Jurnal Kejuruteraan 38(3) 2026: 1379-1395
https://doi.org/10.17576/jkukm-2026-38(3)-29

Validation of Half-Bridge Strain Gauge-based Low-Cost Force Plates in Measuring Vertical Ground Reaction Force and Center of Pressure during Recovery Assessments

Ying Heng Yeo[a], Jia Yi Tay[a], Alexander Wai Teng Tan[a], Nur-Akasyah J.[a], Muhammad Fauzinizam Razali[a,*], Zaidi Mohd Ripin[a], Mohamad Ikhwan Zaini Ridzwan[a], Hazwani Ahmad Yusof[b] & Muhammad Hafiz Hanafi[c]

[a]*Neurorehabilitation Engineering and Assistance Systems Research, School of Mechanical Engineering, Engineering Campus, Universiti Sains Malaysia, Nibong Tebal, Pulau Pinang, Malaysia,*

[b]*Lifestyle Science Cluster, Advanced Medical and Dental Institute, Universiti Sains Malaysia, Kepala Batas, Pulau Pinang, Malaysia,*

[c]*Rehabilitation Medicine Unit, Hospital Universiti Sains Malaysia, Kubang Kerian, Kelantan, Malaysia*

[*]*Corresponding author: mefauzinizam@usm.my*

Received 19 June 2025, Received in revised form 28 January 2026
Accepted 28 February 2026, Available online 30 May 2026

ABSTRACT

Low-cost force plate could potentially be used as a measurement system for recovery assessments. However, its validity in acquiring vertical ground reaction force (GRF) and center of pressure (CoP) obtained during recovery assessments must be validated first. This study aimed to validate the vertical GRF and CoP measurement with half-bridge strain gauge-based low-cost force plates during Berg Balance Scale (BBS) and Trunk Impairment Scale (TIS) assessments. Ten elderly and 13 stroke patients were recruited to perform BBS, TIS assessments, maximal trunk flexion, extension, and lateral bending on low-cost force plates. The vertical GRF and CoP readings were validated with Pearson correlation coefficient (ρ) and intraclass correlation coefficient [ICC (2, 1)] of more than 0.773 and 0.752 respectively except for anterior-posterior CoP readings acquired during TIS task to touch seat with healthy elbow. All CoP-derived metrics were validated with $\rho > 0.903$ and $ICC(2,1) > 0.855$, indicating high consistency and linearity. These findings confirm that the low-cost force plates were sufficiently accurate for measuring vertical GRF and CoP across TIS, BBS and other assessments tasks. As such, the low-cost force plate can be considered a viable, cost-effective alternative for integration into clinical and rehabilitation settings to support recovery evaluation, especially in scenarios where high-cost laboratory systems are impractical.

Keywords: Force plate; validation; ground reaction force; center of pressure; recovery assessment

INTRODUCTION

Recovery assessments such as Berg Balance Scale (BBS) (Berg et al. 1992), Trunk Impairment Scale (TIS) (Verheyden and Kersten 2010), and others are important in evaluating the subject ability to perform simple movements or functional tasks. The assessments are helpful in scenarios such as determining whether a stroke patient is able to carry out activities of daily living independently. These assessments involve a considerable number of tasks. The scoring criteria are different for each task, making them difficult to evaluate by a lay person. Human error may occur, especially when the scoring criteria are difficult to detect by naked eye.

To reduce the difficulty in conducting recovery assessments, a measurement system can be developed with the application of a force plate. The measurement system works by collecting vertical ground reaction force (GRF) (Hong et al. 2016) or center of pressure (CoP) (Bartlett, Ting and Bingham 2014) readings and computing the assessment score from these inputs. Force plate-based measurement system is still in its infancy, where only a few works are dedicated to the development in evaluating assessments such as BBS and TIS (Gallicchio et al. 2016; Bacciu et al. 2017; Sawacha et al. 2013; Mitteregger et al. 2015; Näf et al. 2020; Bruyneel et al. 2022). These studies indicate the potential of force plates in the development of recovery assessment measurement systems.

Several previous works apply machine learning models to predict the recovery assessment scores (Gallicchio et al. 2016; Bacciu et al. 2017; Eichler et al. 2022; Kim et al. 2020; Kim et al. 2021; Yu et al. 2016). Machine learning models require a large amount of data to be trained in order to perform accurate predictions. It is impractical to use expensive laboratory-grade force plates which cost between $10,000 to $20,000 to perform large scale data collection (Mahoney, Wilkinson and Cusumano 2016; Saadprai et al. 2021; Malla et al. 2024). This warrants the need for low-cost force plates. Moreover, with a less price, the low-cost force plate will be more affordable for application in clinical or rehabilitation facilities.

There are a few commercialized low-cost force plates which can be considered in developing a recovery assessment measurement system. However, most commercialized low-cost force plates are not validated comprehensively to measure vertical GRF and CoP during recovery assessments. Some of the low-cost force plates have undergone validation on tasks such as sit-to-stand or stand-to-sit (Abujaber et al. 2015), standing (Clark et al. 2010a; Chang et al. 2014; Scaglioni-Solano and Aragón-Vargas 2014; Weaver, Ma and Laing 2017; Severini et al. 2017; Levy, Thralls and Kviatkovsky 2018; Richmond et al. 2018; Golriz et al. 2012), reaching (Verdini et al. 2019), and squatting (Mengarelli et al. 2018). However, recovery assessments like BBS can involve more tasks including sitting, pivot transfer, taking object from floor, and looking behind, to mention a few. To develop an accurate recovery assessment measurement system, the measurement of vertical GRF and CoP of low-cost force plate during the recovery assessments must be validated.

This study addresses the gap in accessible and cost-effective tools for objective recovery assessment by developing and validating low-cost force plates for clinical use. While laboratory-grade force plates are widely used in research settings, their high cost and limited availability restrict their use in routine clinical practice and large-scale data collection. To overcome this limitation, this study proposes a scalable solution using half-bridge strain gauge load cells, chosen for their affordability and compact size. The developed low-cost force plates are used to capture vertical GRF and CoP data during recovery assessments conducted with elderly and stroke patients. These readings are validated against those from laboratory-grade force plates. This study focuses on two widely used clinical assessments, namely the BBS and the TIS. By confirming the accuracy of the low-cost force plates, this work lays the foundation for their integration into rehabilitation and clinical settings, enabling wider deployment of objective, data-driven recovery monitoring systems at a fraction of the cost.

METHODOLOGY

SUBJECTS

Subject sample size was determined using a technique established in prior research (Arifin, 2018; Bonett, 2002) to obtain intraclass correlation coefficient (ICC) with ±0.02 precision. Based on a comparable previous work focusing on the validity of Nintendo Wii Balance Board in acquiring sit-to-stand vertical GRF (Abujaber et al. 2015), the anticipated ICC was taken as 0.98. Considering a 95% confidence interval and two raters (low-cost and laboratory-grade force plates), a minimum sample size of 17 was needed. Elderly and stroke patients were enrolled to perform the experiment. The inclusion criteria of elderly included:

1. Age of more than or equal to 65 years old.
2. Ability to understand and carry out simple instructions where Mini Mental State Examination (MMSE) was higher than 21.
3. Ability to maintain a stable sitting position.
4. Ability to communicate.
5. Absence of diseases which could interfere with the experiment.

On the other hand, the inclusion criteria of stroke patients were:

1. Age of more than or equal to 18 years old.
2. Time from stroke onset of more than one month.
3. Suffering from stroke, whether cortical or subcortical, ischemic or haemorrhagic.
4. Medical Research Council Scale for lower extremities of less than or equal to three.
5. Modified Rankin Scale between three to four.
6. Ability to understand and carry out simple instructions where MMSE was higher than 21.
7. Not having history of orthopedic disease or other neurological disorder.
8. Not suffering from dementia.
9. Ability to maintain a stable sitting position.
10. Stable hemodynamic state.
11. Ability to communicate.
12. Absence of diseases which could interfere with the experiment.

A total of 23 subjects were recruited in this study which was approved by Universiti Sains Malaysia Ethics Committee under the protocol code USM/JEPeM/22120824. Elderly and stroke patients were included together in this validation study to reflect a broader range of balance and postural control impairments commonly encountered in clinical rehabilitation. The inclusion of both groups was intended to evaluate the performance of the low-cost force plates across a spectrum of recovery assessment scenarios. All the subjects provided written informed consent before taking part in the experiment. The subject information is shown in Table 1.

