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Comparison of posturographic outcomes between two different devices

Lars Reinhardt^{a,b,*}, Florian Heilmann^b, Mirjam Teicher^c, Andreas Lauenroth^a,
Karl-Stefan Delank^a, René Schwesig^a, Rainer Wollny^b, Eduard Kurz^a^a Department of Orthopedic and Trauma Surgery, Martin-Luther-University Halle-Wittenberg, Halle (Saale), Germany^b Institute of Sport Science, Movement Science Group, Martin-Luther-University Halle-Wittenberg, Halle (Saale), Germany^c Institute for Applied Training Science (IAT), Leipzig, Germany

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ABSTRACT

The Interactive Balance System (IBS), a posturography device for assessing posture control, is widely used in clinical and rehabilitation settings. However, data on the validity of the device are unavailable. Fluctuations of the center of pressure (COP) were measured in 24 healthy participants (age: 29 ± 5 (mean \pm SD) years, 12 females) synchronously using the IBS, which was rigidly mounted on a Kistler platform. Four different bipedal conditions were examined: eyes open or closed on stable or soft surfaces. Time series were compared using congruity (CON, proportion of the measurement time during which values of both devices changed similarly in direction), whereas IBS-specific postural outcomes were correlated with traditional postural control outcomes of the Kistler force platform. The time-displacement curves showed similar shapes for CON (>0.9) for each of the four standing conditions without differences between male and female participants ($P > 0.39$). The path length results of both devices showed very high linear associations, explaining on average 92% (medio-lateral) or 96% (anterior-posterior) of the common variance. The Kistler path length of the anterior-posterior direction revealed nearly perfect linear associations with the stability index of the IBS ($r^2 > 0.99$). The results of this study indicate that the IBS provides valid posturographic results. Since the medial-lateral and anterior-posterior trajectories of the IBS can be used to calculate COP fluctuations, comparisons between different measurement systems are possible.

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1. Introduction

Force platforms are used to measure three-dimensional ground reaction forces and moments from which the position of the center of pressure (COP) can be calculated. Despite high costs and required expertise, the detailed quantitative information concerning various kinetic attributes of postural control are frequently assessed in clinical settings. In applying a single force platform setup, all claims regarding postural control are related to COP variations. Different global descriptors of postural steadiness (e.g. COP path length, COP velocity, standard deviation, sway range, ellipse area) were employed to characterize postural control. Since those traditional linear outcomes are unable to characterize the complexity of postural control, non-linear outcome variables were implemented to better characterize the dynamic nature (Blázquez et al., 2009; Collins and De Luca, 1994; Riley et al.,

1999). To compare postural control during the lifespan, Kurz et al. (2018) evaluated COP velocity during single-leg stance in 10-year-old children, young adults and seniors. In contrast, Newell et al. (1997) examined bipedal stance across four different age cohorts. Although both investigations confirmed a U-shaped association of their linear outcomes, Newell et al. (1997) found a decreased complexity and dimensionality in relation to the COP in the 3-year-old children only. Moreover, with global COP descriptors no conclusions can be drawn regarding the loads applied to forefeet or heels as well as below left or right feet.

Another, less complex, way to capture characteristics of postural steadiness is the use of devices which make it possible to quantify the weight or pressure distribution. Accordingly, devices recording signals from multiple force plates (Interactive Balance System, IBS), pressure sensors within insoles or pressure plates are applied. The latter two are especially used in different foot-related and footwear-related conditions (Paillard and Noe, 2015). The IBS incorporates the discrete information from four force plates recording independently but in a synchronized manner (Kohen-Raz, 1991). Based on this and besides the measurement of postural sway, it is additionally possible to reveal asymmetries

* Corresponding author at: Martin-Luther-University Halle-Wittenberg, Faculty of Medicine, Department of Orthopedic and Trauma Surgery, Ernst-Grube-Str. 40, 06120 Halle (Saale), Germany.

