Validation of the Balance Board™ for Clinical Evaluation of Balance Through Different Conditions

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Abstract. The quantitative assessment of balance still needs to be performed in a laboratory equipped with force plates because there is, currently, no other validated tool available. The Wii Balance Board™ (WBB) could be used as a portable, easy-to-use and inexpensive tool to assess balance. Before being used in clinics such kind of tool must go through an important validation process. In clinics not only the total displacement of Center of Pressure (CP) is relevant but other parameters can be derived from CP. The aim of this study was to validate the use of the WBB, compared to FP, in different balance testing conditions (standing and sitting) for multiple parameters derived from CP displacement (CP velocities, area of 95 % prediction ellipse, dispersion of CP from the mean position…). Fifteen subjects participated in this study and performed a combination of single and double legs standing balance tests and a sitting balance test. Bland and Altman plots, paired-sample T-Tests and Pearson's coefficient correlations were computed. For the nine studied parameters excellent correlations were found for each different task (mean correlation = 0.97). Unlike previous work on the WBB these excellent results were obtained without using any calibration procedure. Therefore, the WBB could be used in clinics to assess balance through different conditions.

Keywords: Balance · Force plate · Biomechanics · Motor control

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1 Introduction

The evaluation of balance and postural control is an important field in various domains such as health (e.g. preventions of falls in elderly people) [1], rehabilitation (e.g. balance training after stroke) [2] and sports (e.g. to increase athlete's performance or decrease injuries' risk) [3]. Even though this wide potential field of application, it appears that balance assessment using a force plate (FP) (i.e., during quantitative functional evaluation) in laboratory is not as used as it should be in clinics for patients' evaluation or follow up [4]. Despite this the measurement of the center of pressure (CP) using FP is considered as gold standard to assess balance [5]. This is probably due to the fact FPs are, most of the time, not transportable due to their embedment in the laboratory floor. Their relatively high price is also probably blocking their widespread use outside the laboratory. Access to this kind of tool is therefore limited and does not allow regular measurement for patient follow up or evaluation of a treatment if a specially-equipped laboratory is not available. In daily clinics evaluation of balance is performed using scales such as the qualitative Berg Balance Scale [6]. Despite the fact that these scales have been validated for various neurological conditions [7] they are not sensitive enough to detect small clinically relevant changes [6]. There is thus a need in clinics for portable, easy to use and cost-effective quantitative balance assessment tools. The Wii Balance Board™ (WBB) (Nintendo®, Kyoto, Japan), originally developed for video game control using CP displacements, meets the above criteria. Before being used in clinics such kind of devices must go through a strict validation process. Several works have been done to validate the WBB: estimation of CP path length during standing [8, 9] and force estimation [11]. In clinics, the WBB has been used to assess patients suffering from various diseases such as Parkinson's disease [12] or other conditions as for instance anterior cruciate ligaments injuries [13], and with elderly patients [14, 15]. The scope of these previous studies [8, 9, 12–14] was limited to the analysis of the CP path length during various conditions (double and single limb standing, eyes open or closed, simple or double tasks). However, more reliable and clinically-relevant parameters, such as the Total Mean Velocity (TMV), can be obtained from CP data [16]. The above studies are using a force calibration procedure prior to measurement. An important question that still needs to be answered is whether such a kind of calibration procedure is required in order to get clinically-meaningful results with the WBB. To the best of our best knowledge, no study has evaluated the possibility of the WBB for assessing posture in sitting position, although the study of postural control of patients unable to stand (e.g. paraplegia patients) is clinically of interest [17].

This paper is a complement to a publication presented in the workshop of the 8th International Conference on Pervasive Computing Technologies for Healthcare (PervasiveHealth '14) on the use of serious games to improve balance of cerebral palsy children [18].

The aim of this study was to validate a broad range of parameters derived from CP using the WBB without any calibration to assess posture during several conditions including sitting position what has, to our best knowledge, never been done in previous studies.