TABLE 1. Subject information of the elderly.

Subject	Information	Value
Elderly	Gender (male / female)	4 / 6
	Age (year, mean ± standard deviation)	67.30 ± 2.67
	Height (cm, mean ± standard deviation)	160.10 ± 7.38
	Weight (kg, mean ± standard deviation)	65.15 ± 10.22
Stroke patient	Gender (male / female)	7 / 6
	Age (year, mean ± standard deviation)	47.69 ± 8.17
	Height (cm, mean ± standard deviation)	163.38 ± 9.08
	Weight (kg, mean ± standard deviation)	64.92 ± 13.50
	Type of stroke (ischemic / haemorrhagic)	7 / 6
	Side of affected limb (left / right / both)	9 / 3 / 1
	Time from stroke onset (days, mean ± standard deviation)	246 ± 182

APPARATUS

Two same low-cost force plates were developed and used in this research. They were exempted from medical device registration via Medical Device Authority, Ministry of Health Malaysia, under protocol number FS-GMD-20230308-4. Their dimensions were 0.6 m × 0.4 m × 0.049 m and they included an ESP32 microcontroller, four half-bridge strain gauge load cells, and four HX711 analogue-to-digital converters. The half-bridge strain gauge load cells were similar to that applied in digital bathroom scales which were cheap, small, and widely available. These components provided a sampling rate of 80 Hz and a resolution of 0.0002 N. The sampling rate was suitable for capturing readings resulted from human movements with frequencies below 20 Hz (Khusainov et al. 2013). Each load cell had a capacity of 45 kg, allowing the low-cost force plates to handle a maximum load of 180 kg. The fabrication cost of a low-cost force plate was only around $50. Figure 1 illustrates the low-cost force plates viewed from top and bottom. One-point calibration was implemented on each load cell in low-cost force plates by using a 25 kg weight. To validate the low-cost force plates, two 4060-05 Bertec force plates were employed as laboratory-grade benchmarks. Each Bertec force plate had dimensions of 0.6 m × 0.4 m × 0.05 m.

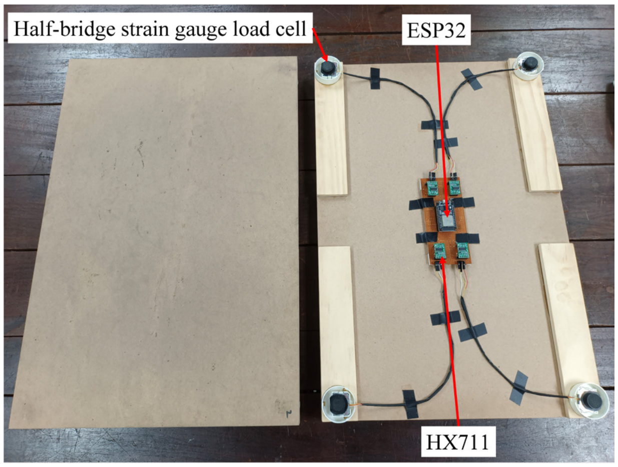

FIGURE 1. The top (left) and bottom (right) views of low-cost force plates.

Figure 2 shows the forces acting on the low-cost and Bertec force plates with free-body diagrams. To simplify comparison, the axes of low-cost and Bertec force plates were oriented in the same directions, with the center point of the low-cost force plate top surface serving as the axis origin. As the load cells were incapable of acquiring bilateral GRF (Horsak et al. 2020; Idrisa et al. 2025), only vertical GRF was analyzed in the free-body diagram of low-cost force plate.

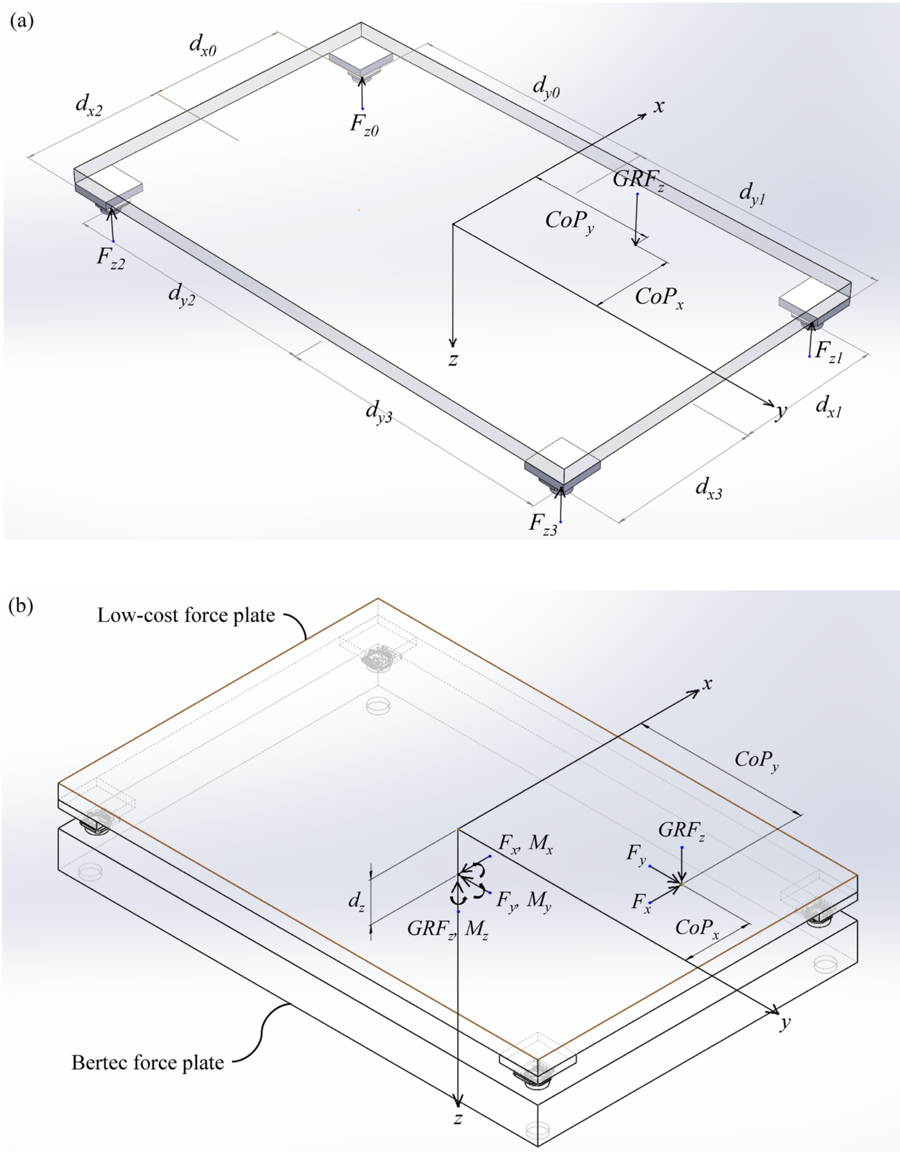

FIGURE 2. (a) Free body diagram of low-cost force plate. (b) Free body diagram of Bertec force plate with low-cost force plate stacked on it.

According to Figure 2, Equations 1 to 3 can be derived to calculate vertical GRF and CoP,

$$GRF_z = F_{z0} + F_{z1} + F_{z2} + F_{z3} \tag{1}$$

$$CoP_x = \frac{F_{z0} \cdot d_{x0} + F_{z1} \cdot d_{x1} - F_{z2} \cdot d_{x2} - F_{z3} \cdot d_{x3}}{GRF_z} \tag{2}$$

$$CoP_y = \frac{-F_{z0} \cdot d_{y0} + F_{z1} \cdot d_{y1} - F_{z2} \cdot d_{y2} + F_{z3} \cdot d_{y3}}{GRF_z} \tag{3}$$

where GRF_z is the vertical GRF, F_z is the vertical GRF exerted on individual load cell, CoP_x is the anterior-posterior CoP, d_x is the distance between load cell and origin in the anterior-posterior direction, CoP_y is the mediolateral CoP, and d_y is the distance between load cell and origin in the mediolateral direction. Equations 4 and 5 are used to calculate the CoP of Bertec force plate,

$$CoP_x = \frac{-M_y - F_x \cdot d_z}{GRF_z} \tag{4}$$

$$CoP_y = \frac{M_x - F_y \cdot d_z}{GRF_z} \tag{5}$$

in which M_y is the moment in mediolateral direction, F_x is the GRF in anterior-posterior direction, d_z is the vertical distance from low-cost force plate top surface to

Bertec force plate top surface, M_x is the moment in anterior-posterior direction, and F_y is the GRF in mediolateral direction.