E-mail address: lars.reinhardt@uk-halle.de (L. Reinhardt).

in the weight distribution or disorders in the interaction of the feet, which point to certain clinical pictures and represent a starting point for further differential investigations. Thus, the IBS is widely used in clinical and rehabilitation settings. Cross-sectional as well as intervention outcomes were reported for different orthopedic (Aydin et al., 2017; Bartels et al., 2018; Kim et al., 2011; Kurz et al., 2019), neurological (Alpini et al., 2012; Oppenheim et al., 1999; Schwesig et al., 2009; Song et al., 2014) as well as metabolic (Wang et al., 2016) diseases. Furthermore, some authors investigated the influence of visual impairments on postural control characteristics (Schwartz et al., 2005; Schwesig et al., 2011). Children (Kohen-Raz and Hiriartborde, 1979; Steinberg et al., 2013) and elderly participants (Dunsky et al., 2017) were also evaluated. Although reliability of the IBS was extensively studied on healthy adults in single (Yi et al., 2014) and double-leg stance (Akkaya et al., 2015; Schwesig et al., 2014a) conditions as well as patient populations (Kurz et al., 2019; Loughran et al., 2005; Schwesig et al., 2014b), data on the validity of the device are unavailable. However, outcomes of COP trajectories measured by laboratory grade force plates are considered the gold standard for analyses of balance performance (Huurnink et al., 2013). Past investigations showed that the time series of the four IBS plates can also be used to calculate trajectories equivalent to the COP displacement (Lambez, 2005). Therefore, this study aimed at evaluating the concurrent validity of the IBS for assessing postural control using a Kistler force platform as the criterion-reference (state of the art).

2. Methods

2.1. Participants and task

Posturography was examined in a population of 24 healthy adults, consisting in equal parts of women (age: 29 ± 4 (mean \pm SD) years; height: 168 ± 6 cm; mass: 61 ± 10 kg; BMI: 22 ± 3 kg/m²) and men (age: 30 ± 5 years; height: 180 ± 5 cm; mass: 80 ± 7 kg; BMI: 25 ± 2 kg/m²). The comparison of means proved no difference in age between both groups ($P > 0.9$).

In accordance with other studies in the same field of research, participants were included in this study subject to the following conditions: (1) no current or past medical diagnosis or injury affecting balance; (2) no use of medication affecting the central nervous system or known to affect balance performance; (3) no symptoms of dizziness or light-headedness; (4) no symptom suggestive of vestibular or neurological disorders; (5) no psychological disorders including depression; (6) no history of two or more unexplained falls within the past six months; (7) normal vision with or without glasses. The study protocol used was approved by the local ethics committee (2016–41), and all participants agreed to enter the study and signed an informed consent.

The first part of the standard examination protocol of the Interactive Balance System (IBS, neurodata, Vienna, Austria) was conducted (Kohen-Raz, 1991) to investigate postural control and achieve comparative data to studies on similar groups of subjects (Schwesig et al., 2014a, Alpini et al., 2012). Accordingly, participants were instructed to stand barefoot, upright and as quietly as possible for 32 s in a fixed order of four conditions: (1) normal standing on stable ground with eyes open (NO), (2) normal standing on stable ground with eyes closed (NC), (3) standing on soft surface with eyes open (PO) and (4) standing on soft surface (foam pads, N110310, Eurofoam GmbH, Kremsmünster, Austria) with eyes closed (PC).

2.2. Data acquisition and preprocessing

During the experiments, the participants stood on the IBS that was firmly attached on top of a reference force platform (KIS, type

9260, Kistler AG, Winterthur, Switzerland). With this configuration (Fig. 1A), a key requirement for comparing the results was achieved because one and the same trial was recorded simultaneously, and not consecutively, by both measuring devices (Haas and Burden, 2000; Huurnink et al., 2013; Peterson Silveira et al., 2017; Reeve and Tyler, 2013).

