



Short communication

Validating a low-cost, consumer force-measuring platform as an accessible alternative for measuring postural sway

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ABSTRACT

The Zibrio SmartScale is a low-cost, portable force platform designed to perform an objective assessment of postural stability. The purpose of the present study was to validate the center of pressure (COP) measurements in the Zibrio SmartScale. Simultaneous COP data was collected by a Zibrio SmartScale and a laboratory-grade force platform (LFP) under the dynamic motion of an inverted pendulum device intended to mimic the sway of a standing human. The inverted pendulum was placed on the Zibrio SmartScale which was placed on the LFP. The pendulum was then displaced to angles of 3° and 5° in both the anterior-posterior (AP) and medial-lateral (ML) directions. The findings of this study show low mean average error (MAE) among the measures taken simultaneously upon the LFP and Zibrio SmartScale with no appreciable difference in error in either AP or ML COP directions. Averaged over repeated trials, the MAE did not surpass 0.5 mm. This represented 0.4% of the total range (± 50 to 60 mm in 5° displacement trials) of simulated COP. The results of this study strongly indicate that the Zibrio SmartScale can perform adequately as a light-weight and low-cost alternative method of COP measurement in comparison to a traditional LFP.

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1. Introduction

Maintaining “good balance” is a critical component of daily life, and requires complex motor control utilizing multiple systems of the body (Lord and Sturnieks, 2005). In the laboratory, balance is most commonly estimated by observing an individual’s postural control during various activities using a force platform to quantify the two-dimensional projection of that individual’s center of gravity with respect to their base of support. This measure is referred to as center of pressure (COP) (Ihlen et al., 2013; Leach et al., 2014; Prieto et al., 1993).

Laboratory force platforms (LFPs) are often considered to be the “gold standard” for assessment of postural control (Tesio et al., 2013), but their high cost (typical LFP cost >\$10,000) and lack of portability (typical LFP mass > 30 kg) are barriers to widespread use. Recent studies have shown promising evidence that low-cost force measuring platforms can serve as viable alternatives for collecting COP data (Chang et al., 2014; Huang et al., 2013; Huurnink et al., 2013; Leach et al., 2014; O’Connor et al., 2016).

The Zibrio SmartScale is a new portable, low-cost force measuring platform designed to collect COP data during quiet standing. It is unique in that it was designed using low-cost off-the-shelf components with scalable manufacturability in mind, positioning it to be widely available for home or clinical use in the near future, at less than a tenth of the burden (cost and mass) of a traditional LFP. The purpose of this study was to validate the Zibrio SmartScale (Fig. 1) against a “gold standard” AMTI LFP. This validation procedure utilized a custom-built mechanical system to produce a consistent and predictable set of dynamic loads, mimicking the trajectory of an inverse pendulum (Winter, 1995). In this way, a set of simulated COP sway trajectories could be captured by the Zibrio SmartScale and LFP simultaneously and compared for coherence and reliability.

2. Methods

2.1. Construction of inverse pendulum

An inverse pendulum was constructed to simulate single degree of freedom postural sway (Fig. 2). The design mirrors that of Leach et al. (2014) and O’Connor et al. (2016) to increase confidence and

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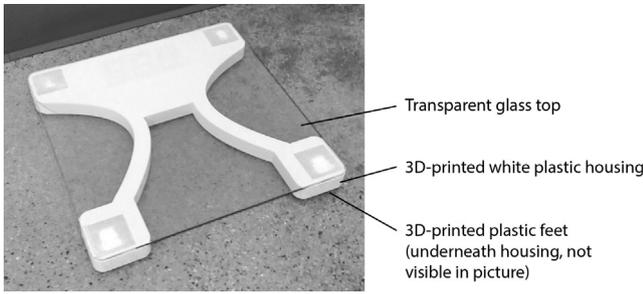


Fig. 1. Zibrio SmartScale device used for center of pressure measurement.