VALIDITY ASSESSMENT

Prior to the validity assessment, the instruments were set up as illustrated in Figure 3. Each low-cost force plate was stacked on a Bertec force plate. A stacked force plate set was put on a chair while another was placed on the floor in front of the chair. The stacked force plates placed on chair were used to collect the vertical GRF and CoP readings generated by the force exertion with pelvis while the stacked force plates placed on floor recorded the readings due to the force exertion by feet.

All experiments were conducted in a stable laboratory setting with limited external disturbances. To minimize the effects of floor vibrations, the force plates placed on the ground were installed on firm, level surfaces, and soft padding was used both for height adjustment and to absorb minor vibrations. Subjects were instructed to minimize extraneous movements during static tasks, and any trials affected by instability or artifacts were repeated. These measures helped ensure that the impact of environmental noise and floor vibrations on measurement accuracy was negligible.

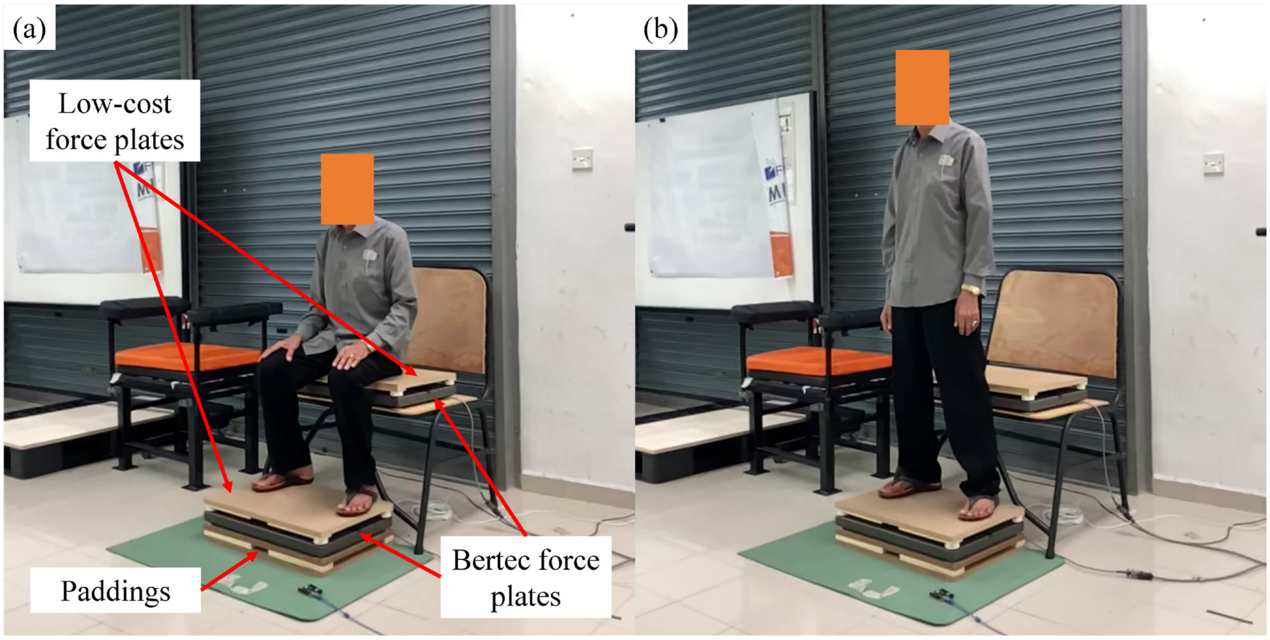

FIGURE 3. Apparatus setup for validity assessment. The subject is performing sitting task in (a) and standing task in (b).

Validity assessment was conducted to validate the vertical GRF and CoP reading measurement of the low-cost force plates during BBS and TIS assessments. The subjects are required to perform 14 BBS tasks on the setup as shown in Figure 3. Table 2 lists the summary of BBS tasks, where the detailed procedures and scoring criteria are based on the previous work (Berg et al. 1992).

TABLE 2. Summary of BBS tasks

BBS task	Description	Force plates involved	
		Chair	Floor
1	Sit-to-stand	✓	✓
2	Standing		✓
3	Sitting	✓	✓
4	Stand-to-sit	✓	✓
5	Pivot transfer	✓	✓
6	Standing with eyes closed		✓

continue...

...cont.

BBS task	Description	Force plates involved	
		Chair	Floor
7	Standing with feet closed to each other		✓
8	Reaching		✓
9	Taking object from floor		✓
10	Looking behind		✓
11	Turning for 360 degrees		✓
12	Placing foot on stool alternatively		✓
13	Tandem stance		✓
14	Standing on one foot		✓

Next, the subjects underwent TIS assessment, specifically TIS 2.0. The assessment consists of 10 tasks which evaluate dynamic sitting balance and four tasks that assess coordination as tabulated in Table 3. The comprehensive TIS methodology and scoring criteria were implemented according to the previous study (Verheyden and Kersten, 2010). All TIS tasks involved both stacked force plates located on chair and floor. Even though TIS was specifically designed for stroke patient, the tasks were performed by elderly as well as the elderly could suffer from deterioration in trunk muscle (Sasaki et al. 2018). For elderly, the healthy body parts stated in Table 3 refer to the body parts at dominant side while hemiplegic body parts refer to the opposite counterparts.

TABLE 3. Summary of TIS tasks

Evaluated ability	TIS task	Description
Dynamic sitting balance	1	Touching seat surface with hemiplegic elbow
	2	Repeating task 1
	3	Repeating task 1
	4	Touching seat surface with healthy elbow
	5	Repeating task 4
	6	Repeating task 4
	7	Lifting hemiplegic pelvis
	8	Repeating task 7
	9	Lifting healthy pelvis
	10	Repeating task 9
Coordination	11	Rotating upper trunk
	12	Rotating upper trunk in six seconds
	13	Rotating lower trunk
	14	Rotating lower trunk in six seconds

Furthermore, the subjects were requested to carry out additional tasks including maximal trunk flexion, extension, and lateral bending as the CoP-derived metrics obtained during the tasks were found to be correlated to TIS score (Näf et al. 2020). During the tasks, vertical GRF readings were recorded from each low-cost force plate load cell while three-dimensional GRF and moment readings were obtained from Bertec force plates.

DATA PRE-PROCESSING

The low-cost force plate vertical GRF readings were gathered at a rate of 80 Hz, which was the HX711 sampling frequency. Sudden spikes in readings were removed by utilizing median filter with a kernel size of five. For static tasks such as BBS task 2, 3, 6, and 7, the readings underwent a zero-phase, fourth-order, low-pass Butterworth filter with a critical frequency of 5 Hz (Prieto et al. 1996). Besides, similar filter with cut-off frequency of 10 Hz was applied on readings obtained during BBS task 13 and 14 (Clark et al. 2010b). The cut-off frequency was slightly higher than that for static tasks even though BBS task 13 and 14 only involved standing. This was because the two tasks were susceptible to relatively dynamic response due to the subject attempt to maintain balance under unstable postures. For the low-cost force plate vertical GRF readings collected during other tasks, low-pass filter was not applied. Equation 1 to 3 were used to compute the vertical GRF and CoP. The CoP readings were deducted by the mean value of CoP computed from the trial readings (Prieto et al. 1996). If vertical GRF was lower than 20 N, the CoP was adjusted to zero via the assumption that there was no subject on the force plate.