The IBS is composed of four separate uniaxial force transducers that are sensitive to the vertical ground reaction forces of the two forefeet and heels. Accordingly, the IBS provides force signals of the four platforms: A (left heel), B (left forefoot), C (right heel) and D (right forefoot). To eliminate the influence of the participants' weight, the force signals were normalized to body mass (BM) prior to all calculations. Further information on the IBS can be found elsewhere (Kohen-Raz, 1991).

Signals from the IBS and KIS were synchronously recorded and digitized with a sampling rate of 500 Hz using a Kistler DAQ system (type 5695B1) and Kistler's BioWare acquisition software (Fig. 1B). Raw data were exported as ASCII files and further processed in MATLAB R2016a (The MathWorks, Natick, MA, USA). As a first step, the signals were downsampled to the default sampling rate of the IBS (32 Hz) and smoothed using a third-order Savitzky-Golay filter (Savitzky and Golay, 1964) with a window width of 19 samples (using the MATLAB function `sgolayfilt`). By means of this filter selection, the signal noise was effectively reduced without changing the characteristics of the trajectories.

2.3. Center of pressure analysis

The path of the COP determined by the Kistler force plate (COP_{KIS}) was analyzed in medial-lateral (x) and anterior-posterior direction (y) and served as the major variable for the validation. Time series of the IBS load cells (A–D) were used to calculate trajectories corresponding to the COP path displacement (Lambez, 2005). However, the measurement units of the IBS are in %BM. Thus, using the time series of the IBS, the displacements of the center of pressure (COP_{IBS}) trajectories were calculated as follows:

$$x_i = (C_i + D_i) - (A_i + B_i); y_i = (B_i + D_i) - (A_i + C_i)$$

2.4. IBS outcomes

To analyze the trials with the IBS software (Tetrax), MATLAB was used to generate compatible import files. After the files had been imported, test evaluations were immediately available within the software in tabular and graphic form (Postural Summary Sheet) and the results were stored automatically in the integrated database. Finally, for further processing in other software, the system-specific parameters for all measurements were exported to an Excel sheet (Microsoft Corporation, Redmond WA, USA).

A detailed description of the IBS parameters can be found elsewhere (Avni et al., 2006; Kohen-Raz, 1991). Thus, in the following paragraph only those parameters are presented with their equations that were used for validation purposes. The validity of the equations was verified by calculating the Tetrax parameters in a MATLAB environment based on raw data.

The Weight Distribution Index (WDI) is a measure for the asymmetry of weight distributions from an expected mean of 25% per plate. Theoretically, the range of values of the WDI is between zero, i.e. the body weight is evenly distributed among the four plates, and 43.3% when the whole-body weight is supported by only one plate. The equation for the WDI is:

$$WDI = \sqrt{\frac{(\bar{A} - 25\%)^2 + (\bar{B} - 25\%)^2 + (\bar{C} - 25\%)^2 + (\bar{D} - 25\%)^2}{4}}$$