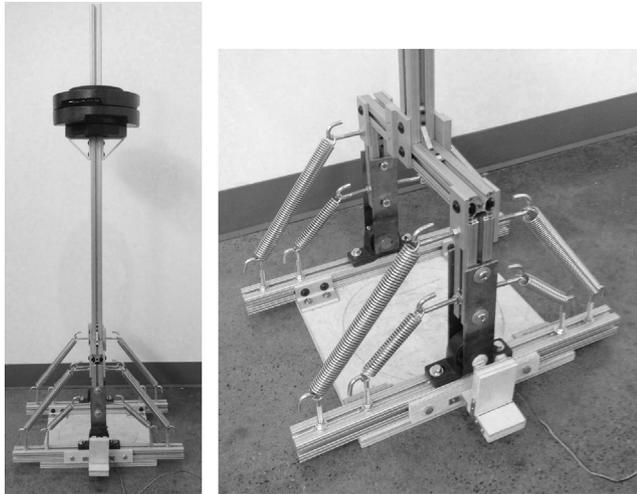


Fig. 2. Custom constructed inverse pendulum and center of pressure trajectory simulator.

evoke consistency among the validation approaches. The inverse pendulum featured two pillow-block bearings, which defined a single axis of rotation, mounted to an aluminum frame. A perpendicular segment was attached to this axis of rotation and bounded to an upright position using four commercially-sourced “short” and four “long” extension springs. Spring constants (k) were estimated for each spring by estimating the slope of the load vs. displacement relationship, yielding approximately $k = 6300 \text{ N/m}$ for the “short” spring and $k = 1500 \text{ N/m}$ for the “long” spring (Fig. 3). The inverse pendulum structure had a mass of 12.7 kg, and was loaded with 29.5 kg at a height of 1.113 m to represent the load at the center of gravity of an average height individual (Hof et al., 2005; Leach et al., 2014). During testing, two 11.34 kg plate-weights were used to stabilize the inverse pendulum at the base. The inverse pendulum was mounted atop a semi-ductile pine

plywood base, approximately $355 \times 355 \times 12.5 \text{ mm}$ ($14'' \times 14'' \times 1/2''$) to ensure constant contact between the inverse pendulum and the Zibrio SmartScale during testing. The total mass of the system was approximately 65 kg.

To simulate COP sway, the pendulum was displaced to produce a set angle of rotation (measured by a potentiometer placed at the rotational axis) and released. The pendulum oscillated in a damped condition until returning to rest, as a function of the extension springs, air, and bearing resistance. The estimated natural frequency of the system was approximately 0.4 Hz, modeled as a physical pendulum with a known load operating under small-angle ($3\text{--}5^\circ$) assumptions (“Physical Pendulum,” n.d.).

2.2. Data collection

An AMTI force plate (OR-6-7-1000, Advanced Mechanical Technology Inc., MA, USA) was used in conjunction with a signal conditioner and amplifier (Gen5, AMTI, MA, USA) to collect tri-axial force and moment measures. The coordinate system of the LFP was defined, and center of pressure measurements were calculated, per manufacturer specifications. Custom LabView 2011 (National Instruments, TX, USA) software was used to collect force plate data prior to processing in Matlab 2014a (Mathworks, MA, USA). The LabView script collected a total of 60 s of data at 100 Hz from the LFP. The height of the LFP was approximately 8.9 cm, and was used as a reference value during data analyses.

The Zibrio SmartScale force plate features four single axis load cells to estimate center of pressure. The height of the Zibrio SmartScale was approximately 4.1 cm, and the weight was approximately 2.9 kg. The following equation was applied to estimate COP, with a known X and Y distance (between load cells located at each of the four corners) of 321 mm:

$$COP_x = -\frac{X}{2} \left(\frac{(Frt + Frh) - (Flt + Flh)}{(Frt + Frh + Flt + Flh)} \right)$$

$$COP_y = \frac{Y}{2} \left(\frac{(Frt + Flt) - (Frh + Flh)}{(Frt + Frh + Flt + Flh)} \right)$$

where Frt, Frh, Flt and Flh are the loads (N) at each of the sensors nearest the right toe (Frt), right heel (Frh), left toe (Flt), and left heel (Flh), respectively. The Zibrio SmartScale collects a total of 60 s of data at 60 Hz during typical operation.

