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RESEARCH ARTICLE

Validation of Electronic Weighing Device for Vertical Ground Reaction Force and Centre of Pressure Measurement; and Clinical Metrics Derivation

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Abstract Custom force plates developed from digital bathroom scales are demonstrated to be an alternative to laboratory-grade force plates. Nevertheless, applying custom force plates are questionable as the measurement accuracy has not been thoroughly validated. This study evaluated the validity of a custom force plate constructed from a digital bathroom scale, which successfully measured vertical Ground Reaction Force (GRF), Centre of Pressure (CoP), and clinical assessment metrics derived from vertical GRF and CoP. The custom force plate data collected during quiet standing, sit-to-stand, gait initialisation, gait, quiet sitting, maximal trunk flexion and extension, and lateral bending were compared to a laboratory-grade force plate. In measuring vertical GRF, CoP, and clinical assessment metrics for all tasks, the validity of the custom force plate was demonstrated through high Pearson correlations, coefficient of determinations, and intraclass correlation coefficients (2, 1) of more than 0.95, 0.89, and 0.95, respectively. Moreover, the performance outcome of the custom force plate was comparable to the commercialised force plates reported in previous studies and successfully matched that of a laboratory-grade force plate. Hence, the custom force plate could be an alternative solution to measure vertical GRF, CoP, and clinical assessment metrics in the biomechanical, biomedical engineering, and clinical rehabilitation field.

Keywords: Force plate, validation, ground reaction force, centre of pressure, biomechanics.

Introduction

The Ground Reaction Force (GRF) and Centre of Pressure (CoP) are essential parameters utilised in biomechanics, which have been extensively investigated with force plates. Furthermore, the metrics to evaluate bodily function or recovery progress are computed in clinical settings with GRF and CoP [1, 2]. Although the biomechanical analysis of patients relies on the measured GRF and CoP [3-5], the accessibility is limited following the relatively high manufacturing costs of laboratory-grade force plates [6, 7]. This observation holds, particularly at healthcare and research facilities in developing countries where the cost of measuring and monitoring equipment is crucial. The high production cost of numerous force plates is also a major concern when analysing complex human motion performed over a long distance. Thus, identifying alternative solutions for measuring biomechanical variables can improve research study feasibility.

Several commercially available force plates have been proposed as alternatives to laboratory-grade force plates. These options offer promising potential for assessing biomechanical variables. Numerous validation studies were performed to evaluate these commercialised force plates, albeit with some drawbacks. For example, the Nintendo Wii Balance Board (NWBB) was discontinued despite receiving extensive validation [8-12]. Alternatively, the BTrackS Balance Plate (BBP) was validated for measuring

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CoP during quiet standing [6, 13, 14]. Nonetheless, the BBP could not record raw vertical GRF [6]. In a different commercially-available product, Midot Posture Scale Analyzer (MPSA) demonstrated a low concurrent validity [15].

A digital bathroom scale can be repurposed as a custom force plate. Digital bathroom scales use half-bridge strain gauge load cells as they are more compact and widely accessible than their full-bridge equivalents used in other studies [16, 17]. Nevertheless, these load cells are less sensitive [18]. Despite this constraint, researchers successfully assessed the reliability and validity of a custom force plate produced from a digital bathroom scale [19]. The study reported excellent cross-correlation and Mean Absolute Error (MAE) for vertical GRF during weight shifting and sit-to-stand movements. Although the vertical GRF measurement of the bathroom digital scale-based custom force plate was effectively investigated, its application for CoP remains unexplored.

Based on vertical GRF and CoP, numerous clinical assessment metrics were applied to evaluate the health and recovery conditions. For example, sway area was calculated during quiet standing to quantify postural sway and balance [20]. In stroke patients, maximum CoP displacement during trunk flexion, extension, and lateral bending was reliably correlated to trunk control [21]. The generated power was also quantified using the vertical GRF obtained during sit-to-stand, which correlated to the participant's physical performance [22, 23]. Moreover, gait abnormalities could be understood by analysing the peaks and valleys of vertical GRF recorded during walking [24]. Although the information obtained was significant, these clinical assessment metrics were not extensively validated. Only clinical assessment metrics derived from quiet standing were validated for NWBB [11, 25, 26], BBP [6], MPSA [15], and *S*-type load cell-based force plates [17]. Additional validation remains necessary for other clinical assessment metrics acquired from various tasks. These tasks included sit-to-stand, quiet sitting, gait initialisation, gait, maximal trunk flexion and extension, and lateral bending.

This study aimed to determine the validity of using a digital bathroom scale to construct a custom force plate. The custom force plate was validated against a laboratory-grade force plate to ensure accurate vertical GRF and CoP measurements during various tasks. This study also assessed the validity of clinical assessment metrics calculated using vertical GRF and CoP, which were not investigated in previous studies. Resultantly, the current study outcome could promote the application of force plates in resource-limited situations.

Materials and Methods

Participants

The sample size required to achieve intraclass correlation coefficient (ICC) precision of ±0.02 was determined using the method developed in previous work [27]. The expected ICC of 0.98 was obtained from the similar study which investigated the validity of NWBB in measuring GRF during sit-to-stand [28]. With 95 % confidence interval and number of raters as two (laboratory-grade and custom force plates), the minimum sample size required was 17. To ensure that equal amount of male and female subjects were recruited, an even total number of 20 healthy participants were involved in this study. The participants were chosen with the following requirements:

1. At least 18 years old;
2. Capable of standing on two feet for at least one hour;
3. No limitations in conducting physical activities;
4. Not afflicted with musculoskeletal or neurological disorders;
5. Did not consume medicine which affected the balance;
6. Not pregnant;
7. Able to provide written informed consent.

The Universiti Sains Malaysia (USM) Ethics Committee approved the project involving 10 male and 10 female participants with the study protocol code USM/JEPeM/PP/23020164 on June 2023. The mean and standard deviation of the participant's age, height, and weight were 30.65 ± 8.48 years old, 165.05 ± 7.99 cm, and 63.59 ± 10.68 kg, respectively.

