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Accuracy of force and center of pressure measures of the Wii Balance Board

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ABSTRACT

The Nintendo Wii Balance Board (WBB) is increasingly used as an inexpensive force plate for assessment of postural control; however, no documentation of force and COP accuracy and reliability is publicly available. Therefore, we performed a standard measurement uncertainty analysis on 3 lightly and 6 heavily used WBBs to provide future users with information about the repeatability and accuracy of the WBB force and COP measurements. Across WBBs, we found the total uncertainty of force measurements to be within ±9.1 N, and of COP location within ±4.1 mm. However, repeatability of a single measurement within a board was better (4.5 N, 1.5 mm), suggesting that the WBB is best used for relative measures using the same device, rather than absolute measurement across devices. Internally stored calibration values were comparable to those determined experimentally. Further, heavy wear did not significantly degrade performance. In combination with prior evaluation of WBB performance and published standards for measuring human balance, our study provides necessary information to evaluate the use of the WBB for analysis of human balance control. We suggest the WBB may be useful for low-resolution measurements, but should not be considered as a replacement for laboratory-grade force plates.

1. Introduction

The Nintendo Wii Balance Board (WBB; Nintendo, Kyoto, Japan) is increasingly used in the rehabilitation and assessment of postural control. Its low cost (<$100 USD) and portability make it an attractive alternative to current methods of measuring balance in research settings that typically require expensive force plates and/or complex instrumentation that is limited to specialized labs. The device is a 23 × 43 cm platform that wirelessly transmits vertical ground reaction forces from under each corner as a user stands or moves on its surface. Commercial games using the WBB have been investigated as potential balance test substitutes [1,2], possible interventions for balance rehabilitation [3–8], and to reduce fear of falling [9,10]. However, the measured forces and COP are not directly accessible to the researcher in consumer video games. To overcome this, a few studies have used custom software to interface a computer to the WBB to measure vertical forces and COP [11,12] as well as provide real-time visual feedback for balance training [13–16].

The wide availability and apparent benefits of the WBB are tempered by the lack of sufficient information about accuracy and reliability of the WBB force and COP, which make it difficult to evaluate its appropriateness as a device for measuring balance control based on recommended criteria. The WBB has been reported to sample each force channel at ~100 Hz, which is above the 40 Hz minimum recommended for recording COP in postural sway [17]. The force sensors have been reported to be linear [18] with COP noise levels of approximately ±0.5 mm [19]. Further validation attempts have compared the COP path length during standing balance between the WBB and laboratory grade force plates [12,18,20]. However, information that is typically available for laboratory-grade force plates, such as the measurement uncertainty and reliability across a range of conditions, multiple devices, and the accuracy of the device's calibration values is currently unavailable.

Our goal was to provide the basic uncertainty metrics for static loads typically provided with calibrated force plates to allow researchers to evaluate whether the WBB is suitable for studying human balance [17] or other applications. We present a standard measurement uncertainty analysis that quantifies the repeatability and accuracy of a single sample of the WBB force and COP measurements. We also present the effects of wear from prolonged use in a student laboratory setting.

2. Methods

2.1. Wii Balance Board description, data interface, and devices tested

The WBB consists of a rigid platform with four uni-axial vertical force transducers located in the feet at the corners of the board, one

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transducer per foot (Fig. 1). Each transducer is a load cell consisting of a cantilevered metal bar with a strain gauge that converts applied force into a voltage that is digitized and transmitted wirelessly by electronics in the WBB [21].

To collect data from the WBB, data was streamed to a computer (Apple MacBook Pro, OSX 10.6) using the Bluetooth HID wireless protocol and custom programs written in Java (Oracle) and Matlab (Mathworks, Natick, MA); see online supplementary data for computer code. Commands to the WBB set the data stream to issue either calibration values or raw sensor values from each of the force transducers. Sensor values were reported as 4 channels of uncalibrated 16-bit digital data sampled at approximately 100 Hz. Internal calibration values were issued as three 16-bit numbers for each sensor that related the raw data stream to three calibration points. The calibration points were determined from regression of the stored values from the 9 boards and were found to be 0, 160, and 320 N, which differ slightly from those previously reported [21]. Raw sensor values were converted into Newtons using the calibration values and the initial offset was recorded when the board was first connected.

We tested 9 WBBs: 3 lightly used and 6 heavily used, and a laboratory-grade force plate (AMTI-OR6-6-1000, AMTI, Watertown, MA). The 3 lightly used boards were obtained from individuals who reported using their WBBs infrequently. The heavily used boards were obtained from an undergraduate teaching laboratory where they were used for student projects each semester since spring 2008 (4 years at time of testing).

