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Reliability and Sensitivity of Smartphone Accelerometer to Assess Postural Balance in Healthy Individuals

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SUMMARY

Background. Inertial sensors within smartphones present a cost-effective and practical option for balance assessment. However, it is crucial to ensure that the extracted parameter is informative about postural control. In this study, we aimed to investigate the smartphone's ability to differentiate between various levels of difficulty in balance tasks and assess the reliability of these measurements.

Methods. In two days, fifteen participants performed five static balance tasks. Acceleration data was collected from a smartphone during each balance task, and the root mean square value was computed from the magnitude of acceleration to obtain a representative measure of body oscillations.

Results. ANOVA revealed a significant effect ($p < 0.001$), and subsequent pairwise comparisons indicated significant differences between tasks based on their difficulty levels. All measures exhibited good-to-excellent intraclass coefficient correlation (> 0.6), with only the semi-tandem task with eyes closed showing a coefficient of variation greater than 10%.

Conclusions. These findings suggest that smartphones offer a sensitive and reliable means of assessing postural balance in static tasks of varying difficulty. Given the widespread accessibility of smartphones, they hold immense value as tools for large-scale balance screening and monitoring in clinical settings.

KEY WORDS

Balance assessment; postural control; reliability; smartphone accelerometer; smartphone sensors.

INTRODUCTION

Human postural control is a complex process that encompasses several physiological systems, including the vestibular, visual, somatosensory, and musculoskeletal systems (1). Individuals with impairments in these systems may present a reduced capability to balance the center of mass after external perturbations, increasing the risk of adverse events, such as falls (2). Falls are particularly prevalent among the elderly population and are a leading cause of hospitalizations (3). In Brazil, between 2000 and 2020, there were 1,746,097 hospitalization cases attributed to falls, imposing substantial costs on the public healthcare system (4). Therefore, assessing postural balance is relevant to establishing interventions capable of mitigating the decay of this function or even increasing its performance over time, reducing the probability of falls and inherent health issues.

In clinical practice, the assessment of postural balance often relies on measuring the maximum time a person can sustain a particular task (5) or from score-based instruments, such as Berg Balance Scale (6). Although these methods are easily accessible and widely used, they do not consider the postural adjustments made throughout the entire task, which can potentially introduce bias into the calculated results. The gold standard for assessing the biomechanical aspects of postural balance involves measuring the displacement of the center of pressure, a variable that has a strong correlation with the history of falls (7). This measurement is typically obtained through the use of force platforms or three-dimensional motion capture systems. However, these instruments are expensive and often located in laboratory settings, requiring professional expertise to collect, process, and interpret the data. Therefore, alternative solutions, such as inertial sensors, have been developed to circumvent these barriers.

In recent years, inertial sensors have gained significant attention, primarily due to their low cost and practicality, and are now extensively employed in the assessment of postural balance (8). Traditionally, inertial sensors include accelerometers, gyroscopes, and magnetometers, and these components may be embedded in mobile electronic devices, such as smartphones and tablets. By utilizing these sensors in such devices, it becomes feasible to acquire data for the evaluation of postural balance in a more accessible manner. However, despite this growing application, it is important to guarantee that the extracted parameter is indeed informative about postural control. Although the validity and within-session reliability of measurements acquired from smartphones have already been documented, particularly in tests involving scenarios with eyes open and closed (9), whether more challenging tasks can also provide reliable information remains an open question. For instance, it remains unclear whether tasks involving single-legged support can yield consistent results across different days, and whether this technique is sensitive enough to distinguish between activities of varying difficulty levels.

In this study, we aimed to explore the smartphone's capability to distinguish between various levels of balance task difficulty by utilizing data from the accelerometer, while also evaluating the reliability of these measurements. Specifically, we assessed the concordance between the root mean square (RMS) value calculated from the accelerometer data acquired over a two-day period and compared the results across five static balance tasks, each graded in terms of difficulty level. If the smartphone is sensitive enough to differentiate between these tasks, we would expect to observe higher RMS values in tasks performed with eyes closed and single-legged support, as compared to tasks performed with eyes open and bipodal support. Moreover, if this technique is reliable between days, we expect to observe an intraclass correlation coefficient (ICC) > 0.6 and a coefficient of variation (CV) ≤ 10%.

MATERIALS AND METHODS

Subjects

Fifteen subjects (4 females) were recruited to participate in this study (mean ± SD; age: 30.73 ± 9.62 years; body mass: 75.27 ± 18.87 kg; height: 173 ± 10.54 cm). All participants were physically active and had not reported any lower limb musculoskeletal injuries within the six months prior to the study, nor did they exhibit any impairments in systems related to postural control.

The study involved two separate laboratory visits. During the first visit, after the participants had read and signed the informed consent form, they familiarized themselves with the postural balance tasks until they felt comfortable and safe to perform the tests. Subsequently, data were collected. On the second visit, the same protocols were re-administered to assess the reliability of the measurements. The experimental procedures conformed to the Declaration of Helsinki and were approved by the local Ethics Committee (name: Instituto Nacional de Traumatologia e Ortopedia; CAAE: 65807122.9.0000.5273 – date of approval: January 31, 2023).