Bertec force plate data including three-dimensional GRF and moments were sampled at 500 Hz, the device default sampling rate after anti-aliasing filter was implemented. Similar to low-cost force plate, the data acquired during BBS tasks 2, 3, 6, 7, 13, and 14 were low-pass filtered. For other tasks, the same low-pass filter was utilized with the critical frequency fixed as 40 Hz, which was half of the low-cost force plate sampling rate. CoP was determined using Equations 4 and 5, with the trial mean subtracted from the CoP values. Again, when the vertical GRF was smaller than 20 N, CoP values were set to zero. The vertical GRF and CoP values were interpolated to match the timestamps of low-cost force plate readings.

STATISTICAL ANALYSIS

To evaluate the validity of low-cost force plate in measuring vertical GRF and CoP, the root mean square error (RMSE) (Oh, Choi and Mun, 2013) between the low-cost and Bertec force plate readings was computed. The magnitude of RMSE represents the degree of deviation from actual readings obtained from Bertec force plates. Prior to RMSE calculation, vertical GRF readings were normalized to unit of body weight percentage (%BW) via division with subject weight followed by multiplication of 100 (Jung et al. 2016).

Linearity between low-cost and Bertec force plate readings was assessed with Pearson correlation coefficient (ρ) (Cohen et al. 2009). Value of ρ was categorized as "very weak" (< 0.2), "weak" (0.2-0.4), "moderate" (0.4-0.7), "strong" (0.7-0.9), or "very strong" (> 0.9) (Learner and Goodman, 1996). ICC (2, 1) was employed to gauge the absolute agreement between the readings, in which the value was classified as "poor" (< 0.5), "moderate" (0.5-0.75), "good" (0.75-0.9), or "excellent" (> 0.9) (Koo and Li, 2016). In calculating ICC (2, 1), two-way mixed-effects model was used. The type was set as single rater and the definition was fixed as absolute agreement. The low-cost force plate vertical GRF and CoP measurements were deemed valid if ρ exceeded 0.7 and ICC (2, 1) surpassed 0.75. The ranges of values indicated good or excellent linear relationship and absolute agreement between the force plate values.

Several metrics that were correlated to the recovery progress such as the ability to maintain balance were derived from CoP for validation purpose. For static standing and sitting BBS task 2, 6, 7, 13, and 14 metrics such as 95% confidence ellipse area, mean CoP distance, mean CoP velocity, root mean square (RMS) distance, sway area, and total CoP path were calculated (Prieto et al. 1996). Moreover, the CoP range in the anterior-posterior direction was calculated for maximal trunk flexion and extension while mediolateral CoP range was computed for maximal trunk lateral bending (Näf et al. 2020). Similarly, the CoP-derived metrics of low-cost and Bertec force plate were compared and validated by using RMSE, ρ, and ICC (2, 1).

RESULTS

Table 4 lists the validity evaluation metrics obtained by comparing the readings recorded from the low-cost and Bertec force plates placed on chair recorded during BBS assessment. Only the results of four tasks were shown as other BBS tasks did not involve interaction with force plates placed on chair. The RMSE ranged from 2.38 %BW to 3.05 %BW for vertical GRF and 0.57 mm to 24.74 mm for CoP. Values of ρ and ICC (2, 1) respectively ranged from 0.888 to 0.999 and 0.885 to 0.998. All the readings were validated with ρ of more than 0.7 and ICC (2, 1) of more than 0.75.

TABLE 4. RMSE, ρ, and ICC (2, 1) achieved by low-cost force plate placed on chair in measuring vertical GRF and CoP during BBS assessment. The acronym "AP" represents anterior-posterior while "ML" means mediolateral.

Task	Readings	RMSE	ρ	ICC (2, 1)
	AP CoP (mm)	16.18	0.942	0.942
1	ML CoP (mm)	24.74	0.888	0.885
	Vertical GRF (%BW)	3.05	0.998	0.997
	AP CoP (mm)	0.57	0.971	0.969
3	ML CoP (mm)	0.86	0.957	0.957
	Vertical GRF (%BW)	2.97	0.997	0.983
	AP CoP (mm)	9.26	0.973	0.971
4	ML CoP (mm)	13.46	0.960	0.959
	Vertical GRF (%BW)	2.38	0.999	0.998
	AP CoP (mm)	10.15	0.965	0.964
5	ML CoP (mm)	12.21	0.970	0.969
	Vertical GRF (%BW)	2.61	0.998	0.997

The RMSE, ρ, and ICC (2, 1) obtained between readings of low-cost and Bertec force plates placed on floor during BBS assessment are tabulated in Table 5. The lowest and highest RMSE recorded for vertical GRF were 1.69 %BW and 6.14 %BW respectively. The range of RMSE for CoP was 0.71 mm to 34.33 mm. Besides, the ranges of ρ and ICC (2, 1) were 0.806 to 0.999 and 0.797 to 0.999. All readings obtained with low-cost force plate located on floor during BBS assessment were validated with ρ and ICC (2, 1) of higher than 0.7 and 0.75 respectively.

TABLE 5. RMSE, ρ, and ICC (2, 1) achieved by low-cost force plate located on floor in measuring vertical GRF and CoP during BBS assessment. The acronym "AP" represents anterior-posterior while "ML" means mediolateral.

Task	Readings	RMSE	ρ	ICC (2, 1)
	AP CoP (mm)	4.65	0.993	0.993
1	ML CoP (mm)	7.81	0.989	0.983
	Vertical GRF (%BW)	2.45	0.998	0.998
	AP CoP (mm)	0.88	0.991	0.991
2	ML CoP (mm)	0.97	0.991	0.991
	Vertical GRF (%BW)	4.52	0.967	0.954
	AP CoP (mm)	1.36	0.958	0.958
3	ML CoP (mm)	3.82	0.806	0.797
	Vertical GRF (%BW)	1.69	0.957	0.948
	AP CoP (mm)	6.94	0.964	0.959
4	ML CoP (mm)	6.45	0.985	0.978
	Vertical GRF (%BW)	4.56	0.992	0.990
	AP CoP (mm)	9.08	0.988	0.988
5	ML CoP (mm)	34.33	0.940	0.933
	Vertical GRF (%BW)	2.75	0.997	0.997
	AP CoP (mm)	0.82	0.995	0.994
6	ML CoP (mm)	0.71	0.994	0.994
	Vertical GRF (%BW)	4.67	0.967	0.953
	AP CoP (mm)	1.12	0.987	0.986
7	ML CoP (mm)	0.95	0.991	0.991
	Vertical GRF (%BW)	5.67	0.948	0.932
	AP CoP (mm)	1.04	0.999	0.999
8	ML CoP (mm)	1.05	0.996	0.996
	Vertical GRF (%BW)	4.66	0.966	0.959

continue...

...cont.

Task	Readings	RMSE	ρ	ICC (2, 1)
	AP CoP (mm)	1.31	0.997	0.997
9	ML CoP (mm)	2.20	0.991	0.991
	Vertical GRF (%BW)	6.14	0.947	0.930
	AP CoP (mm)	1.44	0.997	0.997
10	ML CoP (mm)	1.67	0.996	0.996
	Vertical GRF (%BW)	5.87	0.950	0.935
	AP CoP (mm)	1.96	0.999	0.999
11	ML CoP (mm)	2.72	0.999	0.999
	Vertical GRF (%BW)	2.84	0.984	0.983
	AP CoP (mm)	2.58	0.996	0.996
12	ML CoP (mm)	4.74	0.998	0.998
	Vertical GRF (%BW)	5.37	0.970	0.964
	AP CoP (mm)	0.84	0.996	0.996
13	ML CoP (mm)	0.93	0.996	0.996
	Vertical GRF (%BW)	5.04	0.961	0.951
	AP CoP (mm)	1.81	0.994	0.993
14	ML CoP (mm)	2.45	0.998	0.998
	Vertical GRF (%BW)	4.88	0.962	0.957

According to Table 6, the RMSE for vertical GRF recorded from force plates placed on chair during TIS assessment span from 3.30 %BW to 4.25 %BW while for CoP, the RMSE vary from 1.01 mm to 2.2 mm. The metrics ρ and ICC (2, 1) differed from 0.978 to 0.999 and 0.970 to 0.999 respectively. Thus, all readings recorded with low-cost force plate placed on chair during TIS assessment were validated with ρ and ICC (2, 1) of more than 0.7, and 0.75 respectively.

TABLE 6. RMSE, ρ, and ICC (2, 1) achieved by low-cost force plate placed on chair in measuring vertical GRF and CoP during TIS assessment. The acronym "AP" represents anterior-posterior while "ML" means mediolateral.