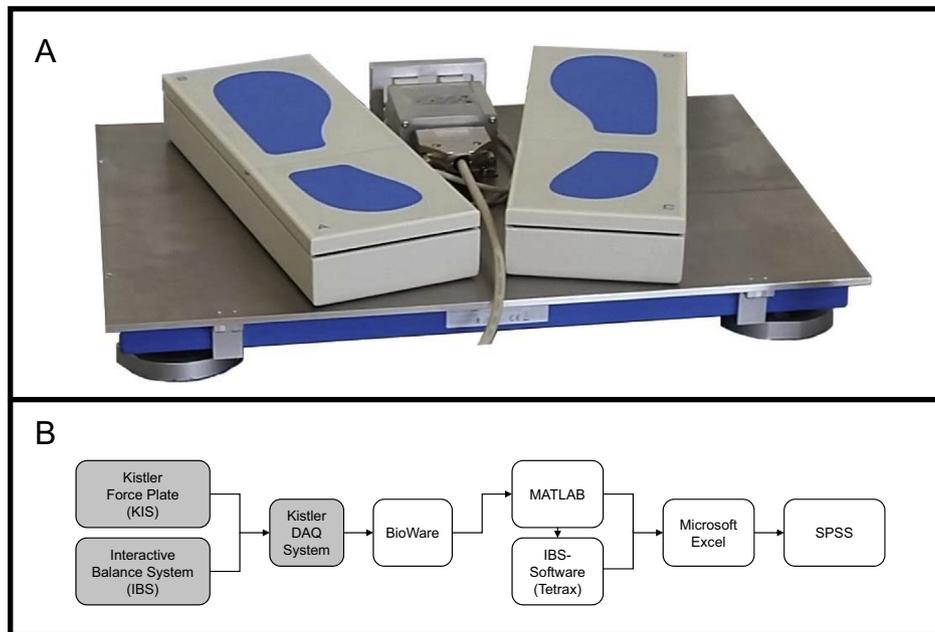


Fig. 1. Experimental setup and data processing. (A) The Interactive Balance System (IBS) was bolted on a steel plate on top of a Kistler force plate (type 9260AA3). (B) Flowchart of data acquisition and processing. Hardware components are depicted as grey and software elements as white boxes.

The general postural steadiness of the participant is expressed by the Tetrax Stability Index (ST), which indicates the amount of force fluctuations among the four plates and is calculated with the following equation:

$$ST = \frac{100}{n} \times \sum_{i=1}^n \sqrt{(A_{i+1} - A_i)^2 + (B_{i+1} - B_i)^2 + (C_{i+1} - C_i)^2 + (D_{i+1} - D_i)^2}$$

The percentage of weight placed on heel and left plates is expressed by the parameter $HEEL$ and $LEFT$, respectively:

$$HEEL = \bar{A} + \bar{C}; LEFT = \bar{A} + \bar{B}$$

2.5. Romberg quotients

To enable the comparability of the measurement systems (different measurement units), we calculated two Romberg quotients (NO/NC, PO/PC) between the different testing conditions for the IBS and the KIS separately according to Colledge et al. (1994). Since COP fluctuations were larger in anterior-posterior direction (Fig. 2), ratios were calculated on the path length results of the anterior-posterior trajectory only.

2.6. Statistics

Statistical analyses were carried out with SPSS 22.0 (IBM SPSS Statistics Inc., Chicago, IL) software. Congruity (CON) is a measure for the similarity between time series and was originally introduced in the field of gait biomechanics (Cavagna et al., 1976). For the present study, CON was defined as the proportion of the measurement time during which COP_{KIS} and COP_{IBS} changed similarly in direction. CON was 1 when both parameters fluctuated identically throughout the whole test time and was 0 in the case of a completely out-of-phase course. CON calculations were performed for both directions, medio-lateral and anterior-posterior, respectively. Since CON only considers the direction of the curve fluctuations, only highly associated COP path length values would indicate com-

parable results of both devices. Outcome or gender comparisons were verified with either paired or unpaired Student t tests. Where appropriate, effect size (ES) was reported. Validity was established by relating the COP path length displacements of the medial-lateral and anterior-posterior trajectories to the results of the Kistler force plate using Pearson correlation coefficients (r) with coefficients of determination (r^2). The relative reliability of the contributions of the visual system (Romberg quotients) was examined using the intraclass correlation coefficient (ICC), whereas the deviation of both measurement systems was inspected with difference plots and corresponding upper and lower limits (1.96SD, see Fig. 3). Possible gender effects were verified using mixed design analyses of variance (four conditions) separately on each IBS postural outcome or Romberg quotients between measurement devices. Practical relevance was estimated calculating partial eta-squared (η_p^2) with values ≥ 0.01 , ≥ 0.06 , ≥ 0.14 indicating small, moderate, or large effects, respectively.

3. Results

Despite the different measurement units, the time-displacement curves for standing on both limbs showed a similar shape (see Fig. 2) and direction changes (congruity, CON) for each of the four standing conditions (Table 1). CON revealed average values of at least 0.91 without differences between male and female participants ($P > 0.27$). CON in anterior-posterior direction (> 0.97) showed a higher accordance as compared with the medial-lateral direction (> 0.91) across all standing conditions ($t(23) < -8.1$, $P < 0.001$, $ES < -1.6$). The highest values were found for the PC condition (Table 1).