Apparatus

The custom force plate employed in this study was granted an exemption from registration of medical devices by the Medical Device Authority, Ministry of Health Malaysia, under the protocol number CIU-20230226-11. Figure 1 depicts the custom force plate from both the perspective and bottom views. The dimensions of the custom force plate were 676 mm × 400 mm × 49 mm. The device also included an ESP32 development board, four half-bridge strain gauge load cells, four HX711 amplifiers, and analogue-to-digital converters. The load cells were obtained from a digital bathroom scale purchased from ProDIY, Malaysia. The load cell had a resolution of 0.00002 kg and a sampling rate of 80 Hz with the application of HX711, which was sufficient for the measurements related to the typical human activities with frequencies below 20 Hz [29]. Each load cell could measure up to 45 kg. Together, the force plate possessed a maximum measurable load of 180 kg. Medium density fiber was used to fabricate the board of custom force plate. The material had modulus of elasticity of 3.59 GPa and modulus of rupture of 35.85 MPa [30]. The custom force plate used in this study (the third device developed in the laboratory to assist in neurorehabilitation) was named NEAR3 (Neurorehabilitation Engineering and Assistance Systems Research 3) to improve readability. The Bertec force plate (model 4060-05) was used as a laboratory-grade reference for validation.

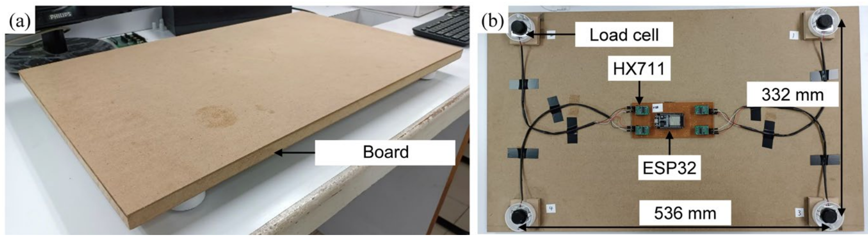

Figure 1. The (a) perspective and (b) bottom views of the custom force plate (NEAR3)

Each load cell underwent a one-point calibration with a 25 kg point load. The forces acting on NEAR3 are depicted by a free-body diagram in Figure 2. The local axis system of NEAR3 and the Bertec force plates was aligned to facilitate performance comparison. The centre point of the NEAR3 platform surface served as the axis origin. Since the load cells could not measure bilateral GRF [31], only vertical GRF was considered for analysis. According to Figure 2, the CoP coordinates consist of anterior-posterior or *x*-axis coordinate (CoP_x) and mediolateral or *y*-axis coordinate (CoP_y). The F_{cz} represents the force acting on NEAR3. Finally, d_{cx} and d_{cy} represented the distances between the load cells and origins in the anterior-posterior and mediolateral directions, respectively.

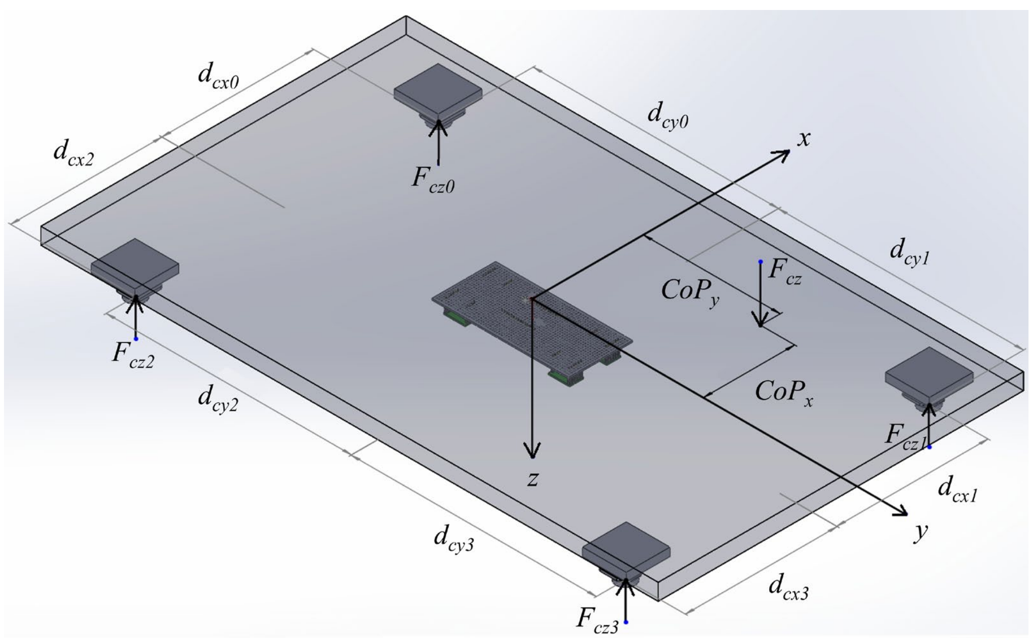

Figure 2. The free-body diagram of NEAR3

The vertical GRF (GRF_z), anterior-posterior CoP (CoP_x), and mediolateral CoP (CoP_y) are obtained from NEAR3 using Equations 1 to 3 as follows:

$$GRF_z = F_{cz0} + F_{cz1} + F_{cz2} + F_{cz3} \tag{1}$$

$$CoP_x = \frac{F_{cz0} \cdot d_{cx0} + F_{cz1} \cdot d_{cx1} - F_{cz2} \cdot d_{cx2} - F_{cz3} \cdot d_{cx3}}{GRF_z} \tag{2}$$

$$CoP_y = \frac{-F_{cz0} \cdot d_{cy0} + F_{cz1} \cdot d_{cy1} - F_{cz2} \cdot d_{cy2} + F_{cz3} \cdot d_{cy3}}{GRF_z} \tag{3}$$

The anterior-posterior and mediolateral CoPs from the Bertec force plate are then computed using Equations 4 and 5 as follows:

$$CoP_x = \frac{-M_{by} - F_{bx} \cdot d_{bz}}{GRF_z} \tag{4}$$

$$CoP_y = \frac{M_{bx} - F_{by} \cdot d_{bz}}{GRF_z} \tag{5}$$

where M_{by} is the mediolateral moment, F_{bx} is the anterior-posterior lateral GRF, d_{bz} is the distance between the top surfaces of the NEAR3 and Bertec force plates, M_{bx} is the anterior-posterior moment, and F_{by} is the mediolateral lateral GRF.