Task	Readings	RMSE	ρ	ICC (2, 1)
	AP CoP (mm)	1.63	0.992	0.992
1	ML CoP (mm)	1.84	0.999	0.999
	Vertical GRF (%BW)	3.30	0.998	0.984
	AP CoP (mm)	1.28	0.995	0.995
2	ML CoP (mm)	2.12	0.999	0.999
	Vertical GRF (%BW)	3.30	0.997	0.985
	AP CoP (mm)	1.45	0.994	0.994
3	ML CoP (mm)	2.20	0.999	0.998
	Vertical GRF (%BW)	3.38	0.997	0.985
	AP CoP (mm)	1.06	0.998	0.998
4	ML CoP (mm)	1.79	0.999	0.999
	Vertical GRF (%BW)	3.31	0.996	0.980
	AP CoP (mm)	1.09	0.998	0.998
5	ML CoP (mm)	1.87	0.999	0.999
	Vertical GRF (%BW)	3.36	0.997	0.981
	AP CoP (mm)	1.25	0.997	0.997
6	ML CoP (mm)	1.86	0.999	0.999
	Vertical GRF (%BW)	3.34	0.997	0.981

continue...

...cont.

Task	Readings	RMSE	ρ	ICC (2, 1)
	AP CoP (mm)	1.32	0.995	0.995
7	ML CoP (mm)	1.76	0.999	0.999
	Vertical GRF (%BW)	3.49	0.997	0.982
	AP CoP (mm)	1.43	0.994	0.994
8	ML CoP (mm)	1.55	0.999	0.999
	Vertical GRF (%BW)	3.58	0.997	0.977
	AP CoP (mm)	1.17	0.991	0.990
9	ML CoP (mm)	1.80	0.999	0.999
	Vertical GRF (%BW)	3.62	0.997	0.980
	AP CoP (mm)	1.18	0.990	0.990
10	ML CoP (mm)	1.74	0.999	0.999
	Vertical GRF (%BW)	3.66	0.997	0.978
	AP CoP (mm)	1.01	0.987	0.986
11	ML CoP (mm)	1.63	0.978	0.978
	Vertical GRF (%BW)	3.81	0.997	0.979
	AP CoP (mm)	1.02	0.991	0.990
12	ML CoP (mm)	1.58	0.989	0.988
	Vertical GRF (%BW)	4.03	0.996	0.975
	AP CoP (mm)	1.76	0.992	0.990
13	ML CoP (mm)	2.02	0.990	0.990
	Vertical GRF (%BW)	4.23	0.996	0.970
	AP CoP (mm)	2.11	0.992	0.990
14	ML CoP (mm)	1.98	0.993	0.993
	Vertical GRF (%BW)	4.25	0.995	0.970

RMSE calculated from low-cost and Bertec force plate vertical GRF readings on floor during TIS assessment vary from 1.81 %BW to 2.55 %BW based on Table 7. In addition, a range of 3.86 mm to 11.76 mm was achieved for RMSE of CoP. Values of 0.753 to 0.986 and 0.724 to 0.985 were obtained for ρ and ICC (2, 1) respectively. The anterior-posterior CoP readings acquired during TIS task 4 which corresponded to touch seat surface with healthy elbow were not validated with ICC (2, 1) less than 0.75. The lower ICC observed for the anterior-posterior CoP readings during TIS task 4 is likely due to asymmetrical loading on the force plate. The uneven force distribution across the load cells in this task may have affected the low-cost system's ability to accurately capture CoP shifts, introducing variability in the estimation and reducing agreement with the laboratory-grade force plate. Apart from this reading, the validity of other readings was justified.

TABLE 7. RMSE, ρ, and ICC (2, 1) achieved by low-cost force plate located on floor in measuring vertical GRF and CoP during TIS assessment. The acronym "AP" represents anterior-posterior while "ML" means mediolateral.

Task	Readings	RMSE	ρ	ICC (2, 1)
	AP CoP (mm)	6.27	0.960	0.960
1	ML CoP (mm)	9.50	0.977	0.974
	Vertical GRF (%BW)	1.81	0.975	0.971
	AP CoP (mm)	6.01	0.960	0.960
2	ML CoP (mm)	8.42	0.981	0.976
	Vertical GRF (%BW)	2.03	0.969	0.964
	AP CoP (mm)	5.17	0.967	0.967
3	ML CoP (mm)	7.63	0.979	0.976
	Vertical GRF (%BW)	2.14	0.976	0.969

continue...

...cont.

Task	Readings	RMSE	ρ	ICC (2, 1)
	AP CoP (mm)	10.62	0.753	0.724
4	ML CoP (mm)	11.36	0.944	0.942
	Vertical GRF (%BW)	1.96	0.984	0.979
	AP CoP (mm)	9.63	0.798	0.780
5	ML CoP (mm)	11.56	0.930	0.928
	Vertical GRF (%BW)	2.01	0.983	0.978
	AP CoP (mm)	9.82	0.798	0.775
6	ML CoP (mm)	11.76	0.939	0.936
	Vertical GRF (%BW)	2.03	0.984	0.980
	AP CoP (mm)	5.13	0.961	0.961
7	ML CoP (mm)	5.56	0.986	0.985
	Vertical GRF (%BW)	2.15	0.975	0.966
	AP CoP (mm)	4.96	0.962	0.961
8	ML CoP (mm)	5.25	0.985	0.984
	Vertical GRF (%BW)	2.20	0.979	0.970
	AP CoP (mm)	5.67	0.974	0.974
9	ML CoP (mm)	6.50	0.981	0.980
	Vertical GRF (%BW)	2.26	0.973	0.961
	AP CoP (mm)	4.60	0.980	0.979
10	ML CoP (mm)	6.22	0.978	0.977
	Vertical GRF (%BW)	2.20	0.980	0.966
	AP CoP (mm)	3.86	0.946	0.946
11	ML CoP (mm)	4.19	0.958	0.956
	Vertical GRF (%BW)	2.26	0.971	0.959
	AP CoP (mm)	4.54	0.933	0.933
12	ML CoP (mm)	4.69	0.962	0.960
	Vertical GRF (%BW)	2.46	0.961	0.941
	AP CoP (mm)	6.37	0.941	0.939
13	ML CoP (mm)	7.97	0.972	0.968
	Vertical GRF (%BW)	2.54	0.972	0.948
	AP CoP (mm)	6.78	0.934	0.931
14	ML CoP (mm)	8.34	0.966	0.962
	Vertical GRF (%BW)	2.55	0.967	0.943

Table 8 shows the validity results of vertical GRF and CoP readings measured during maximal trunk flexion, extension, and lateral bending. The RMSE for vertical GRF and CoP differed from 1.45 %BW to 3.28 %BW and 1.55 mm to 16.70 mm respectively. The values of ρ and ICC (2, 1) spanned from 0.773 to 0.998 and 0.752 to 0.998 respectively. The readings were validated with ρ greater than 0.7 and ICC (2, 1) higher than 0.75.

TABLE 8. RMSE, ρ, and ICC (2, 1) achieved by low-cost force plates in measuring vertical GRF and CoP during maximal trunk flexion, extension, and lateral bending. The acronym "AP" represents anterior-posterior while "ML" means mediolateral.