2.2. Force calibration and method of force application

For testing the AMTI and WBBs, twelve separate masses spanning the range of 0.2–22.5 kg were calibrated (0.16, 0.28, 0.39, 0.94, 1.09, 1.30, 2.19, 2.20, 2.24, 11.04, 11.20, and 22.50 kg) using two laboratory grade force plates (AMTI OR6-6-1000 and MSA-6 amplifier with 1 kHz low-pass filter, 4000× gain, and 10 VDC bridge excitation). Each mass was centered on each force plate and data was collected from all force-plate channels with Vicon (Model 612, 16-bit ADC, 64-channel) at 1080 Hz for 1 s. We used the manufacturer supplied calibration matrix to determine the vertical ground-reaction force. Maximum difference in measurement between the two plates was less than 0.8 N, so the gold-standard value for each mass was calculated as the mean vertical force value of the two measurements divided by the gravitational constant (9.81 m/s/s).

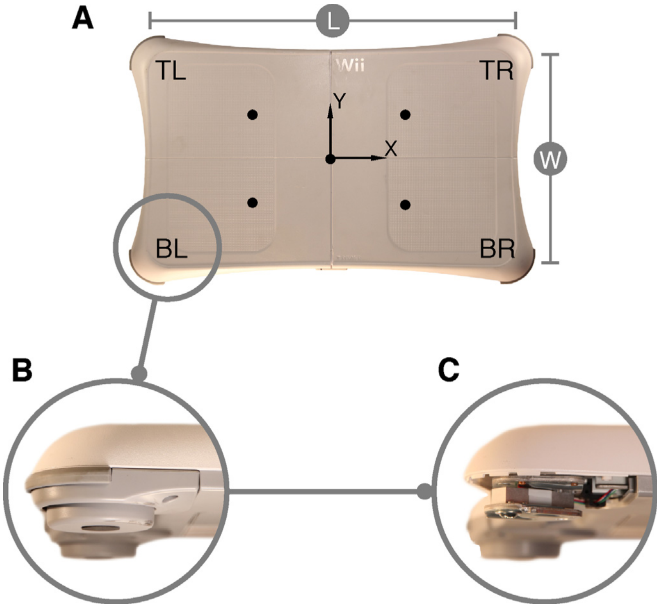

Fig. 1. WBB coordinate system and force transducers. (A) The top surface of the WBB is shown with the coordinates used for computing the COP, sensor locations and the abbreviated protocol testing locations. (B) Foot-pegs housing force sensors are found under each of the four corners of the board. (C) The force sensor consists of a metal beam and strain gauge that acts as a uni-axial force transducer.

Masses were applied at single points using a custom weight-applicator device (Fig. 2). The weight-applicator consisted of a 91 cm steel pole of mass 1.09 kg. The pole was used to apply the desired mass to the WBB with minimal surface area via a 7/16″ UNF acorn nut at the point of application.

2.3. Validation of force measurements

Accuracy of force measurements was done for all WBBs using combinations of the calibrated masses (0–26.8 kg). We did not measure accuracy of the AMTI force plates because they were used to calibrate the applied masses. The custom weight-applicator was used to apply masses to the center of each foot in the original enclosure with the top surface of the WBB face down on a stable surface (Fig. 2). Data were recorded for 0.5 s at each mass level, which were incremented in increasing then decreasing order.

A single lightly used WBB was selected for detailed measurement. The detailed force protocol was applied 5 times to each sensor using 20 different mass levels (no load, 1.1, 2.3, 3.6, 4.7, 5.4, 6.0, 7.2, 12.1, 12.8, 13.3, 14.6, 16.5, 17.2, 17.8, 19.0, 26.8, 27.5, 28.0, and 29.3 kg) for a total of 5 × 20 × 2 = 200 data points for each sensor.

All 9 boards (3 lightly used, 6 heavily) were tested using an abbreviated protocol. The abbreviated force protocol was applied 2 times to each sensor using 5 different mass levels (no load, 4.8, 12.1, 16.6, and 26.8 kg) for a total of 2 × 5 × 2 = 20 data for each sensor.