2 Material and Method

2.1 Participants

Fifteen young healthy adults (age = 24 (2) years, height = 172 (12) cm, weight = 66 (12) kg, 4 women) participated in this study. This study was approved by the Ethical Committee of the Erasme Hospital (CCB: B406201215142) and written informed consent was obtained from all subjects prior to their participation. No participants presented any neurological or orthopedic disorders and none of the subjects was taking medication at the time of the study that may have influenced balance or posture.

2.2 Procedures

A WBB (size 45 cm × 26.5 cm) was placed on the top of FP (AMTI model OR6-6, Watertown, MA, U.S.A., size 50 cm × 46 cm) that was embedded within the laboratory floor. This setting allows simultaneous measurement in order to eliminate bias introduced by subject variability if measurements were performed sequentially [9]. The WBB was connected to a laptop (Intel Core I5, Windows 7, 6 GB RAM) via Bluetooth connection, data were retrieved using a custom-written software based on the wiimotelib software [10]. WBB and FP data collection frequency were 100 Hz and 1000 Hz, respectively. The FP was calibrated before measurement. For the WBB no calibration procedure was used although some methods have been proposed [8, 9, 12–14]. Such calibration-free methodology was adopted because one of the purposes of this study was to evaluate the clinical WWB usability without the practical constraint of systematic calibration.

Participants performed a series of twelve balance tasks in a single session distributed as follows: three repetitions of double limb standing in the middle of the WBB (experimental condition called "Standing" in this study), four repetitions of double limb standing on four different locations on the WBB surface (right, left, front and back sides) ("Positions"), two repetitions of single limb standing (right and left respectively) ("Single Leg") and three repetitions of sitting in the middle of the WBB ("Sitting"). All these repetitions were performed eyes open. Subjects were instructed to stand as still as possible, arms aligned along the body and the eyes fixing a target on the wall in front of them (distance = 2.5 m, height = 1.8 m). The optimal trial duration during balance analysis is still controversial. To assess the body sway in adults 30 s was previously recommended [19]. Data were thus collected during 30 s for each trial. Multiple repetitions were asked in order to fight against inter-trial variability (e.g. positions of the foot on the WBB…).

2.3 Data Processing

Data processing was done using a custom-made Matlab code (The Mathworks, Natick, RI, USA) based on [22]. Previous works have shown that the time interval between samples of WBB were inconsistent [9] therefore linear interpolation of the raw signals of WBB sensors was applied to get a regular sample rate of 1000 Hz [20]. Both data from WBB and FP were then filtered using a second order Butterworth low-pass filter with a cutoff frequency of 12 Hz [8, 9]. For WBB CP, anterior-posterior (CP AP) and medio-lateral (CP ML) displacements were obtained from the 4 four strain gauge loads located at the four corners of the plate using Eqs. 1 and 2 respectively:

$$CPap = FL - PL + PR \tag{1}$$

$$CPml = PL - PR + PR + FL + FR \tag{2}$$

Where PL, PR, FL and FR are the force values from the posterior left, posterior right, anterior left and anterior right WBB sensors respectively [8].

For the FP, CP AP and CP ML displacements were obtained using Eqs. 3 and 4 respectively [21]:

$$CPap = \frac{-5.5 \times Fy - Mx}{Fz} \tag{3}$$

$$CPml = \frac{-5.5 \times Fx + My}{Fz} \tag{4}$$

CP was analyzed during 20 s (between the 5^{th} and the 25^{th} s of each trial).

Most of the papers comparing WBB and FP are only focusing on the total length of CP displacement during the trial [6–12] to analyze balance instability. In this paper, supplementary variables were processed from the available CP data [22]: - the total displacement of sway (DOT); - the area of the 95 % prediction ellipse (often referred to as the 95 % confidence ellipse [23, 24]) (Area); - the dispersion of CP displacement from the mean position (SD ap and SD ml); - the distance between the maximum and minimum CP displacement (AdCP ap and AdCP ml); - the mean velocity of CP displacement (MV ap and MV ml); - and the AP and ML displacements of the total CP sway divided by the total duration of the trial (TMV).