Non-Linearity and Hysteresis Tests

In non-linearity and hysteresis tests, NEAR3 was stacked on Bertec force plate and both force plate readings were tared. The vertical GRF readings of both force plates were recorded without load placing on them. The recording step was repeated by increasing the loads on the stacked force plates by an additional of 5 kg. The repetition was performed until 100 kg loads were used. Then, 5 kg load was removed in succession and the data acquisition step was repeated until no load was left on the stacked force plates. The linearity error was expressed as the maximum deviation of NEAR3 readings from Bertec force plate counterparts while the hysteresis was the peak difference between the NEAR3 readings when same weight was applied during increasing and decreasing loadings [32].

Mechanical Test-Retest Reliability Assessment

Figure 3 illustrates the 25 kg point load placement on NEAR3 with a grid to evaluate the mechanical test-retest reliability of CoP measurements. The readings of the four load cells were recorded during the load exertion on each grid point. A similar procedure was then repeated after four days. Meanwhile, the vertical GRF reliability evaluation was not performed as it was already assessed in a previous study [19].

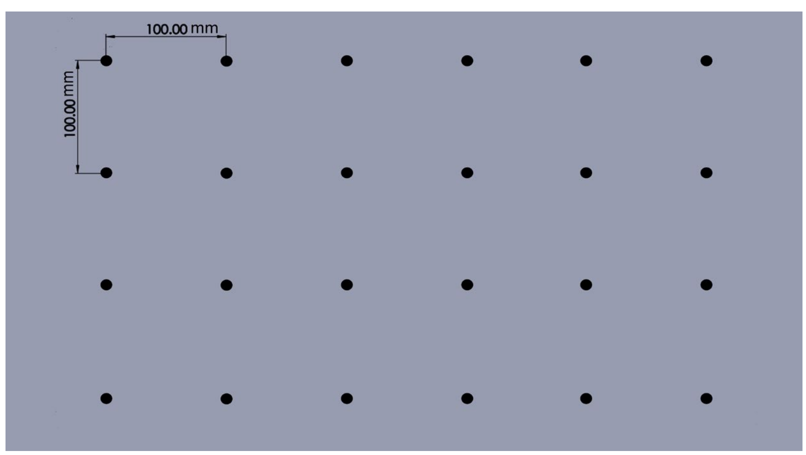

Figure 3. The positions (black dots) where the point load is applied during mechanical test-retest reliability evaluation

Validity Assessment

The NEAR3 was positioned on the Bertec force plate for the experimental setup. On the stacked force plates, the participants were told to complete seven tasks: quiet standing, sit-to-stand, gait initialisation, gait, quiet sitting, maximal trunk flexion and extension, and lateral bending. These tasks were completed according to the protocols outlined in previous studies [21, 33-36]. The stacked force plates were always ensured to be placed on a flat solid stable surface during the experiment.

Figure 4 shows the tasks carried out by a subject during the experiment. In performing quiet standing task as depicted in Figure 4(a), the stacked force plates were placed on the floor. The subjects stood on the stacked force plates for 40 s by placing their feet in the way they felt safe and comfortable [33].They looked at a fixed target located 2 m in front. The steps were repeated with subject eyes closed. During sit-to-stand task as displayed in Figure 4(b), the stacked force plates were placed in front of a chair. The subjects sat on the chair and placed their feet on the stacked force plates. They crossed their arms over their chests and positioned their hip, knee, and ankle joints at approximately 90°. They had to stand up safely as fast as possible after audio cue was given, quickly achieve balance, and stand still in an upright posture for 5 s [34].