The COP path length results of both devices showed very high linear associations, explaining at least 88% of the common variance (Table 2). Like CON , the anterior-posterior trajectories revealed higher relationships throughout the four different standing conditions. Furthermore, the COP path length of the anterior-posterior direction revealed nearly perfect linear associations with ST ($r^2 > 0.99$).

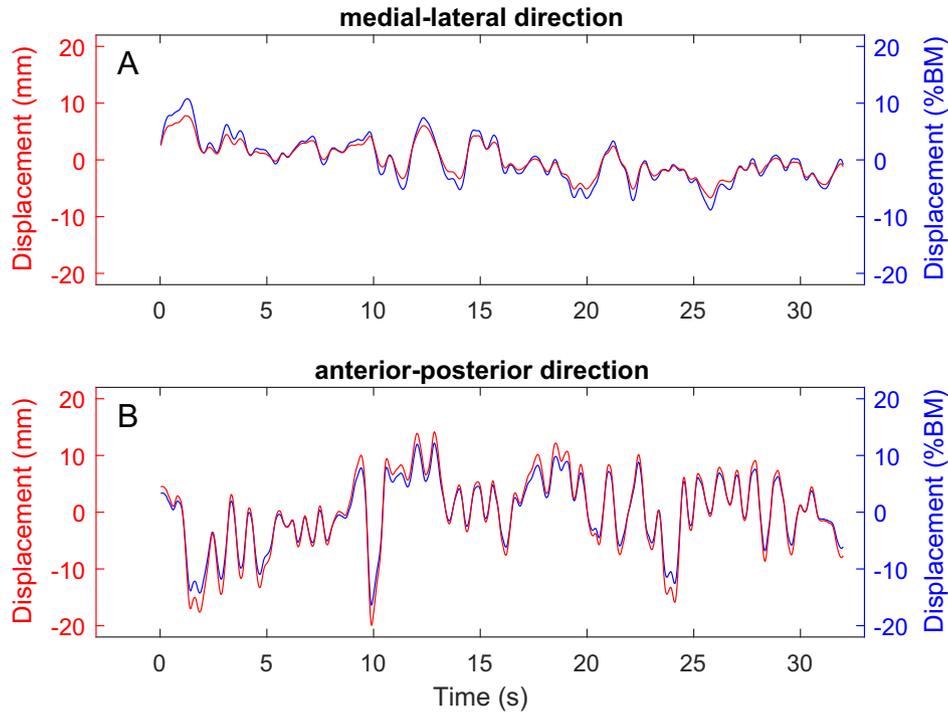


Fig. 2. Example of medial-lateral (A, congruity = 0.96) and anterior-posterior (B, congruity = 0.98) center of pressure trajectories of the Kistler (KIS, red) and the Interactive Balance System (IBS, blue) force plates (normal standing on foam pads with eyes closed, PC). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