In summary, this study computed 9 variables from the data captured in four different conditions (i.e., “Standing”, “Positions”, etc.) resulting in 36 features to be compared between WBB and FP.

2.4 Statistical Analysis

Several statistical tests were performed as follows. All dependent variables were normally distributed (Kolmogorov-Smirnov test); therefore parametric tests were applied. For every parameter Pearson’s correlation coefficients (R), a two-way - random effects - single measure (mean of the trials) intra-class correlation coefficient (ICC) [25] and paired-sampled t-test were computed. Agreement between both devices was examined using Bland and Altman (B&A) plots [26]. After correlation analysis, linear regressions were used to correct results of WBB based on FP data (regression equations are available from Fig. 1); a leave-one-out method was used to evaluate these equations [27]. Those corrected WBB results were compared with FP using paired-sampled t-test, Pearson's correlation and the normalized root-mean square error ($NRMSE = \frac{RMSE}{(WBB + FP)/2} \times 100$). All statistical analysis was conducted using Matlab.

3 Results

Table 1 presents the mean results and statistics of the variables for the four different conditions before applying regressions on WBB data. Linear regression equations and correlations for the four conditions are presented in Fig. 1. Bland & Altman plots are presented in Fig. 2. In order to avoid any bias, due to the fact that for some conditions four trials were recorded and for others one only two, mean values of the conditions were plotted.

Only 4 out of the 36 variables studied did not present statistically significant differences between WBB and FP (paired sampled t-test). However, high correlations were found for every parameter: mean R values were 0.97 for total results (not taking into account the task performed) and 0.92, 0.90, 0.79 and 0.89 for Standing, Single leg, Sitting and Positions respectively.

Those high correlations allow correcting results of the WBB in order to have similar results as those obtained with FP. Equations used to correct these results and codes to calculate these variables in Matlab are presented in Table 2. Results before and after corrections (using leave-one-out method) are presented in Table 3. After correction mean values were similar for correlation (R = 0.97 and 0.96 before and after regression, respectively), very highly significantly increase for P-value ($p < 0.001$ before and $p = 0.97$ after regressions) and the NRMSE is decreased from 25 to 20 %. Results for the different conditions are presented in Table 4.

4 Discussion

Our results are comparable with previous studies concerning CP path length (DOT) in standing position. We also found good correspondence (mean R values = 0.97) between results obtained with WBB and FP in standing positions (double or single leg stance) [8, 9, 12]. Additional to DOT we computed 8 variables that are clinically relevant for posture analysis. According to the FP literature, approximately 40 parameters can be derived from CP including the mean velocity that is considered as the variable offering the highest reliability among different trials [16]. Another FP-based study underlined the importance of the speed by reporting that peak velocity showed the highest reliability [28]. One previous study has shown that WBB and FP show similar results for CP path velocity during single or double legs stance [9]. In this study, the highest correlations were found for TMV during Standing and Single leg compared to correlation for DOT (ICC = 0.96 and R = 0.86 for Standing, ICC = 0.96 and R = 0.92 for Single leg) (values obtained before regression correction, see Table 1). Sitting correlation was found higher for DOT (R = 0.88) than for TMV (R = 0.78). Measurement of velocity of the displacement of CP during single or double legs stance have been found comparable with WBB and FP, similar results were found after