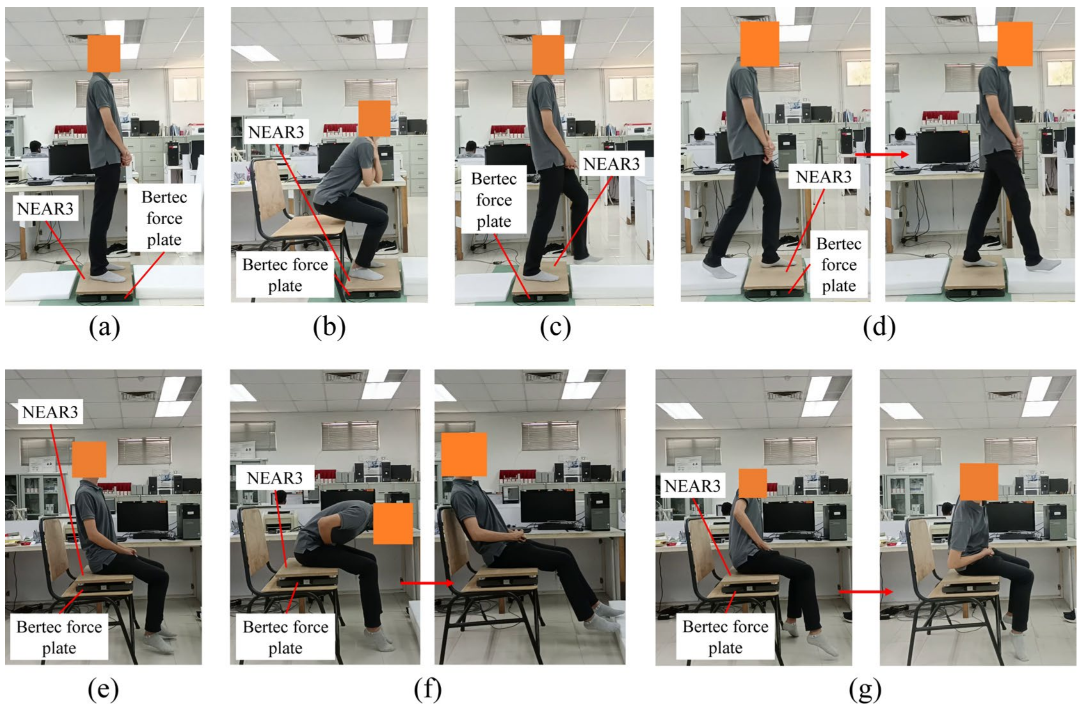

Figure 4. (a) Quiet standing with eyes opened or closed. (b) Sit-to-stand. (c) Gait initialisation. (d) Gait. (e) Quiet sitting. (f) Maximal trunk flexion and extension. (g) Maximal trunk lateral bending

Gait initialization task as shown in Figure 4(c) was carried out by placing stacked force plates on the floor. The subjects walked through the stacked force plates by stepping on the stacked force plates with their left feet. The steps were repeated using their right feet. To conduct gait task as illustrated in Figure 4(d), the subjects walked through the stacked force plates by stepping on the stacked force plates with their left feet. The steps were repeated using their right feet.

The stacked force plates were placed on a custom-made chair before implementing sitting task. According to Figure 4(e). the subjects sat in an upright posture on the stacked force plates for 40 s [21]. Their hands were placed on the abdomen and their feet were ensured to not touch the floor. Next, the subjects performed maximal trunk flexion, followed by extension at their preferred speed [21] as shown in depicted in Figure 4(f). The steps were repeated with maximal trunk lateral bending towards left, followed by right as shown in Figure 4(g).

The vertical GRF readings from NEAR3 and the three-dimensional GRF and moment readings from the Bertec force plate were recorded during the tasks. The quiet standing, sitting, maximal trunk flexion and extension, and lateral bending tasks were performed thrice. Meanwhile, the sit-to-stand, gait initialisation, and gait tasks were repeated 10 times to acquire extra data for future analysis.

Data Pre-processing

Python was used to perform data pre-processing. The data from the NEAR3 force plate were collected at 80 Hz (sampling frequency of the HX711). Median filter with window size of five was implemented on the readings from four load cells. A fourth-order, zero-phase, low-pass Butterworth filter with a 5 Hz critical frequency was applied to the measurements recorded during quiet standing and sitting [17]. Based on Equations 1 to 3, the vertical GRF and CoP were then estimated. The mean value of the trials was subtracted from the CoP [20]. The CoP was adjusted to zero when the vertical GRF was less than 20 N (assuming that no participant was standing on the force plates).

The Bertec force plate readings were collected at 500 Hz after using an anti-aliasing filter. Subsequently, the data collected during quiet standing and sitting were similarly low-pass filtered as NEAR3. A similar filter was applied for the readings acquired during other tasks, with the critical frequency set to half of the sampling frequency of NEAR3. The CoP was then determined through Equations 4 and 5. The trial mean was subtracted from CoP. At loads below 20 N, the CoP values were set to zero. The readings were also interpolated to match the sampling rate of NEAR3.

Since the latency between NEAR3 and Bertec force plate readings was present, a timestamp offset was implemented via template matching [37]. The NEAR3 readings were adjusted 32 timesteps (0.4 s) forward and backwards to determine the temporal position that yielded the lowest sum of squared differences between the readings of NEAR3 and Bertec force plates. For sit-to-stand, gait initialisation, and gait data, the vertical GRF readings were utilised for template matching owing to the significant change in the readings. The template matching was accomplished using anterior-posterior CoP readings for other task data because the vertical GRF remained almost constant during the other tasks and did not provide a perceivable pattern for template matching.

Statistical analysis

Python was used to conduct data processing and statistical analysis. The CoP was estimated for each point load exertion during test-retest reliability assessment as described in Section 2.4 while ICC (2, 1) of each pair of inter-day CoP values was determined with a two-way mixed-effects model (type as a single rater and definition as absolute agreement) [38]. The ICC (2, 1) value is applied to determine the test-retest reliability of CoP measurements, in which the reliability is rated based on the following ICC (2, 1) ranges [38]:

1. < 0.5 is "poor"
2. 0.5–0.75 is "moderate"
3. 0.75–0.9 is "good"
4. > 0.9 is "excellent"

The MAE of the vertical GRF and CoP readings recorded during the validity assessment (mentioned in Section 2.5) was computed to measure the NEAR3 deviation from Bertec force plate readings [39]. Subsequently, the Pearson correlation coefficient (ρ) was calculated to assess the linearity between the readings [40]. The linear correlation strength is then rated based on the ρ ranges as follows [41]:

1. < 0.2 is "very weak"
2. 0.2–0.4 is "weak"
3. 0.4–0.7 is "moderate"
4. 0.7–0.9 is "strong"
5. > 0.9 is "very strong"

The coefficient of determination (R^2) evaluated how closely the NEAR3 values matched those of the Bertec force plate ($R^2 > 0.8$, indicating a satisfactory fit) [42]. Notably, R^2 was not equal to the square of ρ in any situation of this study as there was no linear regression involved [43]. Moreover, ICC (2, 1) was calculated to evaluate the absolute agreement between the readings as performed in previous studies for validity evaluation [19, 28, 44, 45]. Thus, NEAR3 readings were validated if ρ was higher than 0.7, R^2 was greater than 0.8, and ICC (2, 1) exceeded 0.75, suggesting a good or excellent linearity, fit, and agreement between the readings [19, 38, 41, 42].

