Investigating normal day to day variations of postural control in a healthy young population using Wii balance boards

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***Abstract*— The quantification of postural control (PC) provides the opportunity to understand the function and integration of the sensorimotor subsystems. The increased availability of portable sensing technology, such as Wii Balance Boards (WBB), has afforded the capacity to capture data pertaining to motor function, outside of the laboratory and clinical setting. However, prior to its use in long-term monitoring, it is crucial to understand natural daily PC variation. Twenty-four young adults conducted repeated static PC assessments over 20 consecutive weekdays, using WBBs. 16/24 participants (eyes open) and 11/24 participants (eyes closed) exhibited statistically significant differences (p <0.05) between their initial 'once-off' measure and their daily measures of PC. This study showed that variations in PC exist in a healthy population, a once-off measure may not be representative of true performance and this inherent variation should be considered when implementing long-term monitoring protocols.**

I. Introduction

Measurement of postural control (PC) affords a critical window into sensorimotor function, providing a means to evaluate risk of injury/ pathology [1], track recovery and measure response to intervention [2]. Traditionally, PC can be evaluated using a range of static and dynamic protocols. While these protocols have demonstrated value clinically, the scoring systems are subjective and lack sensitivity [3].

To address these limitations, researchers often use force platform derived center of pressure (COP) variables to capture subtle changes in sensorimotor performance [4]. However, such systems are expensive, time consuming, and are rarely available outside of the laboratory. Recently, novel ways of collecting COP data have been demonstrated using technology such as Wii Balance Boards (WBBs) [5]. WBBs possess excellent test-retest reliability, concurrent validity [6] and are consistent and sufficiently accurate, providing an accessible alternative to traditional force platforms [7].

When investigating PC, a once-off measure is typically used to represent a person's 'true' state of function; however, it has been reported that a once-off clinical evaluation of PC, taken weeks or months apart, may not be representative of a person's typical state [8]. As such, if this technology is to be considered for use within the clinical context, tracking long-term fluctuations in performance, then it is critical to understand the inherent natural biological variation captured by these tools. One recent study found that in healthy elderly adults, a once-off clinical measurement may not provide a true picture of a person's PC performance, with participants demonstrating natural variation across an 8-week period [8]. Importantly, while PC performance differs between healthy young and elderly adults [9], no research has sought to characterize PC variability in a young healthy population.

The aims of this study were to investigate daily variations in eyes open (EO) and eyes closed (EC) PC performance across a 4-week period, and investigate if a once-off measure can be considered representative of an individual's true PC performance. It was hypothesized that daily variations in performance exist and a once-off measure may not be representative of a person's true PC.

II. Methods

A. Participants

Twenty-six participants aged 18 – 40, a sample of convenience, were recruited from the wider university population. Exclusion criteria for the study were (1) acute pain preventing comfortable, typical movement, (2) vestibular disorders, (3) visual impairments, (4) neurological disease, (5) recent spells of reported dizziness and/or nausea, (6) lower limb injuries within the last 6 months, (7) long term lower limb immobilization, (8) medications affecting balance and (9) BMI >30. Two participants withdrew from the study within the first two weeks of testing, citing time constraints and lower limb injury, leaving data from 24 participants for analysis. The Institution's Ethical Review Board approved all experimental procedures involving human subjects. All participants provided informed consent and were free to withdraw from the study at any time.

A. Experimental Procedure

Testing was carried out over a 4-week period, Monday-Friday between the hours of 08:00-10:00 am. Day 1 was considered the 'once-off' measure. On this day, participants were required to read an information leaflet and give informed consent. Demographic data was collected, and participants were assigned a specific WBB to account for any discrepancies between WBBs that may be present as a result of the manufacturing process [5]. Each day, participants stood barefoot on their allocated WBB and completed a 40 second EO and EC static PC trial. During the trials, individuals were

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directed to look straight ahead, keeping their hands by their sides. Daily testing was performed in the same manner for days 2-20, taking approximately 3 minutes.