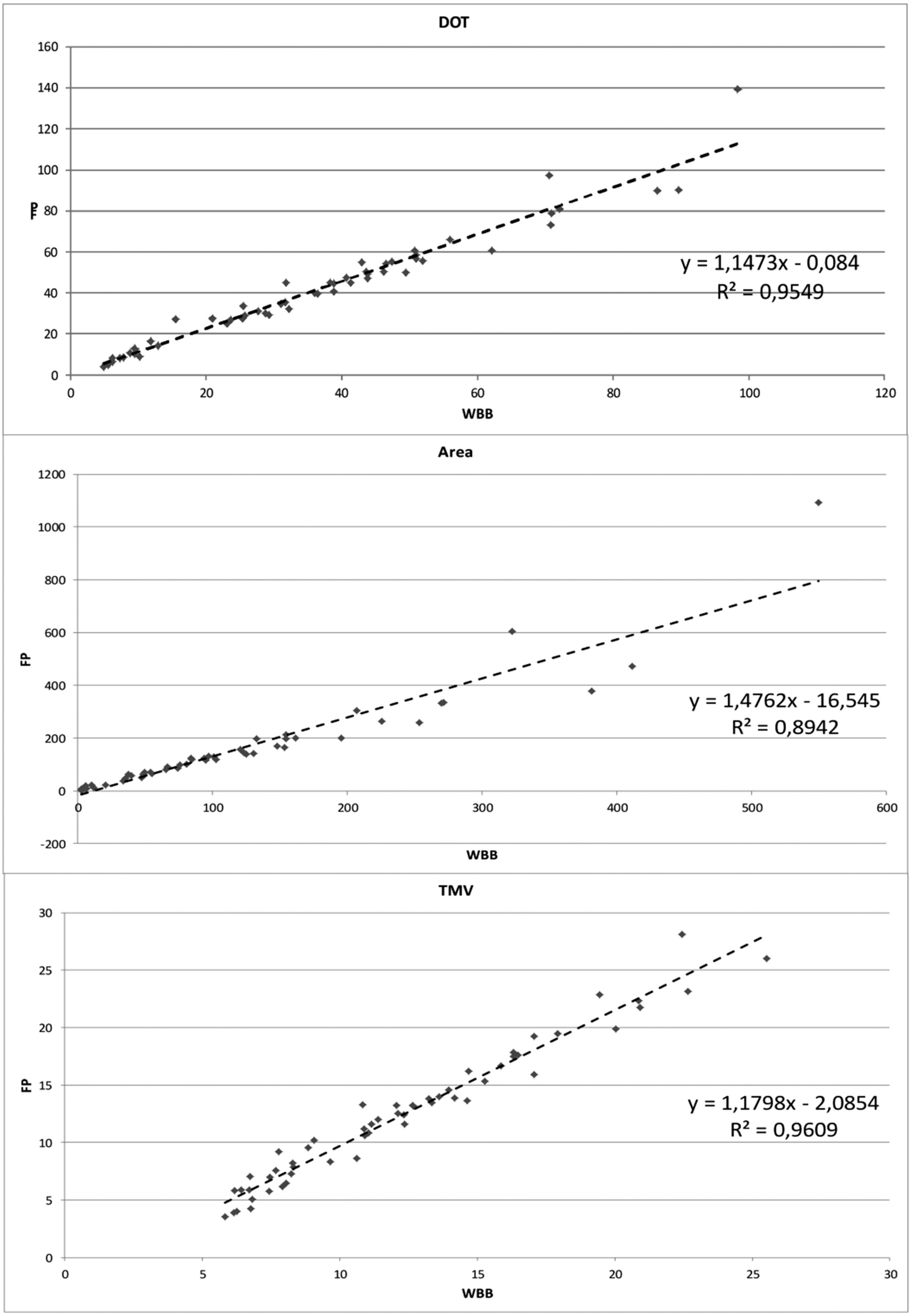

Fig. 1. Scatter plots, correlation lines and equations for three features (DOT, Area and TMV). For each of the four conditions, the mean value over the different conditions was plotted (4 conditions × 15 subjects).