Various clinical assessment metrics are computed from the vertical GRF and CoP measurements as follows:

1. Mean and Root Mean Squared (RMS) distances, total excursion, mean velocity, 95% confidence ellipse area, and sway area calculated from CoP readings of quiet standing and sitting [20];
2. Peak, peak counter, and peak rebound GRFs, rate of force development, and impulse computed from sit-to-stand readings [46-48];
3. Maximal CoP displacement obtained from maximal trunk flexion, extension, and lateral bending reading [21];
4. First and second peaks, valley of vertical GRF, and impulse calculated from gait readings [44].

The MAE, ρ, R^2, and ICC (2, 1) values were calculated between the clinical assessment metrics obtained from the NEAR3 and Bertec force plate readings. The measurement was validated if ρ, R^2, and ICC (2, 1) exceeded 0.7, 0.8, and 0.75 respectively. A Bland-Altman plot [limit of agreement (LoA) of mean ± 1.96 standard deviation] was also constructed to visually observe the agreement between the clinical assessment metrics derived from both force plates [49].

Results

The vertical GRF readings measured during the non-linearity and hysteresis tests were plotted in Figure **5**. It could be observed that both the lines obtained via increasing and decreasing loads overlapped with line of equality, indicating a good linearity and hysteresis properties of NEAR3. The linearity error was 8.401 N (0.48 % of the full-scale output) while the hysteresis was 3.279 N (0.19 %).

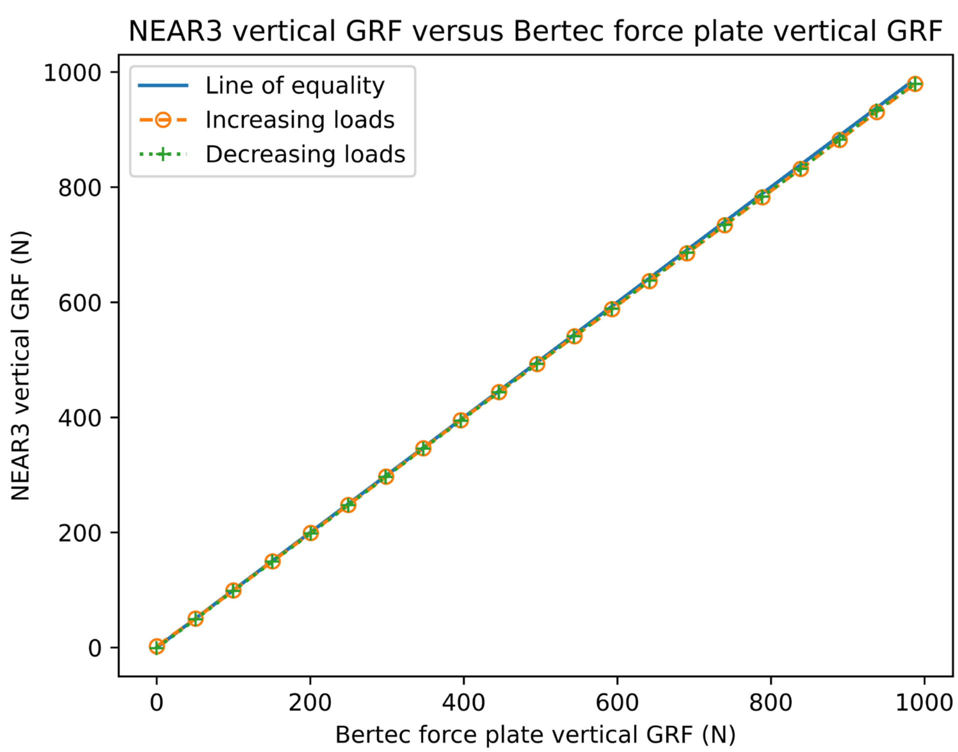

Figure 5. The graph of vertical GRF recorded using NEAR 3 versus vertical GRF measured using Bertec force plate during non-linearity and hysteresis tests

The test-retest reliability assessment of the CoP measurements yielded excellent outcomes, with ICC (2, 1) values of approximately 0.9995 and 0.9997 for anterior-posterior and mediolateral CoPs, respectively. Table 1 summarises the comparison data between the vertical GRF and CoP measurements from the NEAR3 and the Bertec force plates. The CoP and vertical GRF MAE varied between 1.78 to 6.29 mm and 2.21 to 9.9 N, respectively. A strong linear correlation (ρ > 0.9), good fitting ($R^2 > 0.8$), and excellent agreement (ICC > 0.9) were noted across the readings of all tasks. The outcome ranges for ρ, R^2, and ICC (2, 1) were 0.9461 to 0.9999, 0.8862 to 0.9992, and 0.9453 to 0.9996, respectively.

Table 1. Summary of the MAE, ρ, R^2, and ICC (2, 1) between anterior-posterior CoP (AP CoP), mediolateral CoP (ML CoP), and vertical GRF readings from NEAR3 and Bertec force plates