2.3. Experimental procedure

Calibration of the LFP was performed by the manufacturer and vertical loading was verified with a 22.68 kg test load to ensure accuracy. The Zibrio SmartScale was calibrated with the same 22.68 kg test load prior to data collection using a two-point

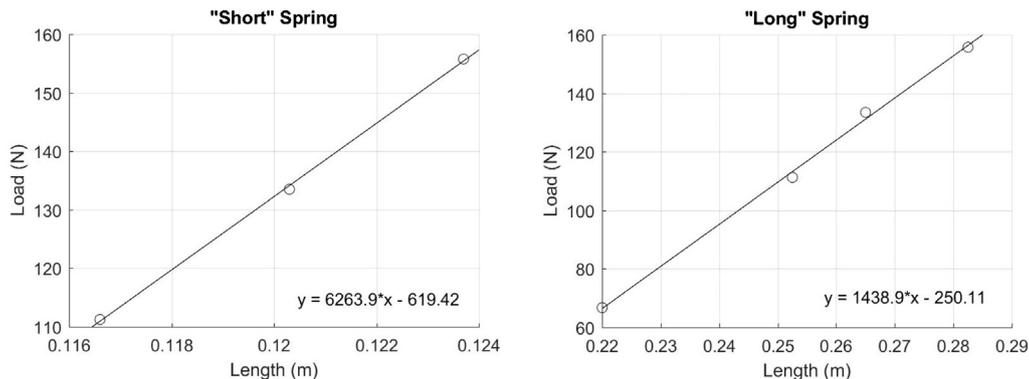


Fig. 3. Estimated spring constants for “short” and “long” off-the-shelf springs.

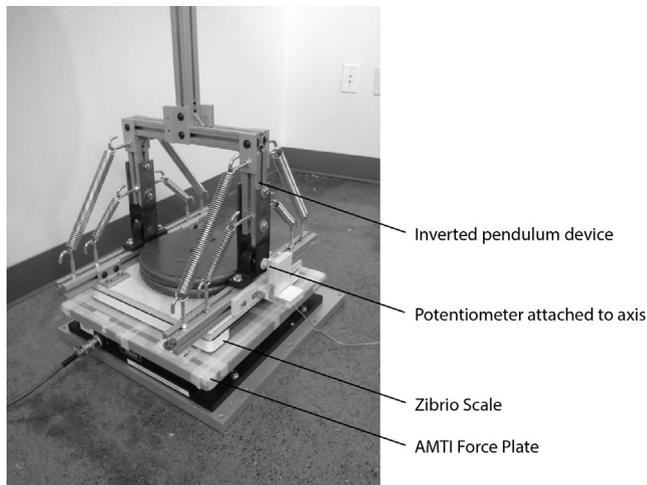


Fig. 4. Full testing assembly including laboratory force platform, Zibrio SmartScale, and inverse pendulum center of pressure simulator.

regression routine, including load and no-load (0 kg) conditions. Preparation of the test assembly followed this protocol: the LFP completely unloaded, initialized and hardware zeroed to remove any load offsets; the LabView LFP data collection software was loaded and initialized to software zero the LFP; the Zibrio SmartScale was placed in the center of the LFP aligning the anterior-posterior (AP) and medial-lateral (ML) axes, and subsequently zeroed using the Zibrio operating software. The inverse pendulum assembly was placed upon the Zibrio SmartScale (Fig. 4) and loaded with two 11.34 kg (25 lb) weights at the base for stability.

Two displacement angles, 3° and 5°, were selected to evaluate the free oscillatory movement of the inverse pendulum. Three data collection trials were performed in both the AP and ML directions. The inverse pendulum was positioned to the initial displacement angle for 3 s prior to release and allowed to freely oscillate throughout the data collection trial.