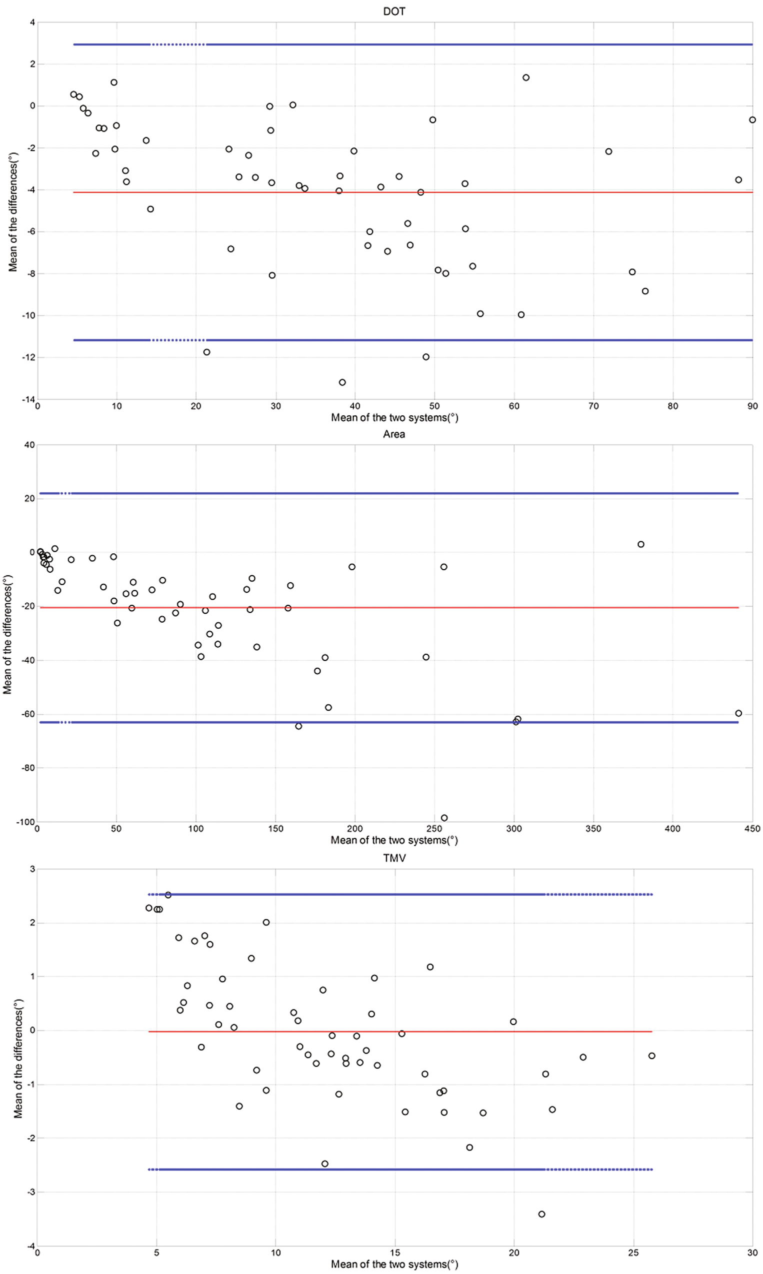

Fig. 2. Bland & Altman plots for three features (DOT, Area and TMV) before regression. For each different condition the mean values were computed (4 × 15 = 60 trials). Red lines (middle one) represent the mean difference between the devices. Blue lines (extremities) indicate upper and lower agreements (1.96 SD).

Table 1. Mean (std) results for the processed variable, Pearson's coefficient correlation (R), IntraClass Correlation Coefficient (ICC) and P-value of paired-sampled t-test. Results obtained before applying linear regression on the WBB results.

