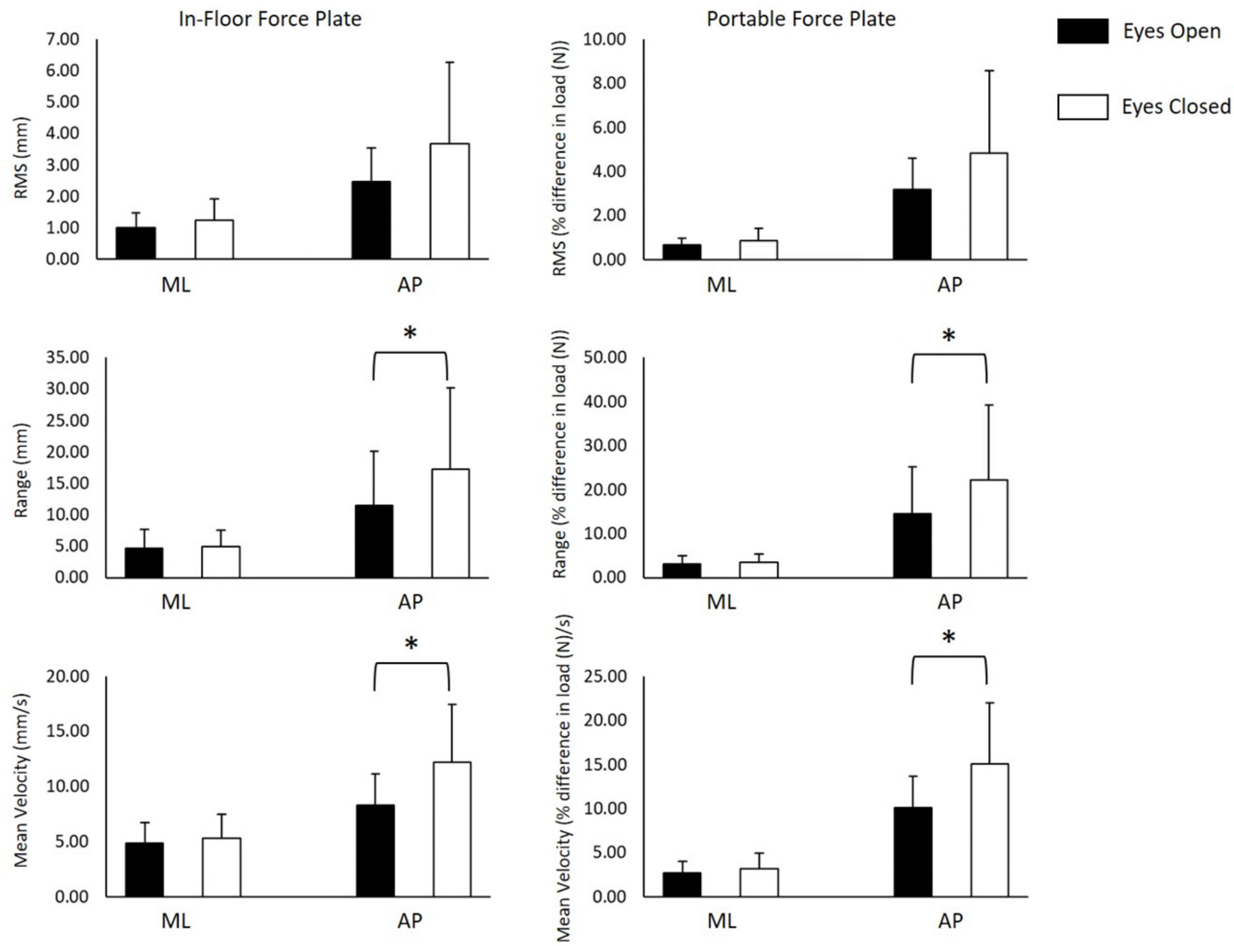

Figure 4. Effect of balance condition on center of pressure (CoP) from in-floor force plate and %-difference in load from portable force plate in both the medial-lateral (ML) and anterior-posterior (AP) axes. Significant differences are noted in brackets ($p < 0.05$).

4. Discussion

The objective of this study was to validate and compare postural sway and balance measurements from a portable force platform by comparing these measurements to simultaneously acquired balance and postural sway measurements from an in-floor mounted force plate. Our results indicate strong correlations between measurements from each device, supporting the use of either force plate device (portable or in-lab) for measuring balance or postural sway, within limited outcomes as presented in this work: RMS, range, and mean velocity in either the ML or AP direction.

Intraclass coefficients were generally low, but similar between devices and within similar range of reported ICC values evaluating the reliability of other portable force plate devices [15]. Of note, significant ICC values were mostly consistent across devices, where ICCs from all outcomes (RMS, range, and mean velocity) during ML eyes open and AP eyes closed measurements were similar and significant. Strong correlations between measurements from both the in-floor and portable force plate devices were observed in all directions (ML or AP), all balance conditions (eyes open or eyes closed), and over all outcomes (RMS, range, mean velocity). This suggests that data obtained from the portable force plate are reliable when compared to the 'gold standard' in-floor force plate. Additionally, both in-floor and portable force plates were able to detect differences in range and mean velocity between eyes open and eyes closed conditions during AP stance measurements. Although there were no differences in RMS outcomes between eyes open and eyes closed conditions during ML or AP stance measurements using either force plate, similar trends between devices were observed. Given that the portable force plate device is able to detect these small changes, we feel confident that it will be acceptable for its intended use for in-field and on-site balance measurements after occupational whole body vibration exposure, known to result in balance decrements [10,12,13].