2.4. Data analysis

During testing, the LFP data collection was initiated first, therefore the 60 s of data collection always ended before the Zibrio

SmartScale data collection. Accounting for operator performance, approximately 40 s of simultaneous data was collected for each data collection trial. To account for differences in data collection initiation and differences in sampling frequency (100 Hz for LFP and 60 Hz for Zibrio SmartScale), effort was taken to align the time series signals for comparison. Each time series signal was low pass filtered using a 4th order, zero-lag Butterworth filter with a 5 Hz cut-off frequency to minimize noise. The beginning of the signals were cropped to the peak displacement of the first oscillation, and analyzed for $n-3$ oscillations, where n was the number of oscillations captured in the LFP time series signal. The Zibrio SmartScale time series signal was resampled to this cropped LFP signal and the cross-correlation between the signals was maximized to align them temporally. To account for the height difference of the Zibrio SmartScale atop the LFP (placing its COP estimates in a different coordinate space from the LFP COP estimates) a compensatory factor was added following the guidance of Leach et al. (2014). Finally, to account for minor offsets in the positioning of the stabilizing loads among trials, the signals were mean-offset (DC offset) to center them.

To estimate the performance and quantify the measurement error between the Zibrio SmartScale and the LFP, the mean absolute error (MAE) among the two synchronized COP displacements in the primary axes of rotation (AP or ML) were calculated, as well as the mean intraclass-correlation coefficient (ICC(1,1)) as a measure of measurement reliability. Finally, percent error magnitude (PEM) (O'Connor et al., 2016) was estimated based upon linear regression between the Zibrio SmartScale and LFP estimates, where deviation from a unity slope ($\pm m = 1$) was considered to be error. Precision was estimated from this regression by calculating the mean standard deviation of the prediction errors (residuals). 95% confidence intervals are presented for all group means to highlight the dispersion of the results.

Hypothesis testing related to the ICC(1,1), where the null hypothesis that $ICC(1,1) = 0$, was performed to characterize the statistical strength of the measurement reliability. A two-way ANOVA was performed to estimate the main effects of *Direction* (AP vs ML) and *Angle* (3° vs 5°) upon MAE, percent error magnitude and measurement precision. Results are reported as means and 95% confidence intervals, and statistical significance is defined at an error rate of $\alpha = 0.05$. Statistical analyses were performed in R (v.3.4.3) (R Core Team, 2017).

