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Short communication

A point of application study to determine the accuracy, precision and reliability of a low-cost balance plate for center of pressure measurement

Daniel J. Goble[a,*], Ehran Khan[b], Harsimran S. Baweja[c], Shawn M. O'Connor[c]

[a] School of Health Sciences, Department of Human Movement Science, Oakland University, 433 Meadow Brook Rd, Rochester, MI 48309, USA
[b] College of Engineering, Department of Mechanical Engineering, San Diego State University, 5500 Campanile Drive, San Diego, CA 92182, USA
[c] College of Health and Human Services, School of Exercise and Nutritional Sciences, San Diego State University, 5500 Campanile Drive, San Diego, CA 92182, USA

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ABSTRACT

Changes in postural sway measured via force plate center of pressure have been associated with many aspects of human motor ability. A previous study validated the accuracy and precision of a relatively new, low-cost and portable force plate called the Balance Tracking System (BTrackS). This work compared a laboratory-grade force plate versus BTrackS during human-like dynamic sway conditions generated by an inverted pendulum device. The present study sought to extend previous validation attempts for BTrackS using a more traditional point of application (POA) approach. Computer numerical control (CNC) guided application of ~155 N of force was applied five times to each of 21 points on five different BTrackS Balance Plate (BBP) devices with a hex-nose plunger. Results showed excellent agreement (ICC > 0.999) between the POAs and measured COP by the BBP devices, as well as high accuracy (<1% average percent error) and precision (<0.1 cm average standard deviation of residuals). The ICC between BBP devices was exceptionally high (ICC > 0.999) providing evidence of almost perfect inter-device reliability. Taken together, these results provide an important, static corollary to the previously obtained dynamic COP results from inverted pendulum testing of the BBP.

1. Introduction

The innate ability of humans to stand upright without falling (i.e. balance) relies on the control of "postural sway". Postural sway is biomechanically defined as sustained oscillatory motion about a fixed postural position in the presence of gravity (Hellebrandt and Braun, 1939). The importance of postural sway was first underscored in the mid-1880s by famed neurologist Moritz Romberg (see Pearce, 2005 for review). Today, postural sway is routinely-assessed as an indicator of poor performance on activities of daily living (Era et al., 1997), high fall risk (Pajala et al., 2008; Thapa et al., 1996) and elevated potential for sport injury (McGuine and Greene, 2000).

For decades, force plates have been a well-recognized means of assessing postural sway. Force plates determine a metric called center of pressure (COP), representing the weighted average location of the ground reaction forces. During quiet standing, COP is correlated with changes in a person's center of gravity and, thus, their postural sway (Browne and O'Hare, 2000). While COP is a sensitive and objective measure of postural sway, the use of force plate-guided balance testing is not currently widespread. This is likely due to the lack of portability, and high cost (~$5000–$100,000 US), of typical force plate systems.

The BTrackS Balance Plate (BBP) is a relatively new force plate that is portable (<7 Kg, no AC power required) and affordable (~$795 US). Using an inverted pendulum device to mimic human postural sway, the BBP was recently shown to have a high degree of COP accuracy (<1% error) and precision (<0.02 cm) relative to a laboratory-grade force plate (O'Connor et al., 2016). There was also no difference found between a single new (out of the box) and used BBP.

The present study sought to extend existing validation work on the BBP by using a point of application (POA) approach to test BBP accuracy and precision. Specifically, POA testing involved application of perpendicular forces to known locations on the surface of a BBP, and comparing their position with concurrently-measured COP. POA is a common approach for determining force plate performance metrics (Bartlett et al., 2014; Bobbert and Schamhardt, 1990; Browne and O'Hare, 2000; Hall et al., 1996), and provides

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[*] Corresponding author.
E-mail address: dgoble@oakland.edu (D.J. Goble).

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an important, static corollary to the previously obtained dynamic COP results from inverted pendulum testing (O'Connor et al., 2016). The present study also aimed to provide more extensive inter-device reliability assessment for the BBP, comparing the results from five different devices.