Tasks to assess the postural balance

The smartphone was positioned on the lower back and fixed using an elastic belt (10). Five tasks were performed in random order to assess static balance: semi-tandem with 1) eyes open and 2) eyes closed; feet parallel with 3) eyes open and 4) eyes closed; 5) unipodal support with the dominant side. In the protocols where participants maintained a feet parallel stance, the hip was maintained in a neutral position, ensuring that the feet were directed forward and kept together (11). For the semi-tandem, the dominant limb was positioned behind, with the hallux placed next to the heel on the contralateral side (12). During tasks with eyes open, participants were instructed to maintain a fixed gaze on a target positioned at eye level and two meters away. Throughout all tasks, the hands remained resting on the waist (12). Each task was performed three times, with each trial lasting for 30 seconds. In the event that a participant could not maintain the designated task position, another attempt was made. In addition, a one-minute break was provided between each task. The average value between the three measures was considered for analysis. This protocol was chosen because the tests have different levels of difficulty (semi-tandem, feet parallel, and unipodal support), as well as stimulating the sensorimotor system in different ways (open and closed eyes).

Data analysis

Acceleration data were acquired from a smartphone (iPhone 7, software version: 15.6.1) with built-in 3D accelerometer using the free MATLAB Mobile app (MathWorks, v.8.9.1). The sampling frequency was determined to be 100 Hz, and the raw data were transmitted via Bluetooth to a personal computer and subsequently analyzed using a custom MATLAB script (MathWorks, v. R2020b).

The 3D acceleration signal was low-pass filtered at 5 Hz using a sixth-order Butterworth filter (13). The magnitude of acceleration was initially calculated using the Euclidean norm (12). Subsequently, the RMS value was computed from the magnitude of acceleration to obtain a measure capable of representing the body oscillations captured by the smartphone throughout each task. To minimize the effect of possible discrepant postural adjustments at the beginning and end of each task, for the calculation of the RMS value, first and last five seconds of each test were discarded. Consequently, a 20-second window for the subsequent analysis was considered.

Statistical analysis

Based on the effect size (Eta squared = 0.6) estimated from our data, acceleration data collected from 15 subjects during five postural balance tasks ensured high (99%) statistical power (*post-hoc* power analysis; G*Power V. 3.1.9.7). Parametric analysis was considered for inferential statistics after ensuring data normality (Shapiro-Wilk test; $p > 0.05$, for all cases) and homoscedasticity (Levene's test; $p = 0.33$). The mean of two days was used to compare the RMS values across the postural balance tasks. One-way repeated-measures ANOVA was applied, and the Bonferroni *post-hoc* adjustment method was used for paired comparisons whenever the main effects were verified. ICC and CV were used to assess the inter-day reliability of the accelerometer data acquired during postural balance tasks. ICC values were calculated using the two-way mixed-effects model and absolute agreement definition (14) and interpreted using thresholds (poor: 0.00-0.39; fair: 0.40-0.59; good: 0.60-0.74; excellent: 0.75-1.00) (15). The averaged CV across participants was calculated for each task, and a one-sample t-test was applied to verify whether the CV is significantly different than a theoretical mean (10%). All statistical analyses were conducted using R programming language (version 4.2.0), and the significance level was set at 5%.

RESULTS

Figure 1 illustrates the magnitude of acceleration during three performed tasks for a representative participant. Visual analysis clearly demonstrates an increase in the acceleration amplitude as the task difficulty level increases.

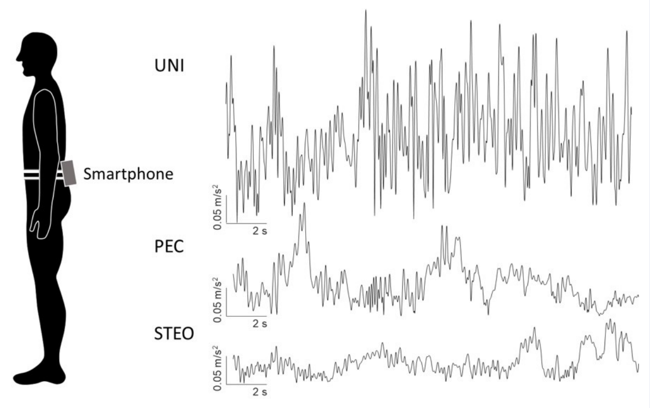

Figure 1. Magnitude of acceleration for a single representative participant.

UNI: unipodal support; PEC: parallel feet with eyes closed; STEO: semi-tandem with eyes open.