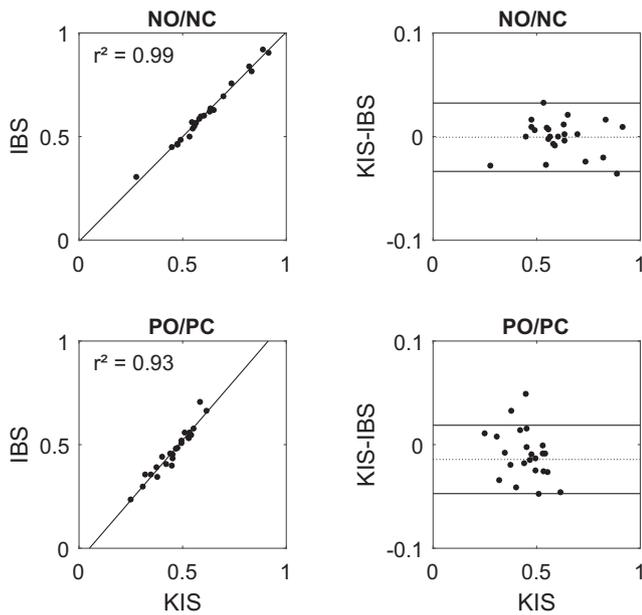


Fig. 3. Linear regression (left column) and difference plots (right column) between the Kistler (KIS) and the Interactive Balance System (IBS). Data of different Romberg quotients (NO/NC, PO/PC) are displayed in rows. The dotted and continuous lines indicate the bias and $\pm 1.96SD$.

The comparisons between the outcomes generated by the Tet-rax software and calculations in MATLAB showed identical ($r^2 \geq 0.99$) results for all parameters (*ST*, *WDI*, *HEEL*, *LEFT*), which underpin the equations presented.

The mixed design ANOVAs revealed no interaction effect between gender and condition for either IBS outcome (*WDI*: $F(3, 66) = 0.9, P > 0.4, \eta_p^2 < 0.04$; *ST*: $F(3, 66) = 0.3, P > 0.7, \eta_p^2 < 0.02$;

HEEL: $F(3, 66) = 1.5, P > 0.2, \eta_p^2 < 0.07$; *LEFT*: $F(3, 66) = 1.9, P > 0.1, \eta_p^2 = 0.08$). For detailed results, please refer to Table 3.

The mixed design ANOVAs on the Romberg quotients calculated showed no interaction effect between gender and Romberg ratios for either measurement device (IBS: $F(1, 22) = 0.5, P > 0.4, \eta_p^2 < 0.03$; KIS: $F(1, 22) < 0.1, P > 0.9, \eta_p^2 < 0.01$). Thus, the reliability was tested across gender. The ratios calculated revealed excellent ICC values [NO / NC: 0.99 (95% CI: 0.98–0.99), PO / PC: 0.94 (95% CI: 0.85–0.97)].

4. Discussion

This study investigated posturographic outcomes between two different devices comparatively. The results showed that the outcomes provided by both devices can be used interchangeably, indicating a high concurrent validity.

The Kistler force plate is considered as gold standard to measure ground reaction forces and balance performance. As such, Kistler force plates were repeatedly used as comparison devices to validate different portable force plates, balance boards, contact mats or insoles (Donath et al., 2012; Haas and Burden, 2000; Hurkmans et al., 2006; Huurnink et al., 2013; Peterson Silveira et al., 2017; Reeve and Tyler, 2013).

The results of different lower-cost portable force platforms were compared with those provided by a Kistler force platform (Donath et al., 2012; Peterson Silveira et al., 2017). Peterson Silveira et al. (2017) evaluated different takeoff components of dynamic tasks with their platform bolted on a Kistler force plate as arranged in this measurement setup. In contrast, Donath et al. (2012) assessed COP path length displacements of double and single limb standing tasks with a random assignment to the testing devices. With the lower-cost force platform, the total COP path length displacements were overestimated considerably. As in the validity study by Haas and Burden (2000), a direct comparison of the measurement devices was prevented due to different measure-

Table 1
Congruity (CON) of the trajectories of the medial-lateral (x) and anterior-posterior (y) directions and in different standing conditions between the IBS and the Kistler (KIS) force plates in male and female participants. Values presented as mean (standard deviation, minimum-maximum).

		male (n = 12)	female (n = 12)	P value
NO	CONx []	0.91 (0.02, 0.88–0.95)	0.91 (0.03, 0.84–0.94)	0.58
	CONy []	0.97 (0.01, 0.96–0.98)	0.97 (0.01, 0.94–0.99)	0.54
NC	CONx []	0.92 (0.02, 0.88–0.94)	0.92 (0.03, 0.87–0.96)	1.00
	CONy []	0.98 (0.01, 0.96–1.00)	0.98 (0.01, 0.97–0.99)	0.27
PO	CONx []	0.93 (0.02, 0.88–0.96)	0.93 (0.02, 0.89–0.96)	0.53
	CONy []	0.97 (0.01, 0.95–0.99)	0.98 (0.01, 0.95–0.99)	1.00
PC	CONx []	0.94 (0.03, 0.87–0.96)	0.94 (0.02, 0.91–0.97)	0.40
	CONy []	0.99 (0.01, 0.97–1.00)	0.99 (0.01, 0.98–0.99)	0.75