2. Methods

2.1. Experimental setup

Five lightly used (<1000 tests) BBP devices (Balance Tracking Systems Inc., CA, USA) were tested in this study. The BBP (Fig. 1) is a FDA registered class 1 medical device with a 40 cm × 60 cm rectangular platform surface and enclosed strain gauge sensors on the underside of each platform corner. Adjustable feet below the sensors allow levelling of the BBP and ensure firm contact of the legs with the surface below. BBP sensors input to a bridge-type circuit board on the BBP, which, in this study, provided vertical force-related voltage signals to a laptop (Dell, TX, USA) via a standard USB cord. Custom data collection software developed in the LabVIew environment (National Instruments, TX, USA), was used to calculate medial lateral (X) and anterior-posterior (Y) COP according to the following formulas:

$$\mathrm{COP\ X} = 24.25((\mathrm{TR} + \mathrm{BR}) - (\mathrm{TL} + \mathrm{BL}))/(\mathrm{TL} + \mathrm{TR} + \mathrm{BL} + \mathrm{BR})$$

$$\mathrm{COP\ Y} = 15.50((\mathrm{TL} + \mathrm{TR}) - (\mathrm{BL} + \mathrm{BR}))/(\mathrm{TL} + \mathrm{TR} + \mathrm{BL} + \mathrm{BR})$$

where TR, TL, BR and BL are the force sensor values from the top right, top left, bottom right and bottom left corners of the BBP respectively.

A Shopbot Buddy Computer Numerical Control (CNC) router (ShopBot Tools, Inc., NC, USA) served as the method of POA delivery, with a manufacturer specified positional accuracy of <0.01 cm. The CNC delivered POA forces using a standard hex-nose spring plunger (McMaster-Carr Supply Co., IL, USA) installed onto the head of the CNC. The spring plunger allowed a relatively constant force to be delivered at a single point on each BBP being tested. Both CNC and BBP devices were calibrated and verified prior to data collection.

2.2. Experimental procedure

At the time of data acquisition, a given BBP was mounted and aligned on the CNC table with its feet stabilized by a custom jig. The jig was aligned such that the X and Y axes of the CNC internal stepper motor controller corresponded with the X (mediolateral) and Y (anterior-posterior) axes of the BBP. The feet of the BBP were adjusted such that the BBP surface was level, and the BBP collection software was used to "zero" the BBP sensors.

Following BBP preparation on the CNC table, POA testing began. POA trials consisted of depressing the spring plunger onto the BBP for several seconds, while the instantaneous X and Y COP locations were manually triggered and recorded from the data collection laptop. For each trial, the spring-loaded plunger was raised, moved to the appropriate X-Y location, and then lowered until ~155 N of force was applied to the BBP surface. This level of force was chosen based on the capacity for force generation of the CNC machine and available plunger characteristics. The full testing protocol consisted of five consecutive trials at each of 21 POAs (Fig. 2), for total of 105 trials. POAs included three locations at the plate midline (X = 0 cm, Y = −5 cm, 0 cm, 5 cm), where COP is commonly seen during standing, and two nine-point grids (X = −25 cm, −20 cm, −15 cm, 15 cm, 20 cm, 25 cm; Y = −5 cm, 0 cm, 5 cm), where the feet are typically placed on the BBP when standing with a natural stance width (Middleton et al., 1999).

2.3. Data analysis

For each BBP, the five COP recordings from a given POA location were first averaged to reduce signal noise. COP data were then corrected for translational and rotational offsets of the BBP COP and CNC X-Y coordinate systems. To accomplish this, linear regressions were performed on the X-Y COP data from each BBP for each of the Y coordinate rows (Y = −5 cm, 0 cm, 5 cm). The three calculated slopes were averaged and converted into a rotational offset θ_{avg} in degrees, and the X-Y COP data were then multiplied by a rotation matrix (rotation by -θ_{avg}) to correct for any rotational offset. Subtracting the averaged COP X and Y values respectively, subsequently corrected any translational offsets.

The agreement between the standard, CNC POA X-Y locations and the measured, BBP X-Y COP was subsequently determined using an absolute (A,1 model) intraclass correlation coefficient (ICC) and its 95% confidence interval lower limit. In addition, two technical performance metrics were quantified from linear regressions between the CNC POAs and BBP COP data. First, the percent error was calculated as an indicator of absolute BBP accuracy according to the following formula:

$$\mathrm{Accuracy} = \mathrm{Percent\ Error} = |(\beta - 1)| * 100$$

where β was equal to the regression slope. Second, BBP precision was quantified as the standard deviation of the regression residuals.