Task	Force plate position	Readings	RMSE	ρ	ICC (2, 1)
Maximal trunk flexion and extension	Chair	AP CoP (mm)	2.92	0.996	0.996
		ML CoP (mm)	3.32	0.870	0.867
		Vertical GRF (%BW)	3.22	0.998	0.987
	Floor	AP CoP (mm)	11.26	0.862	0.862
		ML CoP (mm)	16.70	0.773	0.752
		Vertical GRF (%BW)	1.54	0.993	0.993
Maximal trunk lateral bending	Chair	AP CoP (mm)	1.55	0.988	0.988
		ML CoP (mm)	2.79	0.998	0.998
		Vertical GRF (%BW)	3.28	0.997	0.984
	Floor	AP CoP (mm)	2.63	0.982	0.980
		ML CoP (mm)	8.43	0.978	0.977
		Vertical GRF (%BW)	1.45	0.978	0.976

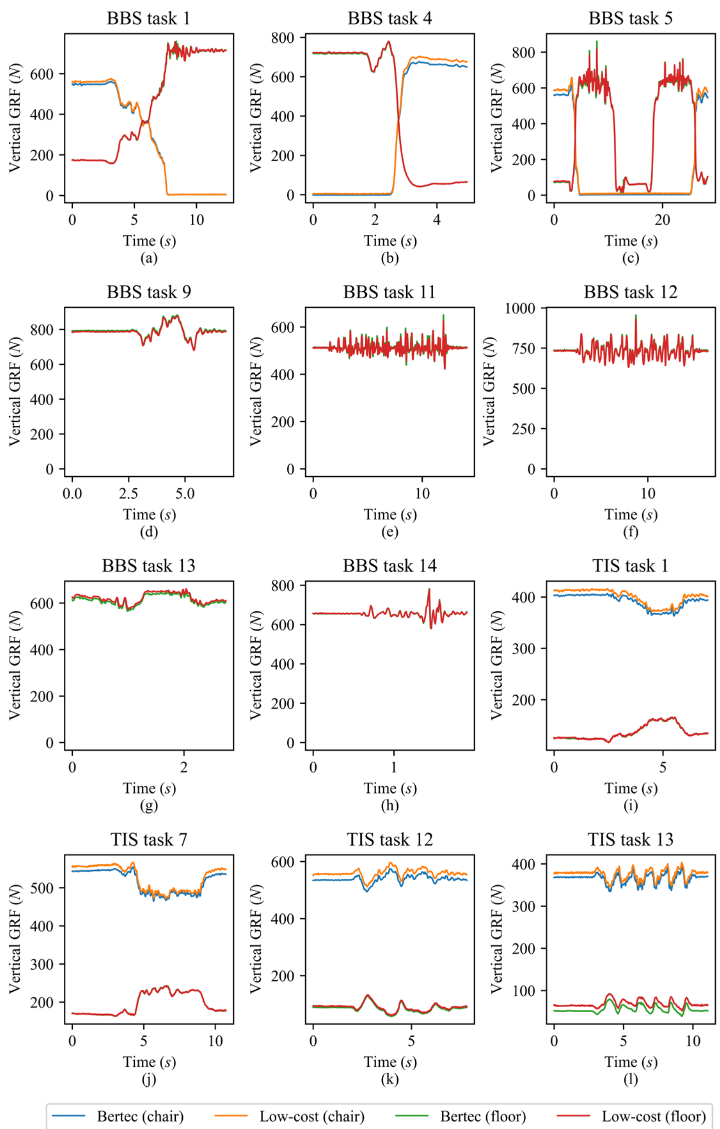

FIGURE 4. Graphs of vertical GRF versus time for different tasks that involve observable changes in vertical GRF. Only a trial is selected randomly to be displayed for each task.

Graphs of vertical GRF against time are plotted in Figure 4 to inspect the fitting of low-cost force plate readings to that of Bertec force plate. Only the tasks that involved noticeable changes in vertical GRF were selected to draw the plots for the purpose of visualization. For the tasks which were repeated, for example TIS task 1 to 6, only one task was selected. The readings plotted were chosen randomly from the trials performed by all subjects. It could be observed that most vertical GRF readings of low-cost force plates overlapped with the counterparts of Bertec force plates. This indicated the acceptable accuracy of low-cost force plates in measuring vertical GRF. Task 1, 4, and 5 showed large changes in readings as the tasks involved weight shifting between force plates located on chair and floor, while others did not.

Figure 5 depicts the CoP paths measured by the force plates when the subjects perform different tasks from TIS and BBS assessment. Only the readings from tasks which did not involve an absence of vertical GRF on the force plates were selected for visualization purpose. The tasks in which load (subject) could be absence were deemed less important because the absence of load (subject) caused zero CoP value. The zero CoP value was not helpful in assessing or predicting the health or recovery conditions. In overall, the CoP paths acquired by low-cost force plates fitted closely to that of Bertec force plates. Notably, the scales of axes could be varied for different tasks, where BBS task 11, turning for 360 degrees recorded the largest CoP displacement while BBS task 3, sitting recorded the smallest displacement.

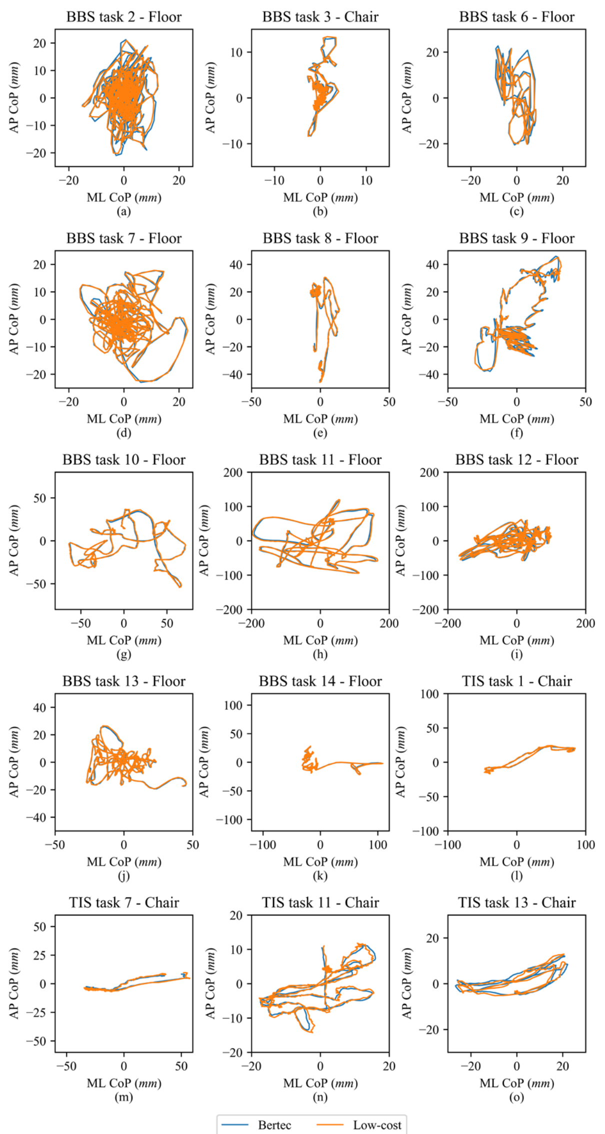

FIGURE 5. CoP paths for different tasks where the path is not discontinued due to vertical GRF exertion. Only a trial is selected randomly to be displayed for each task. The acronym "AP" represents anterior-posterior while "ML" means mediolateral.

The validity results of CoP-derived metrics are summarized in Table 9. It could be observed that ρ spanned from 0.903 to 0.998 while ICC (2, 1) varied from 0.855 to 0.997. All the CoP-derived metrics were validated with ρ higher than 0.7 and ICC (2, 1) higher than 0.75.

TABLE 9. RMSE, ρ, and ICC (2, 1) achieved by low-cost force plate in measuring CoP-derived metrics.