NO, Normal standing on stable ground with eyes open; NC, Normal standing on stable ground with eyes closed; PO, Standing on soft surface with eyes open; PC, Standing on soft surface with eyes closed; P values are based on Student's unpaired t tests.

Table 2
Explained variance between the path length results of the medial-lateral (x) and anterior-posterior (y) trajectories in four different standing conditions in the IBS and Kistler (KIS) force plates (n = 24) as coefficients of determination (r^2).

		NO	NC	PO	PC	mean
KISx	IBSx	0.93	0.92	0.88	0.94	0.92
KISy	IBSy	0.96	0.94	0.95	0.97	0.96

NO, Normal standing on stable ground with eyes open; NC, Normal standing on stable ground with eyes closed; PO, Standing on soft surface with eyes open; PC, Standing on soft surface with eyes closed.

Table 3
Outcomes of the IBS and KIS force plates in male and female participants during the four different standing conditions as calculated with custom Matlab routines. Values presented as mean (standard deviation, minimum-maximum).

		male (n = 12)	female (n = 12)	P value
NO	WDI [%BM]	4.9 (3.0, 1.3–12.2)	5.5 (2.5, 1.0–8.3)	0.60
	ST [100%BM]	10.0 (1.9, 6.8–13.4)	11.8 (4.3, 7.6–23.0)	0.20
	HEEL [%BM]	47 (11, 26–61)	52 (11, 35–66)	0.23
	LEFT [%BM]	52 (2, 48–54)	49 (3, 43–55)	0.05
	IBSx [%BM]	70 (23, 36–117)	79 (21, 57–130)	0.29
	IBSy [%BM]	162 (31, 114–232)	188 (70, 122–357)	0.26
	KISx [mm]	81 (26, 46–132)	88 (20, 66–132)	0.46
	KISy [mm]	122 (24, 88–177)	129 (46, 89–246)	0.60
NC	WDI [%]	5.7 (2.9, 1.2–9.9)	5.1 (2.4, 2.2–10.2)	0.60
	ST [100%BM]	17.1 (5.4, 9.5–26.1)	17.9 (7.4, 7.7–33.6)	0.76
	HEEL [%BM]	46 (11, 33–64)	48 (10, 30–61)	0.69
	LEFT [%BM]	52 (3, 47–58)	49 (3, 43–56)	0.01
	IBSx [%BM]	94 (30, 52–158)	99 (37, 48–173)	0.74
	IBSy [%BM]	293 (101, 164–476)	313 (132, 135–563)	0.69
	KISx [mm]	112 (38, 66–191)	115 (41, 56–211)	0.85
	KISy [mm]	223 (80, 122–373)	212 (82, 101–390)	0.75
PO	WDI [%BM]	6.4 (3.5, 1.9–12.8)	4.9 (2.3, 1.6–9.8)	0.22
	ST [100%BM]	13.0 (3.0, 9.5–18.7)	16.0 (4.4, 10.7–24.5)	0.06
	HEEL [%BM]	40 (9, 25–56)	43 (6, 31–53)	0.33
	LEFT [%BM]	53 (3, 47–56)	51 (4, 46–58)	0.24
	IBSx [%BM]	88 (23, 44–123)	103 (27, 70–149)	0.13
	IBSy [%BM]	215 (61, 141–345)	268 (85, 161–437)	0.09
	KISx [mm]	109 (22, 63–140)	124 (31, 86–181)	0.18
	KISy [mm]	172 (44, 114–269)	197 (60, 121–320)	0.26
PC	WDI [%BM]	5.7 (3.1, 1.8–11.4)	5.4 (2.7, 1.8–9.9)	0.84
	ST [100%BM]	29.8 (11.7, 15.3–60.8)	30.8 (9.5, 18.6–45.2)	0.81
	HEEL [%BM]	43 (10, 28–62)	41 (7, 32–50)	0.67
	LEFT [%BM]	52 (3, 47–60)	51 (3, 46–55)	0.54
	IBSx [%BM]	156 (62, 66–288)	173 (50, 101–260)	0.48
	IBSy [%BM]	527 (225, 286–1141)	546 (182, 331–817)	0.82
	KISx [mm]	195 (77, 86–335)	213 (59, 135–321)	0.53
	KISy [mm]	422 (173, 215–891)	421 (130, 254–599)	0.99