	Variable	*WBB*	*FP*	*R*	*ICC*	*P-value*
Standing	DOT	32 (11)	37 (13)	0.86	0.92	<0.001
	Area	64 (34)	81 (38)	0.95	0.97	<0.001
	RMS ap	1.4 (0.63)	1.6 (0.74)	0.95	0.97	<0.001
	RMS sl	2.6 (0.84)	3.0 (0.91)	0.84	0.91	<0.001
	AdCP ap	7.2 (3.2)	8.4 (3.7)	0.92	0.95	<0.001
	AdCP ml	12.1 (3.8)	13.8 (4.1)	0.87	0.93	<0.001
	MV ap	6.3 (1.9)	5.9 (3.1)	0.96	0.93	0.07
	MV ml	8.0 (2.4)	8.5 (2.7)	0.96	0.98	<0.001
	TMV	11.3 (3.3)	11.6 (4.5)	0.96	0.96	0.2
	Variable	*WBB*	*FP*	*R*	*ICC*	*P-value*
Single leg	DOT	118 (29)	125 (31)	0.92	0.96	0.004
	Area	730 (333)	828 (378)	0.91	0.95	0.003
	RMS ap	5.5 (1.5)	6.0 (1.5)	0.89	0.94	<0.001
	RMS sl	7.1 (1.9)	7.4 (2.1)	0.88	0.93	0.14
	AdCP ap	26.6 (7.1)	29.3 (7.3)	0.86	0.92	<0.001
	AdCP ml	35.1 (9.3)	36.2 (11.1)	0.80	0.88	0.39
	MV ap	31.1 (9.3)	32.9 (9.7)	0.96	0.97	0.002
	MV ml	26.8 (7.8)	27.7 (7.9)	0.96	0.97	0.06
	TMV	45.1 (12.7)	47.3 (13.1)	0.96	0.98	0.005
	Variable	*WBB*	*FP*	*R*	*ICC*	*P-value*
Sitting	DOT	8 (3)	9 (4)	0.88	0.92	<0.001
	Area	5 (5)	8 (9)	0.80	0.81	<0.001
	RMS ap	0.8 (0.5)	0.9 (0.5)	0.74	0.85	0.006
	RMS sl	0.4 (0.2)	0.4 (0.2)	0.90	0.92	<0.001
	AdCP ap	4.7 (2.7)	5.8 (3.1)	0.70	0.82	0.004
	AdCP ml	1.9 (0.9)	2.6 (1.5)	0.84	0.85	<0.001
	MV ap	5.9 (1.7)	5.1 (2.1)	0.79	0.87	<0.001
	MV ml	3.2 (0.6)	3.1 (1.0)	0.66	0.72	<0.001
	TMV	7.4 (1.8)	6.5 (2.4)	0.78	0.86	0.001
	Variable	*WBB*	*FP*	*R*	*ICC*	*P-value*
Positions	DOT	59 (26)	66 (32)	0.92	0.95	<0.001
	Area	220 (187)	292 (290)	0.88	0.88	0.001
	RMS ap	2.9 (1.5)	3.3 (1.8)	0.90	0.94	<0.001
	RMS sl	3.8 (1.6)	4.2 (1.9)	0.83	0.89	0.004
	AdCP ap	14.3 (7.3)	17.3 (10.8)	0.82	0.86	<0.001
	AdCP ml	18.9 (8.4)	21.5 (11.0)	0.78	0.86	0.008
	MV ap	9.3 (3.7)	9.4 (4.8)	0.94	0.96	0.65
	MV ml	11.9 (5.3)	12.6 (5.9)	0.96	0.98	0.01
	TMV	16.9 (6.6)	17.5 (7.9)	0.96	0.97	0.08

regression (Table 3) suggesting us that the WBB could be used to assess these parameters that are the more sensible to compare different age group or different health conditions [29]. Unlike the other previous studies, no calibration procedure was used before measurements. However, results were highly correlated using directly the WBB without any previous step. In order to get similar results with WBB and FP regression equations, were directly integrated into the code used to process these variables from

Table 2. Variables obtained from CP and codes, including correction by regression, to calculate these variables in MATLAB (adapted from [22]). Before using these codes the tendency of the CP signal must be removed (using "detrend" function).

	Code	Regression
DOT	`DOT = sum(sqrt(CPap.^2 + CPml.^2)`	1.1473*DOT-0.084
Area	`[vec,val] = eig(cov(CPap,CPml));` `Area = pi * prod(2.4478 * sqrt(svd(val))`	1.4762*Area-16.545
RMS ap	`RMSap = sqrt(sum(CPap.^2) / length (CPap))`	1.149*RMS ap +0.0196
RMS sl	`RMSml = sqrt(sum(CPml.^2) / length (CPml))`	1.1289*RMS ml +0.0255
AdCP ap	`AdCPap = max(CPap) - min(CPap)`	1.2667*AdCP ap-0.7107
AdCP ml	`AdCPml = max(CPml) - min(CPml)`	1.1464*AdCP ml-0.03
MV ap	`MVap = sum(abs(diff(CPap))) * freq / length(CPap)`	1.2533*MV ap-2.1774
MV ml	`MVml = sum(abs(diff(CPml))) * freq / length(CPml)`	1.1104*MV ml-0.5389
TMV	`TMV = sum(sqrt(diff(CPap).^2 + diff (CPml).^2)) * freq / length(CPap)`	1.1798*TMV-2.0854