2.4. Validation of center-of-pressure

Accuracy of the COP calculation was tested for all WBBs and one AMTI force plate by placing different mass levels at specific spatial locations across the top surface of the device. Masses were applied with the custom weight-applicator and data at each location was recorded for 0.5 s. For the AMTI force plate, forces and moments recorded with respect to the device's calibrated plate center were used to calculate the COP and then translated so the corner of the

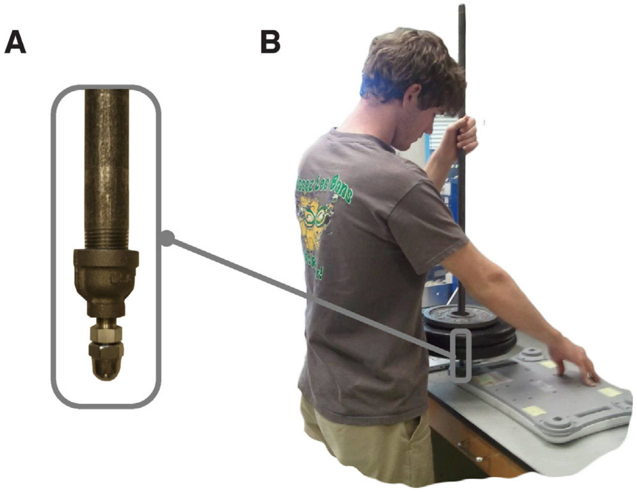

Fig. 2. Custom weight application device. (A) A custom weight-applicator consisting of a metal pole and 7/16″ acorn nut was built to apply concentrated point loads. (B) Calibrated masses were attached to the weight-applicator and the tip of the applicator was placed on the WBB at a desired location.

plate was the origin. For the WBB, COP was calculated using the center of the board as the origin and board dimensions of $W = 228$ mm and $L = 433$ mm as follows:

$$\mathrm{COP}_x = \frac{L}{2}\,\frac{((TR + BR) - (TL + BL))}{TR + BR + TL + BL} \tag{1}$$

$$\mathrm{COP}_y = \frac{L}{2}\,\frac{((TR + TL) - (BR + BL))}{TR + BR + TL + BL} \tag{2}$$

Detailed COP measurement of the single lightly used board was done with 2 different masses (14.3 kg and 45.8 kg) applied 5 times at 30 different locations distributed across the surface of the WBB resulting in $2 \times 5 \times 30 = 300$ data points.

Abbreviated COP measurements were taken from all WBBs and the AMTI force plate. The abbreviated protocol consisted of 2 different masses (14.3 kg and 45.8 kg) applied 2 times at 5 different locations resulting in $2 \times 2 \times 5 = 20$ data points (Fig. 1A).

2.5. Measurement uncertainty analysis

Accuracy and uncertainty were calculated for each device (WBB, AMTI) using measurements from detailed and abbreviated protocols. Uncertainty values were used to provide an estimate of the probable error in a measurement, which gave an interval about the measured value in which the true value was likely contained. The uncertainty analysis was formulated based on general NIST guidelines [22]. All statistical analysis utilized the Student's *t*-distribution with significance set at $p < 0.05$.

We analyzed several sources of error and computed mean uncertainty for four groups consisting of either the AMTI, lightly used WBBs, heavily used WBBs, or all WBBs. For each board we first computed the following measures of error: maximum absolute error, discretization error, repeatability error, and linearity error. Next, these were used to calculate the following components of uncertainty: instrument uncertainty (repeatability and linearity error); first-order uncertainty (operating error); and second-order uncertainty (protocol error). Instrument uncertainty was the root-sum-of-squares (RSS) combination of repeatability and linearity error. First-order uncertainty was calculated as the 95% confidence interval based on the maximum standard deviation observed for each board across all 1 s data samples. Second-order uncertainty calculated as the 95% confidence interval based on the standard deviation of all absolute errors found over the operating range. For each board, each uncertainty component was combined using RSS to estimate total uncertainty. Mean errors and uncertainty for each group was based on an average across devices. Equations for error and uncertainty metrics can be found in the online supplementary data.

All force sensor error metrics were calculated for the WBB groups using both factory-stored and regression-generated calibration values. Mean and maximum differences were recorded between the two calibration methods. Separate errors and uncertainties were calculated for each of the four force sensors and then combined using RSS to generate a combined board value. The effect of wear on force measurement was analyzed with a *t*-test between the mean absolute errors of the lightly and heavily used groups. Total uncertainty for the AMTI force measurement was 1.1 N based on the typical uncertainty (0.5%) of applied weight (222 N) as provided by the manufacturer [23].

COP error metrics and uncertainty values were calculated for the WBB groups (using the factory-stored calibration values) and one AMTI force plate. Location effects were analyzed across WBBs with a paired *t*-test comparing the mean absolute COP location error at the center and corner positions. Similarly, magnitude effects were analyzed with a paired *t*-test comparing the mean absolute COP error between light and heavy masses. Also, max absolute and repeatability errors in force magnitude were computed for the abbreviated COP protocol across all boards using the RSS of the four sensor values. The effect of wear on COP was analyzed with a *t*-test between the mean absolute errors of the lightly and heavily used WBBs. Total uncertainty for the AMTI force plate COP was calculated using typical instrument uncertainty of 1.5 mm supplied by the manufacturer [23].