A. Signal Processing

Quantitative PC data were acquired from the WBBs during the EO and EC quiet standing trials. The data was streamed via Bluetooth to a custom-developed Android application run on a tablet computer (Galaxy Tab A, Samsung). The data processing procedure was carried out in line with previously published methods [8]. Due to the uneven sampling of the COP coordinates, after their calculation for each sample, the time series were interpolated to be evenly sampled at 40 Hz. The COP time series were then filtered through an 8th order zero phase Butterworth low-pass filter with a 5 Hz cut-off frequency. The first and last 3 seconds of the PC data was excluded to allow adequate time for balance stabilization. The remaining 34 seconds of data for each trial was used for analysis. Four PC variables for both EO and EC were collected as per Prieto *et al.*[10]: mean COP distance, sway length, sway area and mean sway frequency.

B. Statistical Methods

Normality of distribution was confirmed using histograms and Shapiro-Wilk tests. Intra-class correlations coefficients (ICC 2, k) were calculated to examine the reliability of each of the four PC parameters across the testing points. Full data sets were available for 18 out of 20 days. To account for missing days, ICCs were calculated for these full data sets. ICC values were described in accordance with the classification system outlined by Cicchetti and Sparrow [11], where a score of ≥ 0.75 was considered excellent, $0.74 - 0.40$ was considered fair to good and < 0.4 was considered poor. Standard error of measurement (SEM), was calculated using the formula:

$$SEM = SD \times \sqrt{(1 - ICC)}$$

where SD was the standard deviation of the mean values (days 2-20) across participants and ICC was the reliability statistic. Minimal detectable change (MDC) was calculated using the formula:

$$MDC = SEM \times 1.96 \times \sqrt{2}$$

The MDC percentage (MDC%) is the MDC divided by the mean. An MDC% of less than 30% is considered acceptable [12]. One-sample t-tests were used to compare the day 1 measure to the day 2-20 measures for each individual. Finally, Romberg ratios were calculated to quantify the impact of the visual system on balance stabilization, whereby the mean values of the EC measures were divided by the mean values of the EO measures.

III. Results

Twenty-four participants (9 female, age 23 ± 3.7 years, height 1.8 ± 0.1m, body mass 72.1 ± 13.3kg, BMI 23.2 ± 2.5), attended an average of 19 out of 20 days. Descriptive and variability statistics are presented in TABLE I. CV ranged from 12-30% for the EO and 16-32% for the EC variables, with mean COP distance possessing the lowest coefficient of variation (CV) across both visual conditions. MDC% demonstrated acceptable measurement error (<30%) for 7/8 parameters. ICC values across all parameters ranged from fair to excellent (> 0.40) for both EO and EC variables. 16/24 participants (EO) and 11/24 participants (EC) exhibited statistically significant differences ($p < 0.05$) between their once-off measure and the continuous daily measures, across all four variables. Statistically significant differences were found for EC testing conditions for mean COP distance (18 participants), sway length (21 participants), sway area (19 participants) and mean frequency (11 participants). EO conditions showed statistically significant differences in mean COP distance (16 participants), sway length (17 participants), mean frequency (16 participants) and sway area (17 participants).

Fig. 1 illustrates the spread of the data for each participant, across the 4-week period for EO sway length, highlighting the inherent variability within participants. The EC condition demonstrated greater degrees of variation when compared to the EO testing conditions for all parameters, however there was only a minimal difference between EO and EC conditions with Romberg ratios ranging from 0.76 - 0.92.

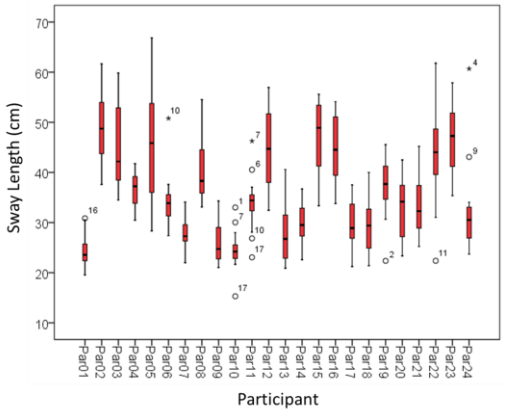

Fig 1: A boxplot demonstrating the EC sway length for the 24 participants. Day numbers next to an o represent outliers (>1.5xIQR) whilst a * represent extreme outliers (>3xIQR).