Task	Parameter	MAE	ρ	R^2	ICC (2, 1)
Quiet standing with eyes opened	AP CoP (mm)	2.29	0.9970	0.9824	0.9915
	ML CoP (mm)	2.90	0.9876	0.9240	0.9632
	Vertical GRF (N)	4.84	0.9989	0.9961	0.9981
Quiet standing with eyes closed	AP CoP (mm)	2.28	0.9957	0.9803	0.9905
	ML CoP (mm)	2.53	0.9949	0.9593	0.9801
	Vertical GRF (N)	4.13	0.9990	0.9969	0.9985
Sit-to-stand	AP CoP (mm)	2.74	0.9939	0.9855	0.9929
	ML CoP (mm)	3.65	0.9719	0.9317	0.9657
	Vertical GRF (N)	4.54	0.9996	0.9992	0.9996
Gait initialisation with left foot	AP CoP (mm)	5.46	0.9902	0.9694	0.9845
	ML CoP (mm)	3.45	0.9926	0.9833	0.9919
	Vertical GRF (N)	6.72	0.9988	0.9977	0.9988
Gait initialisation with right foot	AP CoP (mm)	5.93	0.9911	0.9694	0.9844
	ML CoP (mm)	3.61	0.9916	0.9829	0.9913
	Vertical GRF (N)	6.62	0.9990	0.9976	0.9988
Gait with left foot stepping on a force plate	AP CoP (mm)	6.29	0.9778	0.9518	0.9748
	ML CoP (mm)	5.50	0.9517	0.9001	0.9509
	Vertical GRF (N)	9.26	0.9983	0.9965	0.9983
Gait with right foot stepping on a force plate	AP CoP (mm)	5.69	0.9787	0.9556	0.9770
	ML CoP (mm)	5.36	0.9461	0.8862	0.9453
	Vertical GRF (N)	9.90	0.9983	0.9962	0.9981
Quiet sitting	AP CoP (mm)	2.12	0.9998	0.9968	0.9984
	ML CoP (mm)	1.78	0.9933	0.9718	0.9857
	Vertical GRF (N)	2.21	0.9996	0.9990	0.9995
Maximal trunk flexion and extension	AP CoP (mm)	1.86	0.9999	0.9991	0.9996
	ML CoP (mm)	2.10	0.9949	0.9739	0.9869
	Vertical GRF (N)	2.90	0.9997	0.9989	0.9994
Maximal trunk lateral bending	AP CoP (mm)	2.28	0.9975	0.9924	0.9962
	ML CoP (mm)	2.40	0.9988	0.9972	0.9986
	Vertical GRF (N)	4.60	0.9966	0.9929	0.9964

Figure 6 illustrates the CoP pathways recorded during specific tasks. These tasks were chosen as the corresponding CoP readings were significant for calculating clinical assessment metrics. Only one trial was arbitrarily selected to demonstrate the CoP pathways for each task. Interestingly, the CoP pathways recorded by both force plates were nearly identical (except for quiet sitting). Nonetheless, the MAE of CoP during quiet sitting was less than quiet standing (see Table 1). Hence, the CoP accuracy during quiet sitting was also demonstrated.

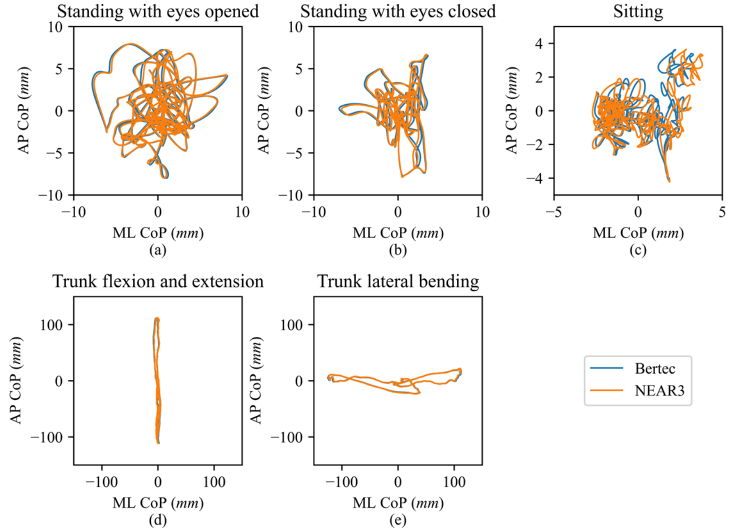

Figure 6. Graphs of anterior-posterior CoP (AP CoP) versus mediolateral CoP (ML CoP) obtained during (a) quiet standing with eyes opened, (b) quiet standing with eyes closed, (c) quiet sitting, (d) maximal trunk flexion and extension, and (e) maximal trunk lateral bending. The blue and orange curves represent CoP pathways recorded using the Bertec and NEAR3 force plates, respectively

The vertical GRF versus time graphs for all tasks are represented in Figure 7. Similarly, the vertical GRF measured with NEAR3 and Bertec force plates closely overlapped.

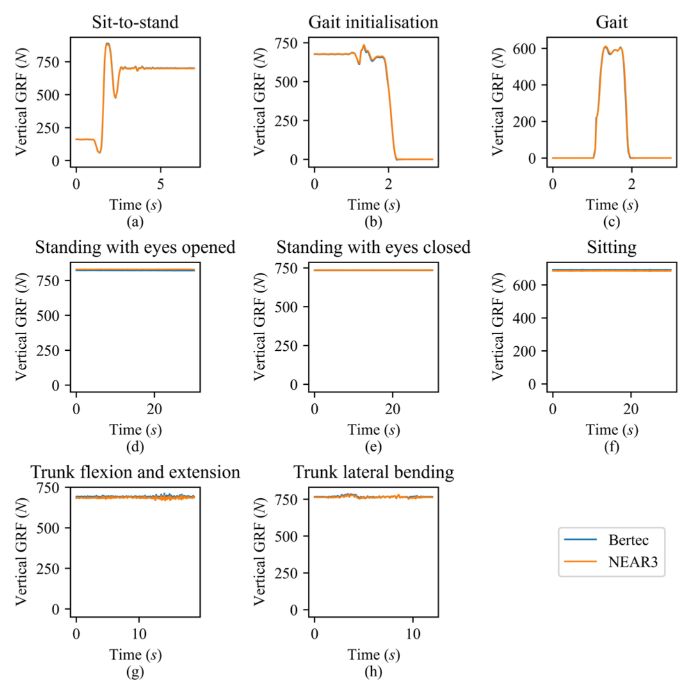

Figure 7. Graphs of vertical GRF versus time obtained during (a) sit-to-stand, (b) gait initialisation, (c) gait, (d) quiet standing with eyes opened, (e) quiet standing with eyes closed, (f) quiet sitting, (g) maximal trunk flexion and extension, and (h) maximal trunk lateral bending. The blue and orange curves represent vertical GRF recorded using Bertec and NEAR3 force plates, respectively

The MAE, ρ, R^2, and ICC (2, 1) were computed between the vertical GRF- and CoP-based clinical assessment metrics obtained from the NEAR3 and Bertec force plate readings (see Table 2). From the table, all clinical assessment metrics exhibited a very strong linear correlation (ρ > 0.9), good fitting (R^2 > 0.8), and excellent agreement (ICC > 0.9) between the two force plates. The outcome ranges of ρ, R^2, and ICC (2, 1) were 0.9840 to 0.9998, 0.9618 to 0.9995, and 0.9823 to 0.9997, respectively.