3. Results

3.1. Uncertainty of force measurements

In the detailed protocol on a single WBB, similar force estimates were found using the regression-generated calibration values compared to the factory-stored calibration measure, thus factory-stored calibration values were used in all further analyses. Using regression-generated calibration values, the RSS combined values of the four force sensors had a max absolute error of 9.9 N, discretization error of 2 mN, linearity error of 4.0 N, and repeatability error of 3.5 N across tested operating points. The factory-stored calibration values resulted in a max absolute error of 12.1 N, discretization error of 2 mN, linearity error of 4.0 N, and repeatability error of 3.5 N. The maximum difference between the calculated values from the regression-generated and factory-stored calibrations was 1.6 N with a mean difference of 0.4 N.

Force measurement error and uncertainty were of the same order of magnitude between the detailed and abbreviated protocols when applied to a single WBB; therefore, we used the abbreviated protocol for analyses of all devices (Table 1). In both abbreviated and detailed protocols, total uncertainty was less than the combined maximum absolute error across all four sensors (±3.5 vs 1.7 N, upper-right; ±8.8 vs 2.0 N upper-left; ±2.1 vs 4.1 N lower-right; ±2.0 vs 7.7 N lower-left) (Table 2).

We found no difference between groups consisting of either lightly used WBBs, heavily used WBBs, or all WBBs in mean absolute error for the combined force sensors (Table 3). No statistically significant differences were found between the mean absolute errors of lightly (0.8 ± 0.3 N) and heavily (1.2 ± 1.2 N) used WBBs ($p = 0.26$).

3.2. Uncertainty of center-of-pressure

Similar levels of COP error and uncertainty were found in the detailed and abbreviated protocol when applied to a single WBB (Table 1), so the abbreviated protocol was used on all devices. COP errors in the long and short dimensions (COP_x, COP_y) were consistent across board location, load level, and board wear (Table 3). A statistically significant increase in mean absolute error of COP was found between the center (1.1 ± 0.3, 0.9 ± 0.3) mm and corner positions (2.0 ± 0.6, 1.9 ± 0.3) mm ($p < 0.004$) and also

Table 1
Comparison of detailed and abbreviated protocol results for a single lightly used board using factory-stored calibration values.

	Force (N)		COP_x (mm)		COP_y (mm)	
	Detailed	Abbrev.	Detailed	Abbrev.	Detailed	Abbrev.
Errors						
Max abs	12.1	9.0	6.3	5.4	12.8	6.9
Linearity	4.0	3.2	2.7	1.9	2.0	1.6
Repeatability	3.5	5.6	3.1	2.2	2.0	2.4
Uncertainty						
Instrument	5.3	6.4	4.1	2.9	2.8	2.9
First-order	6.7	2.8	3.0	2.3	2.5	1.7
Second-order	4.3	6.3	2.5	3.5	5.3	3.5
Total	9.6	9.4	5.6	5.1	6.5	4.9

Table 2
Comparison of error and uncertainty components from the abbreviated protocol across all WBBs using factory-stored calibration values.

Mean uncertainty components	Force (N)	COP_x (mm)	COP_y (mm)
Errors			
Max abs	10.3	3.7	4.1
Linearity	3.2	1.5	1.1
Repeatability	4.5	1.5	1.3
Uncertainty			
Instrument	5.5	2.1	1.7
First-order	2.6	2.6	1.5
Second-order	6.6	2.3	2.6
Total	9.1	4.1	3.5

between light (1.6 ± 0.4, 1.6 ± 0.2) and heavy (2.1 ± 0.8, 1.8 ± 0.2) mass levels ($p < 0.04$). Force magnitude had an average max absolute error across all of the boards of 10.6 ± 2.1 N and repeatability of 1.3 ± 1.4 N. Finally, no statistical difference was found in mean absolute error ($p = 0.16$, 0.79) between lightly (2.0 ± 0.3, 1.6 ± 0.2) mm and heavily (1.5 ± 0.4, 1.5 ± 0.2) mm used WBBs.