IV. Discussion

The findings from this study are significant, as they elucidate that patterns of static PC variation exist, and a once-off measure may not be representative of an individual's true performance.

The primary aim of this study was to investigate variations in PC in a healthy young population and determine if a once-off measure of PC sufficiently represents an individual's performance over a 4-week period. The CV provides a means to evaluate the precision and repeatability of the PC measurements, demonstrating a CV of 12%-30% (EO) and 16%-32% (EC). When the CV is viewed in conjunction with the SEM, MDC and MDC%, it is observed that 3/4 EO variables and all EC variables demonstrated acceptable levels of random error measurement (MDC% < 30%) (TABLE I). Importantly, only sway area EO did not demonstrated acceptable MDC%, with sway length and mean sway frequency (EO & EC) demonstrated the lowest MDC%. For example, the group mean EO sway length was 27.73cm, with an MDC of 3.60cm. This suggests that in a long-term monitoring protocol, a change of > 3.60cm in sway length is

TABLE I: The descriptive (mean and SD) and variability statistics (CV, ICC (95% CI), SEM, MDC and MDC%) for all four variables, across both visual conditions. In addition, the Romberg ratio (EC/EO) is presented to capture the differences in performance between EO and EC conditions.

Postural Control Variables		Mean	SD	CV %	ICC	95% CI	SEM	MDC	MDC%	Romberg Ratio
Eyes Open	Mean COP Distance (cm)	0.46	0.05	11.79	0.59	(0.30-0.79)	0.04	0.10	21.00	0.84
	Sway Length (cm)	27.73	5.35	19.30	0.94	(0.90-0.97)	1.30	3.60	12.99	0.77
	Sway Area (cm^2)	47.60	14.17	29.77	0.80	(0.66-0.90)	6.30	17.48	36.71	0.76
	Mean Sway Frequency (Hz)	0.34	0.05	16.12	0.85	(0.74-0.92)	0.02	0.06	17.59	0.92
Eyes Closed	Mean COP Distance (cm)	0.55	0.09	15.71	0.80	(0.68-0.90)	0.04	0.11	19.27	-
	Sway Length (cm)	36.07	8.07	22.38	0.96	(0.93-0.98)	1.59	4.42	12.25	-
	Sway Area (cm^2)	62.80	20.19	32.15	0.90	(0.83-0.95)	6.32	17.52	27.89	-
	Mean Sway Frequency (Hz)	0.37	0.08	22.94	0.93	(0.88-0.97)	0.02	0.06	16.82	-

required to be considered 'clinically real'.

The ICC results ranged from 0.59 - 0.94 (EO) and 0.80 - 0.96 (EC), with mean COP distance consistently showing the lowest, and sway length demonstrating the highest ICC, across both EO and EC visual conditions. While it is not overtly clear why the EO condition generally possessed lower ICC scores, one potential explanation is the lower level of inter-subject variability shown by the EO conditions, potentially serving to depress the ICC scores [13]. As a result, when the ICC scores are viewed in conjunction with the CV, it is observed that the inter-subject variability is likely greater than intra-subject variability across most variables. While the intra-session reliability of COP measures in a young population has previously been demonstrated for both EO and EC testing conditions, no research has investigated the reliability and inherent variability of measures of PC over a prolonged period, in a young healthy population.

Previous research investigating the reliability of WBB COP measures has detailed the intra-day variability over two different measurements, where ICC scores of greater than 0.90 were observed for both EO and EC sway path length [14]. This indicates that their observed levels of intra-day variability are comparable to the levels of inter-day variability observed in our study. However, this comparison should be viewed with caution due to the different ICC methods used in these studies. Previous research has demonstrated differences in PC between young and elderly populations [9]. As such, our findings can be compared to those of McGrath *et al*. [8]. Generally, it appears that a young population investigated in the present study demonstrates lower levels of variability than the older cohort reported by McGrath *et al.* [8]. They found that sway length and mean sway frequency demonstrated the lowest intra-individual variability in an elderly population. In this study, mean COP distance across both testing conditions demonstrated the lowest level of variability, followed by sway length and mean sway frequency. An important difference between this study and the current study is that the former was home-based and unsupervised, whereas our study was a supervised clinic-based protocol. The main consequence of this is that one might expect less variability (age group) and measurement error (supervised environment). As such, we conclude that the variability that was observed in our study is natural biological variation that exists in the expression of PC on a day-to-day basis, supporting the argument that these parameters may be used as part of a daily monitoring program.