Table 3. Mean (std) differences (WBB-FP), Pearson's coefficient correlation, P-value of paired-sample t-test and NRMSE for the different variables before and after correction of the WBB results using linear regression.

	PRE				POST			
	Diff.	R	P	NRMSE	Diff.	R	P	NRMSE
DOT	−5 (7)	0.98	<.001	22	0 (6)	0.97	.97	16
Area	−34 (80)	0.95	.002	69	−1 (73)	0.92	.88	51
RMS ap	−0.3 (0.3)	0.98	<.001	21	0 (0.2)	0.97	.99	14
RMS ml	−0.3 (0.5)	0.96	<.001	23	0 (0.5)	0.96	.96	19
AdCPap	−1.7 (2.3)	0.96	<.001	28	0 (1.9)	0.95	.98	19
AdCPml	−1.7 (3.1)	0.95	<.001	27	0 (3.0)	0.94	.98	24
MV ap	0.3 (1.1)	0.96	.02	15	0 (0.9)	0.96	.97	12
MV ml	−0.4 (0.9)	0.99	.003	11	0 (0.8)	0.98	.99	10
TMV	−0.1 (1.4)	0.98	0.52	12	0 (1.2)	0.98	.98	10
MEAN	/	0.97	<.001	25	/	0.96	.97	20

CP. This approach is hence more user-friendly compared to an approach where a calibration procedure is required prior to the use of the WBB.

The use of the WBB to assess balance in sitting position was not tested before despite the fact that the quantitative evaluation of sitting balance is being studied for patients that cannot stand (independently) [17]. Results of our study suggest that the

Table 4. Pearson's coefficient correlation, P-value of paired-sample t-test and NRMSE for the different variables after correction of the WBB results.

	Variable	*R*	*P-value*	*NRMSE*
Standing	DOT	0.85	0.97	20
	Area	0.95	0.97	17
	RMS ap	0.95	0.92	15
	RMS sl	0.82	0.99	18
	AdCP ap	0.91	0.93	19
	AdCP ml	0.86	0.97	16
	MV ap	0.96	0.95	15
	MV ml	0.95	0.98	10
	TMV	0.95	0.97	12
	Variable	*R*	*P-value*	*NRMSE*
Single	DOT	0.91	0.93	11
	Area	0.90	0.93	21
	RMS ap	0.87	0.93	13
	RMS sl	0.86	0.88	15
	AdCP ap	0.81	0.82	15
	AdCP ml	0.77	0.96	19
	MV ap	0.95	0.92	10
	MV ml	0.95	0.97	9
	TMV	0.95	0.93	9
	Variable	*R*	*P-value*	*NRMSE*
Sitting	DOT	0.87	0.95	25
	Area	0.72	0.97	92
	RMS ap	0.68	0.86	44
	RMS sl	0.85	0.92	33
	AdCP ap	0.64	0.93	47
	AdCP ml	0.82	0.90	37
	MV ap	0.76	0.84	25
	MV ml	0.65	0.97	23
	TMV	0.75	0.84	23
	Variable	*R*	*P-value*	*NRMSE*
Positions	DOT	0.92	0.97	21
	Area	0.86	0.95	59
	RMS ap	0.89	0.99	27
	RMS sl	0.81	0.97	28
	AdCP ap	0.80	0.98	40
	AdCP ml	0.75	0.98	35
	MV ap	0.94	0.99	17
	MV ml	0.96	0.98	14
	TMV	0.95	0.99	14

WBB provides results that are correlated with results of the FP even if those correlations are lower than for standing conditions (R = 0.79 compared to R = 0.92 for double legs and R = 0.90 for single legs). This lower correlation could be due to the hardware configuration of the WBB, as it is composed of four strain gauge load sensors.