Table 2. The MAE, ρ, R^2, and ICC (2, 1) between vertical GRF- and CoP-based clinical assessment metrics computed with NEAR3 and Bertec force plate readings

Task	Clinical Assessment Metric	MAE	ρ	R^2	ICC (2, 1)
Quiet standing with eyes opened	95% confidence ellipse area (mm^2)	7.65	0.9968	0.9930	0.9966
	Mean distance (mm)	0.08	0.9977	0.9938	0.9970
	Mean velocity (mm s^{-1})	0.11	0.9986	0.9936	0.9969
	RMS distance (mm)	0.09	0.9981	0.9945	0.9973
	Sway area (mm^2s^{-1})	0.25	0.9985	0.9966	0.9983
	Total excursion (mm)	3.39	0.9986	0.9936	0.9969
Quiet standing with eyes closed	95% confidence ellipse area (mm^2)	6.69	0.9984	0.9965	0.9983
	Mean distance (mm)	0.07	0.9986	0.9968	0.9985
	Mean velocity (mm s^{-1})	0.16	0.9993	0.9960	0.9981
	RMS distance (mm)	0.08	0.9986	0.9966	0.9984
	Sway area (mm^2s^{-1})	0.29	0.9993	0.9978	0.9989
	Total excursion (mm)	4.71	0.9993	0.9960	0.9981
Sit-to-stand	Impulse (Ns)	7.23	0.9998	0.9995	0.9997
	Peak counter GRF (N)	1.97	0.9861	0.9678	0.9838
	Peak vertical GRF (N)	5.84	0.9979	0.9954	0.9977
	Peak rebound GRF(N)	4.59	0.9988	0.9968	0.9984
	Rate of force development (Ns^{-1})	105.83	0.9840	0.9669	0.9832
Gait with left foot stepping on a force plate	Impulse (Ns)	3.82	0.9992	0.9979	0.9990
	First peak of vertical GRF (N)	5.24	0.9979	0.9948	0.9974
	Second peak of vertical GRF (N)	5.27	0.9977	0.9955	0.9977
	Valley of vertical GRF (N)	5.72	0.9976	0.9927	0.9964
Gait with right foot stepping on a force plate	Impulse (Ns)	4.82	0.9971	0.9930	0.9965
	First peak of vertical GRF (N)	6.22	0.9982	0.9936	0.9968
	Second peak of vertical GRF (N)	8.76	0.9981	0.9893	0.9946
	Valley of vertical GRF (N)	5.43	0.9973	0.9937	0.9968
Quiet sitting	95% confidence ellipse area (mm^2)	1.73	0.9915	0.9763	0.9887
	Mean distance (mm)	0.07	0.9933	0.9840	0.9921
	Mean velocity (mm s^{-1})	0.16	0.9912	0.9618	0.9823
	RMS distance (mm)	0.07	0.9943	0.9866	0.9934
	Sway area (mm^2s^{-1})	0.15	0.9953	0.9839	0.9924
	Total excursion (mm)	4.71	0.9912	0.9618	0.9823
Maximal trunk flexion and extension	Maximum anterior-posterior CoP displacement (mm)	1.13	0.9994	0.9983	0.9992
Maximal trunk lateral bending	Maximum mediolateral CoP displacement (mm)	1.65	0.9981	0.9951	0.9976

The Bland-Altman plots for each clinical assessment metric were depicted in the Supplementary File 1, in which under 3% of all data points fell outside of the LoA. Less than 9% of the data points for each clinical assessment metric were outside the LoA.

Discussion

The vertical GRF and CoP measurement validities of NEAR3 were investigated using a laboratory-grade force plate in this study. Since ICC (2, 1) values achieved in the test-retest reliability assessment were greater than 0.999, NEAR3 demonstrated exceptional reliability in measuring CoP. Meanwhile, the vertical GRF and CoP measurements were validated as ρ, R^2, and ICC (2, 1) values were greater than 0.88. All vertical GRF- and CoP-based clinical assessment metrics obtained from NEAR3 were validated with ρ, R^2, and ICC (2, 1) values above 0.96. As revealed by the Bland-Altman plots, over 97% of the data points fell within the LoA.

Figure 8 reveals the reported MAE, ρ, and ICC values for acquiring clinical assessment metrics with NEAR3 and commercialised or custom force plates investigated in the previous works. The NEAR3 successfully outperformed its counterpart in terms of MAE for measuring vertical GRF during sit-to-stand (4.54 versus 10.1 N) [19] as shown in Figure 8(a). This performance disparity could be attributed to variations in force plate materials, dimensions, subject demographics, and procedures in the two studies. NEAR3 achieves ρ of more than 0.99 for CoP mean, RMS distance, mean velocity, sway area, and total excursion during quiet standing with eyes opened, which is similar to that recorded with BBP [6] as shown in Figure 8(b).