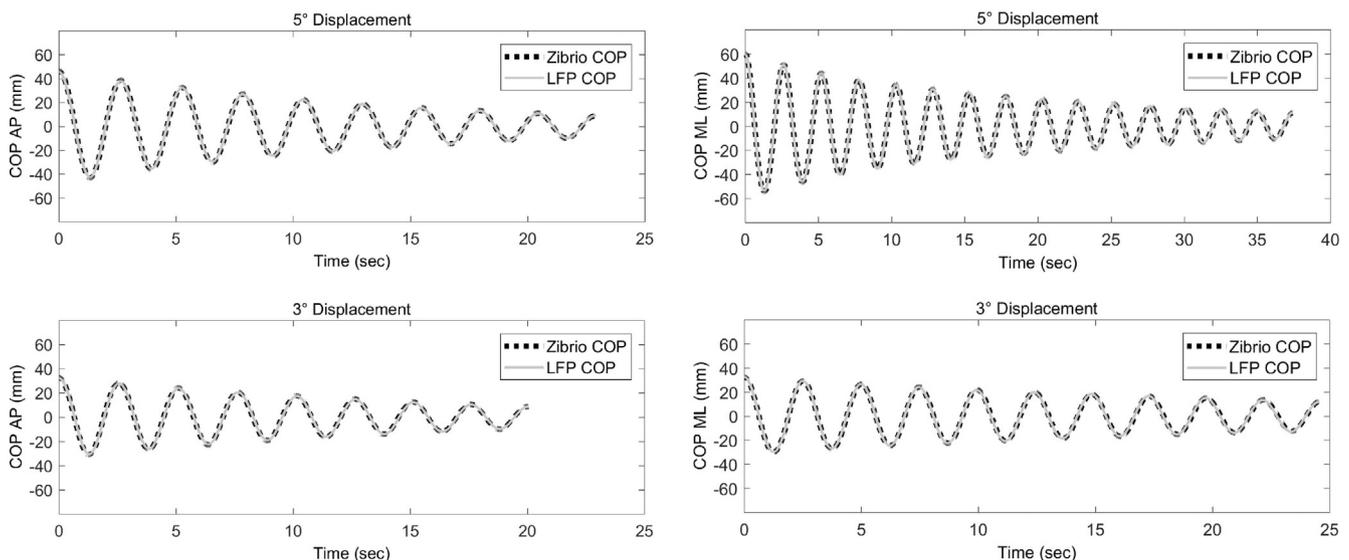


Fig. 5. Zibrio SmartScale and laboratory force platform COP measures in the AP and ML directions at 3° and 5° of displacement.

Table 1

Average MAE, maximum AE, PEM and the distribution of prediction errors (precision) calculated between COP estimates from an LFP and Zibrio SmartScale in AP and ML directions, with 95% confidence intervals.

Direction	Angle	MAE (mm)	Max. AE (mm)	PEM (%)	Precision (mm)
AP	3°	0.39 [0.18–0.60]	0.93 [0.32–1.9]	1.09 [0.97–1.2]	0.42 [0.17–0.68]
	5°	0.39 [0.17–0.59]	1.25 [0.32–1.5]	1.38 [1.3–1.5]	0.40 [0.14–0.65]
ML	3°	0.31 [0.10–0.52]	0.84 [0.23–1.5]	0.09 [0.05–0.22]	0.37 [0.11–0.62]
	5°	0.40 [0.19–0.60]	1.49 [0.88–2.1]	0.33 [0.20–0.46]	0.51 [0.26–0.77]

3. Results

The comparison of COP estimates between an AMTI LFP and the Zibrio SmartScale show strong coherence and reliability with minimal error (Fig. 5). There were no significant differences among MAE in either direction (AP or ML $p = 0.70$), at either angle (3° or 5°, $p = 0.67$), or within-and-between direction and angle ($p = 0.62$), nor were the maximum absolute errors significantly different (AP or ML, $p = 0.79$, 3° or 5°, $p = 0.11$ or direction by angle interaction $p = 0.56$). Percent error magnitude (PEM) showed significant differences among AP and ML directions ($F_{1,8} = 326$, $p = 0.000$) as well as differences among angles ($F_{1,8} = 21.7$, $p = 0.002$). However, no significant differences were observed among the direction by angle interaction ($p = 0.736$). Finally, no significant differences were observed among measures of error dispersion in either direction (AP or ML, $p = 0.80$), at either angle (3° or 5°, $p = 0.59$), or within-and-between direction and angle ($p = 0.46$), suggesting consistent precision across conditions. These results are summarized in Table 1. The ICC(1,1) estimate found very high reliability among COP estimates captured on the LFP and those captured on the Zibrio SmartScale. Mean ICC(1,1) [95% CI] was found to be 0.9995 [0.9995, 0.9994] and 0.9997 [0.9996, 0.9997] at 3° and 5° displacement in the AP direction, respectively. In the ML direction, ICC(1,1) was found to be 0.9996 [0.9996, 0.9997] and 0.9997 [0.9997, 0.9997] at 3° and 5°, respectively.