Summary values from the above metrics (i.e. ICC, accuracy and precision) were further subjected to paired *t*-test analyses to determine the effect of direction (X vs. Y). Statistical significance was considered at the $p < 0.05$ level. As a final step, inter-device

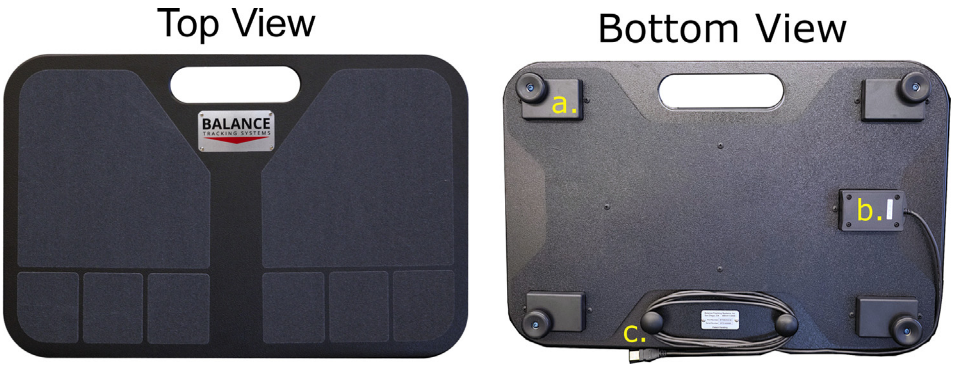

Fig. 1. Top (left) and Bottom (right) views of the BBP. Labelled are (a) one of the four enclosed sensors in the plate corners, (b) the enclosed bridge-type circuit board, and (c) the USB connector for interfacing with the laptop.

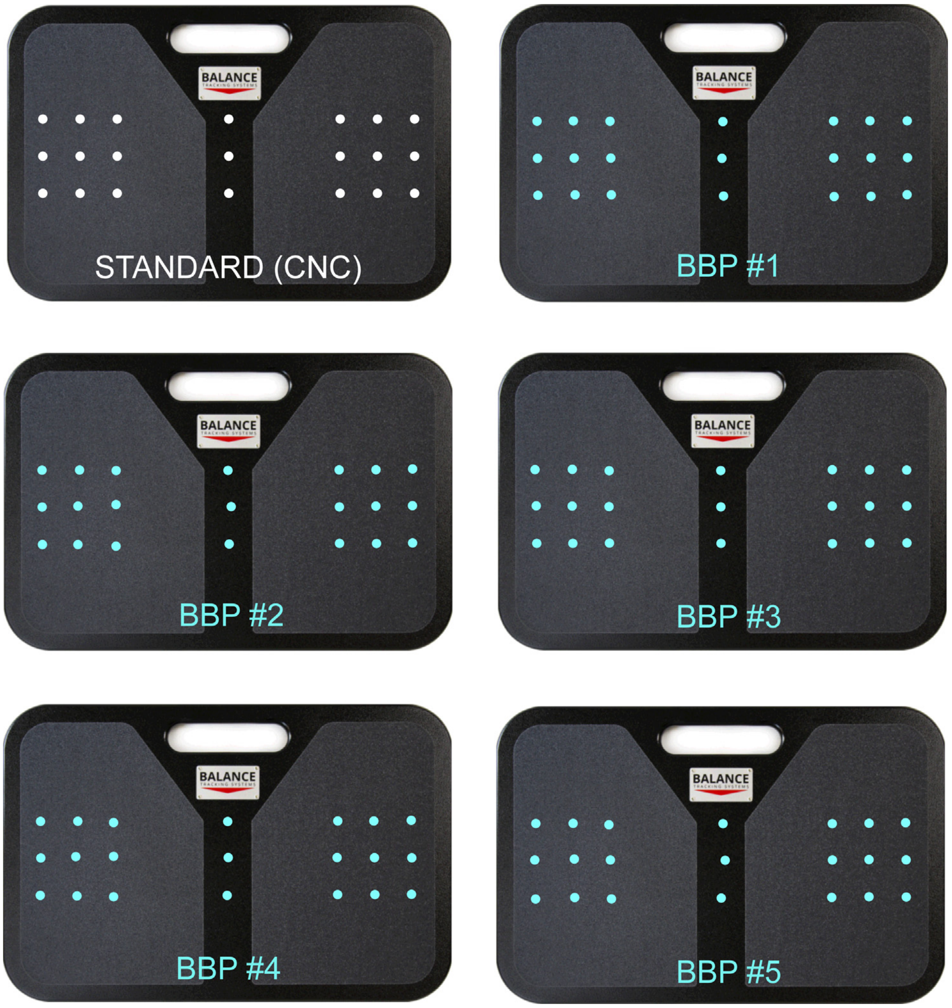

Fig. 2. In the top left corner is a visual depiction of the POA locations implemented by the CNC machine as a standard of comparison. The remaining images represent the average of five COP recordings for each POA on each BBP (#1-#5) tested.

reliability was assessed by calculating consistency ICCs for COP data in the X and Y directions across all BBP devices tested.