The second aim of our study was to determine if a once-off measure of PC sufficiently represents an individual's performance over a protracted period. One sample t-tests found that both EO (16/24) and EC (11/24) exhibited statistically significant differences across all 4 variables. When viewed in conjunction with the variability analysis, it is evident that as variation increases, there is an increased likelihood that a once-off measure may be statistically different from daily measures. Despite this, it is unclear at what cut-off point a person's once-off measure does not represent their true PC, supporting the findings of McGrath *et al.* [8]. The results presented in this paper are important as they indicate that while the WBB derived measures of PC are reliable and demonstrate relatively low levels of random error variation, a single 'once-off' measurement does not sufficiently represent an individual's PC over time. As such, the work presented in this study and that of McGrath *et al.* [8] would suggest that long-term measurement protocols may be more suitable for the evaluation of PC performance.

The third aim of this study was to compare patterns of fluctuation between COP measures in EO and EC static stance. Romberg ratios demonstrated a minimal difference between EO and EC testing conditions across all parameters (0.76-0.92). Importantly, across the four variables, the EC condition consistently elicited more instability than the EO condition. However, as the difference was small, this suggests that different visual conditions do not appear to have a large impact on PC in this young healthy population. The lack of a large difference between visual conditions may be as a result of eye closure not adequately challenging the young healthy population [3].

This study has identified that natural biological variation exists in COP measures. This suggests that individual level long-term monitoring protocols may be more appropriate and provide more valuable information than traditional once-off measures. Continuous monitoring may be utilized to determine an individual's baseline pattern of variation. This may be applied in clinical practice through long-term tracking of injury/ pathology risk, recovery and response to interventions. For example, fatigue has been shown to negatively influence PC performance [15, 16], potentially increasing an individual's propensity to injury [17]. As such, longitudinal monitoring paradigms may be used to model an individual's 'normal' PC, with large alterations outside of an acceptable range aiding in the identification of those who may be at an increased risk of pathology. Furthermore, such

methods may be used to help identify when an individual's performance has returned to pre-injury levels to ensure safe return to activity. For example, concussion is one of the most common sports injuries and has been shown to negatively influence PC. However, traditional measures lack sensitivity and typically do not detect alterations beyond 3 - 4 days [18]. Despite this, recent research has demonstrated that individuals may possess PC deficits beyond recovery [19], potentially contributing to an increased risk of future injury [20]. As such the longitudinal tracking of PC may allow the monitoring of an individual's recovery, helping to ensure athletes are safe to return to play. However, further research is required to determine if longitudinal measurement of PC can provide clinically useful, population specific information about an individual's motor function.

Some key limitations of this study should be acknowledged. Firstly, a relatively small sample size was employed, potentially influencing statistical power. However, the time-intensive requirements placed on volunteers in this study hampered the recruitment of a larger cohort. Secondly, weekend testing was not conducted throughout this study due to time-constraints on participants. However, it has been suggested that testing PC every three days may sufficiently detect changes in PC performance in a long-term monitoring programs for otherwise healthy older adults [8]. Thirdly, the presented study did not take into account the impact of changes in an individual's activity, health-status, fatigue and sleep, among other factors. Thus, further research should investigate the effect such contextual factors have on the long-term fluctuations in PC.

V. Conclusion

This study was the first to characterize inherent natural biological variation in static PC in a young healthy population. This research demonstrated that a once-off measure of PC may not be truly representative of a person's sensorimotor state, and that levels of variation were comparable between EO and EC conditions. This indicates that long-term monitoring paradigms may be more appropriate than traditional methodologies in the quantification of injury/ pathology risk, recovery and response to intervention. However, the results presented within this paper should be interpreted within the context of the young cohort and the modest sample-size. Further research should investigate the utility of long term-monitoring paradigms within clinical contexts, aiding the development of digital biomarkers. Furthermore, research should investigate the effect contextual factors such as physical activity, sleep, fatigue and health-status have on PC variation.

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