4. Discussion

Mean absolute error (MAE) was selected as the primary estimate of error among the Zibrio SmartScale and the LFP as it retains the original units of observations, allowing for an unambiguous interpretation of the results. The findings of this study show very little MAE at both 3° and 5° of initial displacement, and no appreciable difference in error in either AP or ML directions. Averaged over repeated trials, the MAE did not surpass 0.5 mm, barely 0.4% of the total range ($\pm 50 - 60$ mm in 5° displacement trials; Fig. 5) of COP simulated. The distribution of maximum AEs were also calculated to observe the worst-case predictions, and showed no significant differences among direction or pendulum displacement, and upper limits of 1.9 mm and 2.1 mm in the AP and ML directions, respectively. Although 3–4 times larger than the MAE, these AEs were within the observed range previously characterized (Bobbert and Schamhardt, 1990; Cedraro et al., 2009; Gill and O'Connor, 1997). PEM was also calculated to provide a direct comparison with previous methods performed by O'Connor et al. (2016). Although we saw slightly higher average PEM (averaging both AP and ML directions: $0.723 \pm 0.61\%$ vs. $0.646 \pm 0.40\%$) than O'Connor et al. (2016), this difference of 0.1% was considered to be minimal. Surprisingly, significant differences were observed among the PEM estimates in the AP and ML directions. However, this difference was very small in magnitude, <1–2%, which was not considered to be clinically relevant within the context of the range of COP typically observed during human postural sway (Nejc et al., 2010; Winter, 1995). Precision, measured as the standard deviation of the residuals, was observed to be poorer than

that found in O'Connor et al. (2016), 0.42 ± 0.17 mm versus 0.15 ± 0.22 mm, suggesting a larger magnitude standard deviation of errors among predictions, however, with less variability among repeated trials. Intraclass correlation measures (ICC(1,1)) were perhaps the most telling result, showing near-unity estimates of the measurement agreement among the two systems.

Although the results of this study suggest very compelling performance from the Zibrio SmartScale, it is important to note the following limitations. The Zibrio SmartScale is a low-cost device comprised of consumer off-the-shelf components, and is therefore susceptible to component and batch variability. This study evaluated only one ($n = 1$) Zibrio SmartScale, which implies that, although the results are promising, continued evaluation of multiple Zibrio SmartScales is required to ensure consistent performance. The measurements performed using the inverse pendulum device were completed a short time after calibration and zero-offset preparation of the Zibrio SmartScale. In the current study, only a subset of the displacement angles measured in O'Connor et al. (2016) were measured using the inverse pendulum (3° and 5° angular displacement) due to mechanical limitations of the device. The need to stabilize the inverse pendulum atop a base plate, similar Leach et al. (2014) and O'Connor et al. (2016), will likely have added COP estimate errors specific to this apparatus and inapplicable to measures produced by the feet during upright human posture, which represent independent points of contact. The results presented here cannot comment on the continued reliability of the Zibrio SmartScale over time. Factors such as temperature, positioning and/or environmental noise, or simply battery performance, may influence the Zibrio SmartScale's ability to accurately collect COP information.

Evaluating COP accuracy directly is challenging in practice, requiring complex test jigs with accurate linear positioning and loading capabilities (Bobbert and Schamhardt, 1990; Cedraro et al., 2009, 2008; Gill and O'Connor, 1997). Contrary to manufacturer specifications, these independent evaluations of “gold standard” LFPs for COP accuracy have estimated errors in the range of ± 2.5 mm for static loads, such as those used in this study, and up to ± 40 mm for highly dynamic loads, such as those observed in gait. Without direct evaluation of COP accuracy for the Zibrio SmartScale using specialized hardware, these errors must be considered within the context of COP estimates during future evaluations of postural stability. Despite these limitations, the results of this study strongly support the notion that the Zibrio SmartScale can perform adequately as a light-weight and low-cost alternative to COP measurement in comparison to a traditional LFP. Future studies will focus on the reliability of COP measurements over time, especially after regular use, as well as the evaluation of human sway data in a way that random and time-variant components of COP, applied naturally by two points of contact, can be compared with “gold standard” estimates from an LFP.

Declaration of Competing Interest

Zibrio Inc. employs the authors Ms. Bartlett, Dr. Forth and Dr. Madansingh, representing a potential for conflict-of-interest. Dr.

Layne, from the University of Houston, provided guidance throughout the study to minimize these conflicts. Under his supervision, Ms. Bartlett and Dr. Forth performed the data collection, while Dr. Madansingh performed the data analysis, blinded to the data collection. Ms. Bartlett was responsible for manuscript preparation and each author reviewed independently before collation by Ms. Bartlett.

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