Task (force plate position)	CoP derived metrics	RMSE	ρ	ICC (2, 1)
BBS task 2 (floor)	95% confidence ellipse area (mm^2)	87.26	0.997	0.997
	Mean CoP distance (mm)	0.33	0.997	0.997
	Mean CoP velocity ($mm\ s^{-1}$)	1.49	0.994	0.985
	RMS distance (mm)	0.41	0.997	0.997
	Sway area ($mm^2\ s^{-1}$)	7.75	0.995	0.993
	Total CoP path (mm)	163.87	0.994	0.985
BBS task 6 (floor)	95% confidence ellipse area (mm^2)	78.60	0.997	0.997
	Mean CoP distance (mm)	0.28	0.998	0.997
	Mean CoP velocity ($mm\ s^{-1}$)	3.58	0.973	0.945
	RMS distance (mm)	0.38	0.997	0.996
	Sway area ($mm^2\ s^{-1}$)	12.05	0.992	0.987
	Total CoP path (mm)	37.92	0.984	0.961
BBS task 7 (floor)	95% confidence ellipse area (mm^2)	179.91	0.946	0.918
	Mean CoP distance (mm)	0.54	0.976	0.962
	Mean CoP velocity ($mm\ s^{-1}$)	4.11	0.948	0.876
	RMS distance (mm)	0.65	0.967	0.959
	Sway area ($mm^2\ s^{-1}$)	26.49	0.923	0.855
	Total CoP path (mm)	250.23	0.971	0.893
BBS task 13 (floor)	95% confidence ellipse area (mm^2)	117.97	0.997	0.996
	Mean CoP distance (mm)	0.44	0.995	0.995
	Mean CoP velocity ($mm\ s^{-1}$)	4.36	0.984	0.970
	RMS distance (mm)	0.53	0.995	0.995
	Sway area ($mm^2\ s^{-1}$)	30.86	0.982	0.971
	Total CoP path (mm)	82.28	0.986	0.981
BBS task 14 (floor)	95% confidence ellipse area (mm^2)	643.39	0.989	0.990
	Mean CoP distance (mm)	1.41	0.997	0.997
	Mean CoP velocity ($mm\ s^{-1}$)	10.92	0.926	0.919
	RMS distance (mm)	1.53	0.997	0.997
	Sway area ($mm^2\ s^{-1}$)	129.14	0.970	0.969
	Total CoP path (mm)	96.71	0.903	0.900
Maximal trunk flexion and extension (chair)	Anterior-posterior CoP range	7.32	0.990	0.987
Maximal trunk lateral bending (chair)	Mediolateral CoP range	8.33	0.992	0.977

DISCUSSION

The validity of low-cost force plates in measuring vertical GRF, CoP, and CoP-derived metrics obtained during recovery assessments was evaluated in this work. From Table 4 to 8 and Figure 4 to 5, it can be inferred that most of the readings acquired with low-cost force plate are validated with ρ of more than 0.7 and ICC (2, 1) of greater than 0.75. Besides, all CoP-derived metrics can be measured with ρ and ICC (2, 1) higher than 0.7 and 0.75 respectively according to Table 9. The results indicated a good linearity and agreement between the readings and CoP-derived metrics of low-cost and Bertec force plates.

Particularly from the results as tabulated in Table 5 and 9, validation has been verified on vertical GRF readings recorded during BBS task 10, looking behind (ρ = 0.950, ICC = 0.935), which are applied in predicting BBS score

(Gallicchio et al. 2016; Bacciu et al. 2017) and mean CoP velocity obtained from BBS task 6, standing with eyes closed ($\rho = 0.973$, ICC = 0.945), that is correlated with BBS score (Sawacha et al. 2013). In addition, the anterior-posterior and mediolateral CoP ranges measured during maximal trunk flexion, extension, and lateral bending that are correlated with TIS score (Näf et al. 2020) are validated with ρ and ICC of more than 0.990 and 0.977 respectively according to Table 9. The validation of the readings and CoP-derived metrics correlated to BBS and TIS scores demonstrated the capability of the low-cost force plates to be used for recovery assessment measurement system. Moreover, with most readings and CoP-derived metrics acquired from different tasks validated, the potential of the low-cost force plate to be utilized as measurement system for other recovery assessments was obvious.

CONCLUSION

The vertical GRF and CoP readings recorded by low-cost force plate were validated for most tasks. The vertical GRF and CoP readings measured during BBS assessment were validated with ρ and ICC (2, 1) of more than 0.806 and 0.797 respectively. Besides, ρ and ICC (2, 1) of higher than 0.798 and 0.775, respectively were achieved for readings acquired during TIS assessment, apart from the anterior-posterior CoP readings obtained during the tasks to touch the seat with healthy elbow. Readings measured during maximal trunk flexion, extension, and lateral bending were validated with ρ and ICC (2, 1) of greater than 0.773 and 0.752 respectively. The validity of CoP-derived metrics was evaluated with ρ and ICC (2, 1) of larger than 0.903 and 0.855. It could be concluded that the low-cost force plates were accurate enough to be used for various recovery assessment measurement systems. Future work will aim to leverage these validated measurements by integrating them with machine learning techniques to enable automated and objective scoring of assessments such as BBS and TIS.

ACKNOWLEDGEMENT

This work was supported by the Collaborative Research in Engineering, Science and Technology (CREST) Center, Universiti Sains Malaysia, and SAS Institute Sdn. Bhd. under "Grant No. 304.PMEKANIK.6050419.C121" and "Incentive No. R502-KR-GOT001-0000001255-K134".

DECLARATION OF COMPETING INTEREST

None.

REFERENCES

Abujaber, S., Gillispie, G., Marmon, A. & Zeni, J. Jr. 2015. Validity of the Nintendo Wii Balance Board to assess weight bearing asymmetry during sit-to-stand and return-to-sit task. *Gait & Posture* 41(2): 676–682. https://doi.org/10.1016/j.gaitpost.2015.01.023

Arifin, W. N. 2018. A web-based sample size calculator for reliability studies. *Education in Medicine Journal* 10(3). https://doi.org/10.21315/eimj2018.10.3.8

Bacciu, D., Chessa, S., Gallicchio, C., Micheli, A., Pedrelli, L., Ferro, E., Fortunati, L., La Rosa, D., Palumbo, F., Vozzi, F. & Parodi, O. 2017. A learning system for automatic Berg Balance Scale score estimation. *Engineering Applications of Artificial Intelligence* 66: 60–74. https://doi.org/10.1016/j.engappai.2017.08.018

Bartlett, H. L., Ting, L. H. & Bingham, J. T. 2014. Accuracy of force and center of pressure measures of the Wii Balance Board. *Gait & Posture* 39(1): 224–228. https://doi.org/10.1016/j.gaitpost.2013.07.010

Berg, K. O., Wood-Dauphinee, S. L., Williams, J. I. & Maki, B. 1992. Measuring balance in the elderly: Validation of an instrument. *Canadian Journal of Public Health* 83(Suppl. 2): S7–S11.

Bonett, D. G. 2002. Sample size requirements for estimating intraclass correlations with desired precision. *Statistics in Medicine* 21(9): 1331–1335. https://doi.org/10.1002/sim.1108

Bruyneel, A.-V., Mesure, S., Reinmann, A., Sordet, C., Venturelli, P., Feldmann, I. & Guyen, E. 2022. Validity and reliability of center of pressure measures to quantify trunk control ability in individuals after stroke in subacute phase during unstable sitting test. *Heliyon* 8(10). https://doi.org/10.1016/j.heliyon.2022.e10891

Chang, J. O., Levy, S. S., Seay, S. W. & Goble, D. J. 2014. An alternative to the balance error scoring system: Using a low-cost balance board to improve the validity/reliability of sports-related concussion balance testing. *Clinical Journal of Sport Medicine* 24(3): 256–262. https://doi.org/10.1097/jsm.0000000000000016

Clark, R. A., Bryant, A. L., Pua, Y., McCrory, P., Bennell, K. & Hunt, M. 2010a. Validity and reliability of the Nintendo Wii Balance Board for assessment of standing balance. *Gait & Posture* 31(3): 307–310. https://doi.org/10.1016/j.gaitpost.2009.11.012

Clark, R. A., Bryant, A. L., Pua, Y., McCrory, P., Bennell, K. & Hunt, M. 2010b. Validity and reliability of the Nintendo Wii Balance Board for assessment of standing balance. *Gait & Posture* 31(3): 307–310. https://doi.org/10.1016/j.gaitpost.2009.11.012

Cohen, I., Huang, Y., Chen, J., Benesty, J., Benesty, J., Chen, J., Huang, Y. & Cohen, I. 2009. Pearson correlation coefficient. *Noise Reduction in Speech Processing*: 1–4.

Eichler, N., Raz, S., Toledano-Shubi, A., Livne, D., Shimshoni, I. & Hel-Or, H. 2022. Automatic and efficient fall risk assessment based on machine learning. *Sensors* 22(4). https://doi.org/10.3390/s22041557

Gallicchio, C., Micheli, A., Pedrelli, L., Fortunati, L., Vozzi, F. & Parodi, O. 2016. A reservoir computing approach for balance assessment. Dlm. Douzal-Chouakria, A., Vilar, J. A. & Marteau, P.-F. (pnyt.). *Advanced Analysis and Learning on Temporal Data*, hlm. 65–77. Cham: Springer International Publishing.