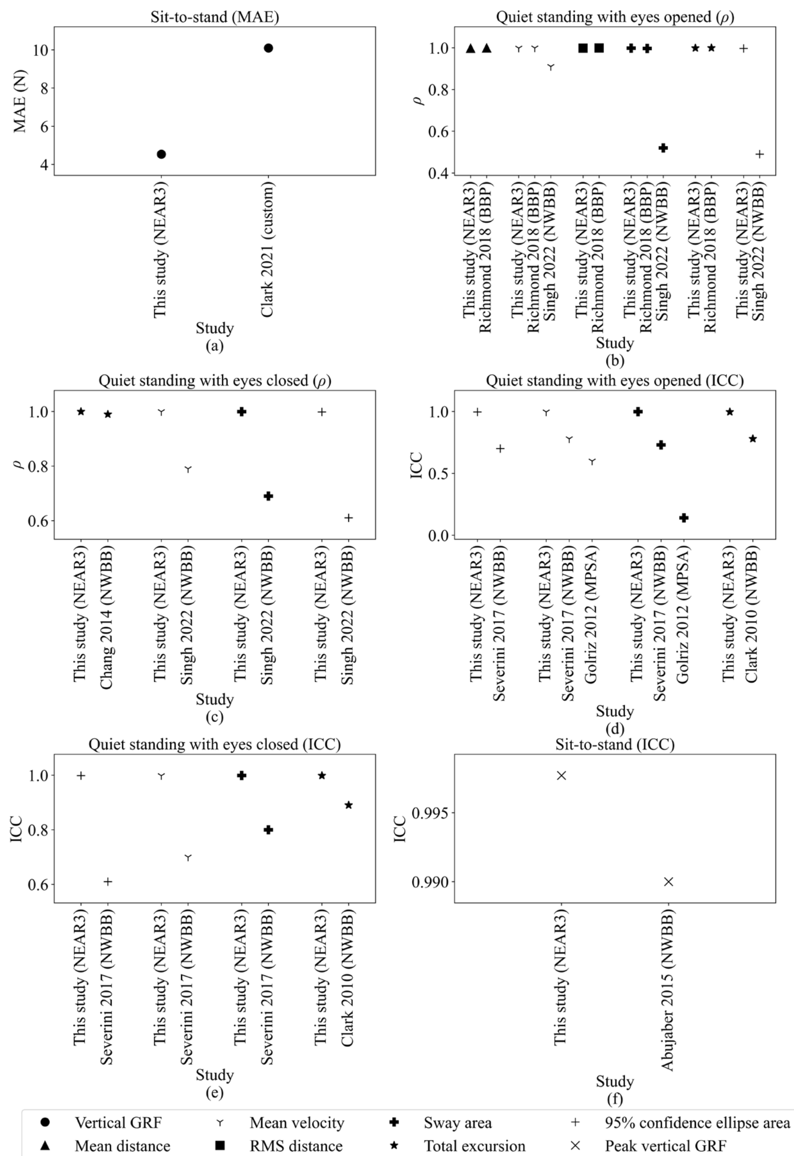

Figure 8. Graphs of MAE, ρ, and ICC versus study for different clinical assessment metrics obtained during different tasks, including (a) MAE recorded for sit-to-stand task, (b) ρ recorded for quiet standing with eyes opened task, (c) ρ recorded for quiet standing with eyes closed task, (d) ICC recorded for quiet standing with eyes opened task, (e) ICC recorded for quiet standing with eyes closed task, and (f) ICC recorded for sit-to-stand task

Values of ρ recorded by NEAR3 and NWBB investigated in the previous work by Chang *et al*. [50] for CoP total excursion obtained during quiet standing with eyes closed range between 0.99 and 1 as depicted in Figure 8(c). In measuring peak vertical GRF during sit-to-stand task, NEAR3 achieves ICC of 0.9977, almost equal to the ICC obtained using NWBB [28] according to Figure 8(f). The results demonstrated the validity of NEAR3 which approached that of accurate commercialised force plates such as BBP and NWBB.

NEAR3 validity in measuring CoP total excursion, mean velocity, 95% confidence ellipse area, and sway area during quiet standing was observed to be consistently better than that of several commercialised force plates as reported in some previous works by Severini *et al*. [11], Golriz *et al*. [15], Clark *et al*. [25], and Singh *et al*. [51]. This is shown in Figures 8(b) to 8(e) via higher values of ρ and ICC achieved by NEAR3 than that of NWBB and MPSA. Nevertheless, the direct performance comparison should be viewed carefully, as the commercialised and laboratory-grade force plate data were not obtained simultaneously in these previous studies [11, 15, 25, 51].

Apart from the information illustrated in Figure 8, during quiet standing with eyes opened, the ICC (2, 1) for the CoP mean velocity, 0.9969, is comparable or better than the anterior-posterior mean velocity recorded in an earlier study which applies custom force plate with full-bridge strain gauge load cells (ICC > 0.75) [17]. This finding revealed that the sensitivity of half-bridge strain gauge load cells could be adequate for acceptable performance in clinical assessment metric measurement. Besides, NEAR3 achieved ρ of 0.9996 in measuring vertical GRF during sit-to-stand task, which was close to the ρ of 0.996 recorded in a recent work that investigated validity of a Kinetic Step Box force plate [52]. MAE ranging from 2.29 mm to 2.90 mm was recorded with NEAR3 in measuring the CoP during quiet standing with eyes opened task, which was similar as the mean difference of lower than 2.7 mm obtained in a recent work studying K-Deltas force plates [53].

Despite the good performance of NEAR3, the device still faced several limitations. The maximum measurable load was 180 kg, where each load cell could only withstand a load of up to 45 kg before yielding and non-linearity occurred. Therefore, the loading process could cause faulty readings and break the load cell if a heavy subject was positioned directly on a load cell at the platform corner. Furthermore, this study did not verify measurement validity on some tasks, such as the validity of clinical assessment metrics for quiet standing on an unstable surface (foam) conducted in previous work [6]. Thus, future development of NEAR3 should be undertaken to address these limitations.

Conclusions

In conclusion, the custom force plate, NEAR3, successfully demonstrated high validity in measuring vertical GRF and CoP in this study. The clinical assessment metrics could also be measured validly with NEAR3. Besides, the performance of NEAR3 matched that of laboratory-grade and commercialized alternatives. These results demonstrated its potential as an alternative solution in future developments.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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