3. Results

Correspondence between the CNC-delivered POAs and the COP measured by each BBP is visually depicted in Fig. 2. Technical performance metrics are provided for each BBP in Table 1 (X COP direction) and Table 2 (Y COP direction). Based on the ICC results, there was almost perfect absolute agreement between the CNC and BBP in all cases (ICC > 0.999, ICC lower limit >0.998). There was statistically significant greater agreement in the X versus Y COP direction (t_4=5.0, $p < 0.01$). However, the magnitude of this difference in absolute terms was negligible.

With respect to BBP accuracy, the percent error for all BBP devices was effectively small (<1.5%), with an average percent error <0.5%. There was no significant difference between accuracy in the X versus Y COP directions ($t_4 = -0.6$, $p = 0.60$). For precision, the standard deviation of the residuals was <0.15 cm on average for the X and Y COP directions. There was no difference in precision between X and Y across BBP devices ($t_4 = 2.1$, $p = 0.11$).

ICC values calculated across BBP devices revealed that inter-device reliability (consistency) was almost perfect. In both the X and Y COP directions the average ICC was >0.999, with an average lower limit also >0.999.

Table 1
Performance Metrics for each BBP in the COP X direction.

	Overall agreement		Accuracy	Precision
	Average ICC	ICC lower limit	Percent error	SD of residuals
BBP #1	>0.999	>0.999	0.35%	0.08 cm
BBP #2	>0.999	>0.999	0.13%	0.13 cm
BBP #3	>0.999	>0.999	0.14%	0.06 cm
BBP #4	>0.999	>0.999	0.01%	0.12 cm
BBP #5	>0.999	>0.999	0.50%	0.16 cm
Average	>0.999	>0.999	0.23%	0.11 cm

Table 2
Performance metrics for each BBP in the COP Y direction.

	Overall agreement		Accuracy	Precision
	Average ICC	ICC lower limit	Percent error	SD of residuals
BBP #1	>0.999	>0.999	0.28%	0.07 cm
BBP #2	>0.999	0.999	0.04%	0.12 cm
BBP #3	>0.999	>0.999	1.20%	0.05 cm
BBP #4	>0.999	>0.999	0.29%	0.11 cm
BBP #5	>0.999	>0.999	0.09%	0.10 cm
Average	>0.999	>0.999	0.38%	0.09 cm

4. Discussion

The present study extended previous validation work of the BBP that utilized an inverted pendulum approach to demonstrate high COP accuracy and COP precision relative to a laboratory-grade force plate (O'Connor et al., 2016). Specifically, a more traditional, POA approach was employed using a CNC router to measure the accuracy and precision of static COP data. ICC results from both studies show that the BBP operates with a high degree accuracy (<1% average percent error) and precision (<0.1 cm average standard deviation of residuals), regardless of force application method (pendulum versus CNC POA). Further, an assessment of inter-device reliability in the present study demonstrated that data from five BBP devices was interchangeable (Lee et al. 1989), with an average ICC of >0.999.

One advantage of the POA approach used in this study is that the CNC machine used for testing was more accurate (<0.01 cm) than the laboratory-grade force plate (0.02 cm) previously utilized by O'Connor et al., 2016. Despite this, several limitations should be highlighted with respect to the present methodology. First, the forces applied to the BBP by the CNC router with hex-plunger was approximately 155 N (~16 Kg), far less than that experienced when a typical adult (50th percentile male = 78 Kg) stands on the device. This reduced force level may cause a small reduction in accuracy and/or precision, as was found previously for Nintendo Wii Balance Board (Bartlett et al., 2014). Beyond this, it should be noted that points applied in this study were unilateral in nature or along the plate midline. Standard postural sway testing with the BTrackS Balance Plate involves two feet shoulder width on the device, (i.e. bilateral application of force).

It should also be acknowledged that the magnitude of errors in this study could have been affected by the rounded-shape of the plunger surface used to apply POAs to the BBP surface. A rounded-shape surface does not allow for a true "point" of application to be made upon the BBP but, rather, a very small surface of points at the contact location of the rounded tip. The advantage of using this method rather than a sharp point on the plunger is that potential damage to the BBP surface was prevented by distributing the POA load. Such damage might have negatively influenced the perpendicular application of POAs and COP data.

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Conflict of Interest Statement

D Goble holds an equity stake (i.e. stock options) in the parent company for the BTrackS Balance Plate. Authors Khan, Baweja and O'Connor have no conflicts of interest to declare.

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