Golriz, S., Hebert, J. J., Foreman, K. B. & Walker, B. F. 2012. The validity of a portable clinical force plate in assessment of static postural control: Concurrent validity study. *Chiropractic & Manual Therapies* 20(1): 15. https://doi.org/10.1186/2045-709x-20-15

Hong, C. Y., Guo, L. Y., Song, R., Nagurka, M. L., Sung, J. L. & Yen, C. W. 2016. Assessing postural stability via the correlation patterns of vertical ground reaction force components. *Biomedical Engineering Online* 15(1): 90. https://doi.org/10.1186/s12938-016-0212-z

Horsak, B., Slijepcevic, D., Raberger, A.-M., Schwab, C., Worisch, M. & Zeppelzauer, M. 2020. GaitRec, a large-scale ground reaction force dataset of healthy and impaired gait. *Scientific Data* 7(1): 143. https://doi.org/10.1038/s41597-020-0481-z

Idrisa, N. I. F., Nora, E. M., Osmib, S. K. C., Makhtara, S. N. & Tawila, S. N. M. 2025. Development of strain measurement system for detecting rubber elasticity for structural health monitoring applications. *Jurnal Kejuruteraan* 37(1): 457–469.

Jung, Y., Jung, M., Ryu, J., Yoon, S., Park, S.-K. & Koo, S. 2016. Dynamically adjustable foot-ground contact model to estimate ground reaction force during walking and running. *Gait & Posture* 45: 62–68. https://doi.org/10.1016/j.gaitpost.2016.01.005

Khusainov, R., Azzi, D., Achumba, I. E. & Bersch, S. D. 2013. Real-time human ambulation, activity, and physiological monitoring: Taxonomy of issues, techniques, applications, challenges and limitations. *Sensors* 13(10): 12852–12902. https://doi.org/10.3390/s131012852

Kim, Y. W., Cho, W. H., Joa, K. L., Jung, H. Y. & Lee, S. 2020. A new auto-scoring algorithm for balance assessment with wearable IMU device based on nonlinear model. *Journal of Mechanics in Medicine and Biology* 20(10): 2040011. https://doi.org/10.1142/S0219519420400114

Kim, Y. W., Joa, K. L., Jeong, H. Y. & Lee, S. 2021. Wearable IMU-based human activity recognition algorithm for clinical balance assessment using 1D-CNN and GRU ensemble model. *Sensors* 21(22): 7628.

Koo, T. K. & Li, M. Y. 2016. A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *Journal of Chiropractic Medicine* 15(2): 155–163. https://doi.org/10.1016/j.jcm.2016.02.012

Learner, J. & Goodman, N. W. 1996. Descriptions of correlation. *The Lancet* 348(9021): 199–200. https://doi.org/10.1016/s0140-6736(05)66149-1

Levy, S. S., Thralls, K. J. & Kviatkovsky, S. A. 2018. Validity and reliability of a portable balance tracking system, BTrackS, in older adults. *Journal of Geriatric Physical Therapy* 41(2): 102–107. https://doi.org/10.1519/jpt.0000000000000111

Mahoney, J., Wilkinson, T. & Cusumano, J. 2016. *A Low-Cost Balance Board for Quiet Stance Testing*.

Malla, M. A., Al-Beaka, O. H., Hameed, D. M., Al-Hatab, M. M. M., Al-Nima, R. O., Jarjees, M. S. & Al-Maqsood, K. A. K. 2024. Adopting machine learning to automatically identify a suitable surgery type for refractive error patients. *Jurnal Kejuruteraan* 36(4): 1749–1757.

Mengarelli, A., Verdini, F., Cardarelli, S., Di Nardo, F., Burattini, L. & Fioretti, S. 2018. Balance assessment during squatting exercise: A comparison between laboratory grade force plate and a commercial, low-cost device. *Journal of Biomechanics* 71: 264–270. https://doi.org/10.1016/j.jbiomech.2018.01.029

Mitteregger, E., Marsico, P., Balzer, J. & van Hedel, H. J. 2015. Translation and construct validity of the Trunk Control Measurement Scale in children and youths with brain lesions. *Research in Developmental Disabilities* 45–46: 343–352. https://doi.org/10.1016/j.ridd.2015.08.007

Näf, O. B., Bauer, C. M., Zange, C. & Rast, F. M. 2020. Validity and variability of center of pressure measures to quantify trunk control in stroke patients during quiet sitting and reaching tasks. *Gait & Posture* 76: 218–223. https://doi.org/10.1016/j.gaitpost.2019.12.011

Oh, S., Choi, A. & Mun, J. 2013. Prediction of ground reaction forces during gait based on kinematics and a neural network model. *Journal of Biomechanics* 46. https://doi.org/10.1016/j.jbiomech.2013.07.036

Prieto, T. E., Myklebust, J. B., Hoffmann, R. G., Lovett, E. G. & Myklebust, B. M. 1996. Measures of postural steadiness: Differences between healthy young and elderly adults. *IEEE Transactions on Biomedical Engineering* 43(9): 956–966. https://doi.org/10.1109/10.532130

Richmond, S. B., Dames, K. D., Goble, D. J. & Fling, B. W. 2018. Leveling the playing field: Evaluation of a portable instrument for quantifying balance performance. *Journal of Biomechanics* 75: 102–107. https://doi.org/10.1016/j.jbiomech.2018.05.008

Saadprai, S., Vorapojpisut, S., Srikajohnlap, C. & Rungroungdouyboon, B. 2021. Design and development of a low-cost force plate with software application for analyzing balance and coordination training for the elderly. *Journal of Exercise Physiology Online* 24(2).

Sasaki, E., Sasaki, S., Chiba, D., Yamamoto, Y., Nawata, A., Tsuda, E., Nakaji, S. & Ishibashi, Y. 2018. Age-related reduction of trunk muscle torque and prevalence of trunk sarcopenia in community-dwelling elderly: Validity of a portable trunk muscle torque measurement instrument and its application to a large sample cohort study. *PLoS ONE* 13(2): e0192687. https://doi.org/10.1371/journal.pone.0192687

Sawacha, Z., Carraro, E., Contessa, P., Guiotto, A., Masiero, S. & Cobelli, C. 2013. Relationship between clinical and instrumental balance assessments in chronic post-stroke hemiparesis subjects. *Journal of NeuroEngineering and Rehabilitation* 10(1): 95. https://doi.org/10.1186/1743-0003-10-95

Scaglioni-Solano, P. & Aragón-Vargas, L. F. 2014. Validity and reliability of the Nintendo Wii Balance Board to assess standing balance and sensory integration in highly functional older adults. *International Journal of Rehabilitation Research* 37(2): 138–143. https://doi.org/10.1097/mrr.0000000000000046

Severini, G., Straudi, S., Pavarelli, C., Da Roit, M., Martinuzzi, C., Di Marco Pizzongolo, L. & Basaglia, N. 2017. Use of Nintendo Wii Balance Board for posturographic analysis of multiple sclerosis patients with minimal balance impairment. *Journal of NeuroEngineering and Rehabilitation* 14(1): 19. https://doi.org/10.1186/s12984-017-0230-5

Verdini, F., Mengarelli, A., Tigrini, A., Strazza, A., Nardo, F. D., Cardarelli, S. & Fioretti, S. 2019. Accuracy evaluation of force measurement through the Wii Balance Board during squat and functional reach tests. Dlm. *2019 IEEE 23rd International Symposium on Consumer Technologies (ISCT)*, hlm. 291–295.

Verheyden, G. & Kersten, P. 2010. Investigating the internal validity of the Trunk Impairment Scale (TIS) using Rasch analysis: The TIS 2.0. *Disability and Rehabilitation* 32(25): 2127–2137. https://doi.org/10.3109/09638288.2010.483038

Weaver, T. B., Ma, C. & Laing, A. C. 2017. Use of the Nintendo Wii Balance Board for studying standing static balance control: Technical considerations, force-plate congruency, and the effect of battery life. *Journal of Applied Biomechanics* 33(1): 48–55. https://doi.org/10.1123/jab.2015-0295

Yu, L., Xiong, D., Guo, L. & Wang, J. 2016. A remote quantitative Fugl-Meyer assessment framework for stroke patients based on wearable sensor networks. *Computer Methods and Programs in Biomedicine* 128: 100–110. https://doi.org/10.1016/j.cmpb.2016.02.012