Mean absolute error in COP under the abbreviated protocol was not significantly different between the first WBB tested (1.6 ± 1.7, 1.7 ± 1.7) mm and the AMTI force plate (1.2 ± 1.1, 2.3 ± 1.7) mm ($p = 0.37, 0.24$). For the AMTI force plate, COP was found to have a max absolute error of (4.8, 5.6) mm, linearity error of (1.6, 2.3) mm, and repeatability error of (1.5, 1.6) mm across tested operating points. The total uncertainty of COP was ±(3.5, 4.7) mm made up of component uncertainties of ±(2.2, 2.8) mm instrument, ±(1.3, 1.0) mm first-order, and ±(2.4, 3.6) mm second-order.

4. Discussion

Here we have provided information about the accuracy and uncertainty of the WBB that may be used to evaluate the suitability of the WBB for various applications, and more specifically for human postural control measures. We found the total uncertainty of force measurements to be within ±9.1 N and COP location within ±4.1 mm across boards, which is much higher than the recommended uncertainty of 0.1 mm for posturography applications [17]. Repeatability of a single measurement within a board was better (4.5 N, 1.5 mm), suggesting that the WBB is best used for relative measures using the same device, rather than absolute measurement across devices. As previously reported, we also found that the WBB behaves linearly with only a slight increase (~1 mm) in COP measurement error for different locations across the board and increased magnitudes of weight. Also, the maximum absolute error and repeatability were similar whether load was applied to the surface of the board (max. abs. error: 10.6 N, repeatability: 1.3 N) or the individual sensors (max. abs. error: 12.1 N, repeatability: 3.5 N).

Table 3
Comparison of mean and standard deviation of total uncertainty across groups tested with the abbreviated protocol.

Total uncertainty						
Group	Force (N)		COP_x (mm)		COP_y (mm)	
	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.
WBB						
Lightly used	7.6	3.6	4.9	0.2	3.7	1.0
Heavily used	9.8	4.6	3.8	0.6	3.4	0.4
All	9.1	4.2	4.1	0.7	3.5	0.6
AMTI						
Data sheet	1.1	–	1.5	–	1.5	–
Measured	–	–	3.5	–	4.7	–

We did find that the WBB is likely robust in high use scenarios, as wear over 4 years did not significantly impact the performance of the devices. While encouraging, it is important to note that this is not sufficient evidence that the WBB has a lifetime similar to equipment in gait-laboratories that often last decades. Also, we found that the internally stored factory calibration values were comparable to the values we identified empirically as the mean error between these methods (0.4 N) was less than the total force uncertainty. Therefore, the WBB can be used off-the-shelf without additional calibration to achieve the aforementioned level of uncertainty. However, as with laboratory-grade force plates, frequent calibration of the device would result in less uncertainty of the measurement and improved accuracy.

Our uncertainty estimates are likely conservative due to limitations of our measurement protocol. Weight calibration was done with force plates in a laboratory setting, which likely was affected by environmental factors and the working condition of the equipment. These effects limited the accuracy and resolution of the gold standard measurement and made it impossible to directly compare force uncertainty between the WBB and AMTI force plate. Our force uncertainty for the WBB (±9.1 N) was greater than manufacturer reported values for the force plate (AMTI = ±1.1 N). However, the COP total uncertainty was similar in the WBB (±4.1, 3.5 mm) and AMTI force plate (±3.5, 4.7 mm). These results, coupled with high second-order uncertainty (protocol error), suggest variability in repeatedly placing masses in the same location on the surface of each device. By utilizing more precise methods for locating the mass on the surface, COP uncertainty for the force plate measurement may approach uncertainty values reported by AMTI (±1.5 mm) and instrument uncertainty (±2.1 mm) for the WBB.

In static analyses, the WBB may be sufficient to detect differences in postural sway of greater than 10 mm, which could distinguish healthy and impaired populations during standing balance [24]; however, it is a uni-axial device and it falls short of recommended accuracy for posturography of 0.1 mm [17]. Based on prior reports [1,12,15,16,18,20] and our preliminary analysis, the WBB samples at ~100 Hz, which should be sufficient to record low-frequency movements such as quiet standing (0.01–10 Hz) [25]. However, to fully validate the WBB, a thorough analysis of its cross-talk and dynamic properties must be completed.

In conclusion, the WBB is an inexpensive, portable device that may be useful for measuring vertical ground-reaction forces and COP with limitations on accuracy and precision. As the WBB is about an order of magnitude less accurate then a laboratory-grade force plates in vertical force measurement, and two orders of magnitude less accurate than recommended for COP location for posturography, it should not be considered to be equivalent to laboratory-grade equipment. However, if calibrated with laboratory-grade force plates, the WBB may provide an estimate of force and COP measures that could be useful for situations where lower accuracy and precision is acceptable.

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Conflict of interest statement

The authors have no conflict of interest and have no financial connection with Nintendo or AMTI.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gaitpost.2013.07.010.

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