NO, Normal standing on stable ground with eyes open; NC, Normal standing on stable ground with eyes closed; PO, Standing on soft surface with eyes open; PC, Standing on soft surface with eyes closed; WDI, Weight distribution index; ST, Stability index; HEEL, Percentage weight load on heels; LEFT, Percentage weight load on left side; IBSx, path length of the medial-lateral center of pressure trajectory calculated by the IBS; IBSy, path length of the anterior-posterior center of pressure trajectory calculated by the IBS; KISx, path length of the medial-lateral center of pressure trajectory determined by Kistler; KISy, path length of the anterior-posterior center of pressure trajectory determined by Kistler; BM, Body mass; P values are based on Student's unpaired t tests (unadjusted).

ment units. To overcome this limitation and to improve comparability with other investigations, we applied the congruity method and calculated Romberg quotients on the results of both devices. The congruity method is borrowed from analyses of kinematic features of locomotion (Cavagna et al., 1976) and was not applied in comparisons of time series in postural control studies. However, our results clearly demonstrated an excellent agreement between the two devices concerning the directional changes of the COP path. Moreover, the agreement between data collected with both devices was established with difference plots on Romberg quotients which confirmed a very strong agreement with negligible systematic errors. Romberg quotients are typically used to differentiate clinically between patients with sensory impairments. In a previous study where Romberg quotients were applied comparably, the authors found higher mean ratios for the stable and lower mean ratios for the soft surface conditions, respectively (Colledge et al., 1994). Their participants relied more heavily on the presence of vision in the soft surface condition than our participants did. Due to the fact that the dimensions and material properties of the foam pads used had a significant effect on postural control surrogates (Di Berardino et al., 2009), an interpretation of this result is not possible, since the authors did not specify the characteristics of their foam pads. Despite a likely introduced variability, relative reliability of the Romberg quotients was excellent. Further, the anterior-posterior COP path displacement measures obtained showed very high Pearson's correlations. This indicates linearity and consistency of measurement outcomes from the IBS with the KIS. The lowest common explained variance between the COP path length results between both devices was found in the medial-lateral trajectory of the PO standing condition. This suggests that the summed vertical loads of the IBS closely approximate the single multi-dimensional load under the bipedal standing conditions examined.

In this study we examined relatively young, healthy participants. Therefore, it is not possible to transfer these findings to clinical populations, as specific balance impairments were not present in the participants studied. However, testing in healthy subjects to establish validity is warranted before targeting patients. Thus, future studies need to address the validity in different patient populations and examine the sensitivity to change to increase confidence after interventions. To examine the ability of the IBS to judge balance performance during single-leg stance would improve applicability to clinical and rehabilitation settings. Furthermore, future studies should consider comparing the output from the IBS to at least two distinct Kistler force plates as well as different pressure distribution devices.

In conclusion, the results of this study indicate that the IBS provides valid posturographic results. Moreover, the IBS is a simple and clinically feasible option to assess postural control characteristics. Since the medial-lateral and anterior-posterior trajectories of the IBS can be used to calculate COP fluctuations, comparisons between different measurement systems are possible.

Conflict of interest

The authors stated that they had no interests which might be perceived as posing a conflict or bias.

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