A common strategy to induce an unbalanced standing condition is to have participants stand on a non-compliant surface, such as foam [18,21]. In this study, we opted instead to have participants close their eyes to create a moderately unbalanced standing position. As the standing surface of these measurement devices is slightly elevated, and participant foot placement upon each of the portable force platforms requires some intent and precision, adding a sufficient layer of a non-compliant surface may lead to an unsafe or unstable standing position. Instead, to safely create a modified unbalanced standing position, we had participants close their eyes [26–28].

In this participant sample, a single outlier was present in most trials (observed in Figure 3). Upon further investigation, this point was most often the first trial from the same participant. We reevaluated these output waveforms and recalculated all balance and postural sway outcomes to verify for errors in data collection or instrumentation but found no change in outputs. Upon further reinvestigation of notes recorded during this participant's session, this participant met all study eligibility criteria but did voluntarily disclose that they were within two years of recovering from invasive systemic cancer treatments and did have some recurring balance issues for which they were not treated nor receiving medication. Further details on the type of treatment were not disclosed nor requested or further investigated. To ensure that observed trends were still valid, we removed the outlier from our analysis and re-performed the statistical analysis. Correlation coefficients were unchanged. Although it is beyond the scope of this work, this result does postulate that there may opportunities to evaluate perturbations in balance and postural sway and related rehabilitation in patients undergoing or recovering from invasive systemic medical treatments.

4.1 Strengths

A primary strength of this study is the use of simultaneous measurements to validate force plate outcomes. The small floor footprint of the portable force plates, when removed from the accompanying base, provides an important opportunity to place the portable force plates directly upon the in-floor force plate. Additionally, by placing a clear polycarbonate sheet on top of the portable force plates, participants are able to adjust and move above the portable force plates to achieve a comfortable balanced position. Although the participant is slightly elevated when standing upon the combined force plate devices, even if the portable force plates were placed in the accompanying base, they would be standing at a similarly elevated position. These simultaneous measurement events are an important aspect of validating balance and postural sway measurements as demonstrated by moderate ICC values in this work and others [15,29] that there may be considerable variability between balance and postural sway measurements within participants even in measurements acquired within a short time from one another (e.g., 10 minutes).

To our knowledge, this is the first validation study with this particular model of portable force plate device, even with the addition of a clear polycarbonate sheet. This design is easy to use and easy to set-up, making it a cost-effective option for a portable device for our planned in-field studies. Many portable force plate and balance measurement devices are available, over a range of complexities and prices. This validation study and our presented results of high correlations between the portable device and the in-floor 'gold standard', as well as both devices being able to detect subtle differences in measurements between a balanced and unbalanced position, provides some credence to this cost-effective and easy to use option.

4.2 Limitations

This study does have certain limitations. First, using the proposed configuration and given outcome settings of the portable FP4 force plate devices of either a single mass (kg) or force (N) value from each individual portable force plate, it is only possible to evaluate one of either ML or AP sway at a time. As such, it is necessary to perform two independent measurements to measure both ML and AP sway from any single participant. Because these are two different measurement instances, it is not advisable to calculate balance or postural sway measurements that require simultaneous input from both motion axes, such as the 95%CI circle or ellipse, or directionally combined RMS and mean velocity outcomes [25]. Given that the intent for this portable device is to perform balance and postural sway measurements after occupational whole-body vibration exposure at the job site, this portable force plate device is able to measure single-axis outcomes including RMS, range and mean velocity, each shown to be affected by whole-body vibration exposure [12,14,24].

Second and related to the previously discussed limitations in postural sway outcomes, in this configuration the portable force plate device is limited to measuring balance while the participant is in a bi-pedal shoulder-width stance. The nature of a single output values from each portable force plate requires that the difference of outputs from two portable devices be calculated to determine distance-based balance measurements, such as RMS, range or mean velocity. It may be possible to add two more portable force plates, that would require the participant to center a single foot on a quadrant of four plates for uni-pedal measurements, but this is beyond the scope and available equipment for this specific study.

Third, the design additions of the portable measurement system may have certain small effects on output interpretation. As both the participant's feet and the clear polycarbonate sheet bridge the individual portable force plates to measure AP sway, there may be some warping or deformation of the polycarbonate sheet where the loaded edge of the force plates meet the underside of the polycarbonate sheet. We did inspect the polycarbonate sheet before and after every trial measurement for obvious deflections but noted none. When in double-shear, as is the case of this configuration, displacement of a polycarbonate sheet has been reported at a break load of 3.36kN or approximately 750lbs [30], which is well above any anticipated applied load. Given the high correlations between outcomes from the portable force plate and the in-floor force plate, any effects in deformation or load distribution that may be related to deformation of the polycarbonate sheet are negligible.

It is important to consider that the outcomes of each device are fundamentally different, the in-floor force plate providing outputs in units of distance (mm or mm/s) and the portable force plates providing outputs in units of %-difference of mass (kg) or force (N) between the two portable plates. As such, we advise that only one type of plate is used for all measurements within a chosen study. Comparisons of the actual individual values measures using each of the in-floor force plate and portable force plates differ and should not be combined within the same analysis.

5. Conclusion

In summary, we found that the portable force plates and accompanying clear polycarbonate sheet is reliable in measuring balance and postural sway when compared to the 'gold standard' in-floor force plate. The presented portable force plate system can be a valuable data collection tool in situations where participants are not able to visit a laboratory, e.g., worksite, field, patient residence.

6. Funding Source

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