A previous study has estimated dead weight noise and how this noise can affect the measurements [30]. The same study suggested that the noise can be increased when CP velocities are low [30]. Our results obtained in the sitting condition confirm this; the WBB seems less sensitive when CP amplitudes and velocities are low.

Due to the hardware configuration and the low price of the WBB it might be expected that the position of the subject relative to the sensors could influence the results. Subjects were asked to stand at the four extreme positions of the WBB, results were compared to FP and expressed in percentage (100 % is the results of FP). An ANOVA was applied to compare differences between WBB and FP for the four positions and the position in the middle of the WBB. No difference was found for the five positions. A graphical representation of these results is presented in Fig. 3. It is interesting to note that for the different positions CP displacements are higher than for the centered positions. Since these results are higher for both WBB and FP we can assume that it is not due to the WBB. These results are probably due to the fact that when the subject is standing at the side of the WBB, his balance is less stable, inducing an increase in the base of support. In clinics it is not possible to ensure that all subjects always stand on exactly the same spot on the balance board, but it is expected that subjects stand more or less in the middle of the WBB. Our results show that small position changes on the WBB do not influence the results.

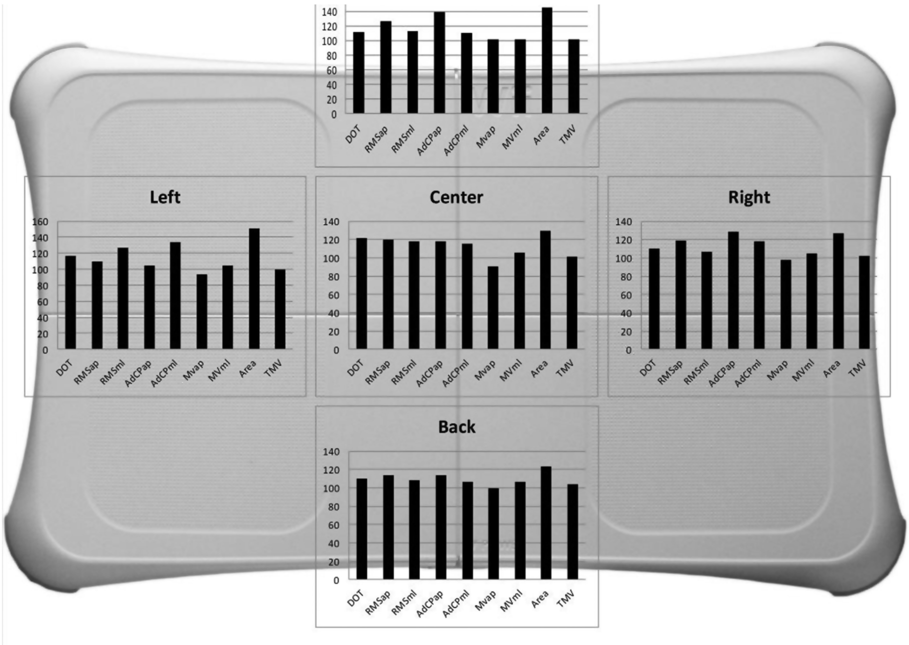

Fig. 3. Influence of the position of the body related to the WBB on the results. Results of the WBB are expressed in percentage of FP's value. No significant statistical difference was found between the different positions (ANOVA).

5 Conclusion

This study confirms the good results previously presented of the WBB compared to gold standard laboratory FP. This study provides relevant additional data. The first aspect is that it is not required to perform any calibration procedure prior to using the WBB to assess balance. Instead of a calibration procedure we directly applied regression equations within the code used to provide clinical parameters derived from CP displacement. The WBB provides comparable data for displacements and velocities derived from CP in standing (double or single legs) and sitting positions. The position of the subject relative to the WBB does not have influence on the results. Therefore the WBB can be used to assess and to follow in a quick and inexpensive way the patients' evolution.

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