Regarding the group analyses, ANOVA revealed a significant effect ($F = 26.03$, $p < 0.001$, Eta squared = 0.6), with pairwise comparisons indicating a significant difference between the tasks (**figure 2**). The mean and ± SD across two days for tasks semi-tandem with eyes open, semi-tandem with eyes closed, feet parallel with eyes open, feet parallel with eyes closed, and unipodal support were 0.071 ± 0.019 m/s^2, 0.088 ± 0.025 m/s^2, 0.084 ± 0.019 m/s^2, 0.106 ± 0.030 m/s^2, and 0.157 ± 0.032 m/s^2, respectively.

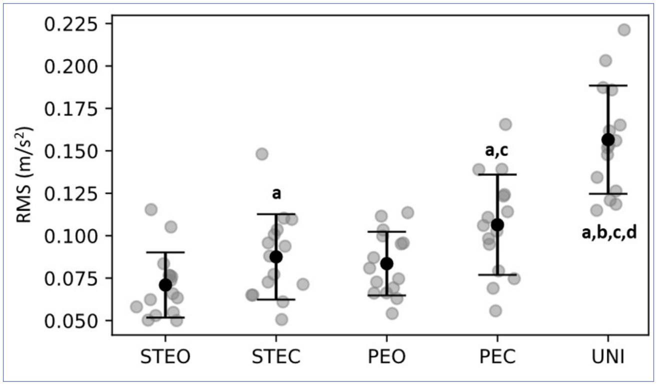

Figure 2. Mean and standard deviation of RMS values for each postural task.

STEO: semi-tandem with eyes open; STEC: semi-tandem with eyes closed; PEO: parallel feet with eyes open; PEC: parallel feet with eyes closed; UNI: unipodal support; **(a-d)** significantly greater than STEO, STEC, PEO, and PEC, respectively ($p < 0.01$ for all cases).

Table I. Absolute values and between-day reliability of RMS acceleration measurements.

Task	Mean ± SD (m/s²)		ICC	95%CI		P-value	CV%	95%CI		P-value
	Day 1	Day 2		Inferior limit	Superior limit			Inferior limit	Superior limit	
Semi-tandem EO	0.073 ± 0.022	0.069 ± 0.020	0.841	0.525	0.946	< 0.001	11.49	0.072	0.158	0.471
Semi-tandem EC	0.091 ± 0.034	0.084 ± 0.024	0.625	-0.116	0.874	0.038	18.72	0.123	0.251	0.011
Feet parallel EO	0.083 ± 0.018	0.084 ± 0.024	0.735	0.211	0.911	0.009	12.90	0.074	0.184	0.273
Feet parallel EC	0.102 ± 0.028	0.111 ± 0.035	0.873	0.624	0.958	< 0.001	11.21	0.058	0.166	0.637
Unipodal support	0.150 ± 0.028	0.163 ± 0.039	0.866	0.601	0.955	< 0.001	8.02	0.039	0.121	0.313

EO: eyes open; EC: eyes closed.

As reported in **table I**, tasks semi-tandem with eyes open, feet parallel with eyes closed, and unipodal support showed excellent inter-day reliability (ICC > 0.75; CV < 12%, for all cases), while the task feet parallel with eyes open had good inter-day reliability. The task semi-tandem with eyes closed showed the lowest ICC and had a CV significantly greater than 10%, suggesting high inter-day variability.

DISCUSSION

The present study aimed to investigate whether different levels of difficulty in assessing static balance can be differentiated using measurements obtained from smartphone, and whether this measure is reliable across two days. The results indicate that the RMS value extracted from the smartphone accelerometer was sensitive to differentiating tasks with varying levels of difficulty. Additionally, our findings showed good-to-excellent between-day reliability of the RMS value obtained from each postural balance task.

Regarding the outcome used to assess postural balance, analysis of the magnitude of acceleration during tasks suggested that this method was sensitive enough to reveal balance adjustments induced by more challenging conditions. Specifically, tasks with greater difficulty levels, such as unipodal support and parallel feet with eyes closed, exhibited significantly higher RMS values than those with lower difficulty levels (**figure 2**). With respect to visual restricted feedback tasks, a greater RMS value observed in those tasks with eyes closed compared to eyes open with bipodal support can be explained by reduced visual input. Along with other sensory inputs, vision provides direct information about body position and orientation in relation to the environment, playing a crucial role in generating precise motor commands for postural adjustments (16). When visual input is transiently removed or restricted, balance performance during a quiet stance is altered because of its effect on the perception and representation of body positions and oscillations. Additionally, even performed with eyes open, unipodal support showed the greatest RMS value, indicating that it was indeed the most challenging task. Since during single leg stance the base of support in the mediolateral direction is smaller, restricting the control of postural stability (17), a higher magnitude of acceleration during all task is excepted (**figure 1**). These findings are in line with previous research using dedicated accelerometer devices to assess postural control in healthy subjects (18,19), and reinforce the utility of smartphones to assess balance during quiet stance tasks graded by difficulty level.

Reliability analysis revealed that the semi-tandem with eyes open, feet parallel with eyes closed, and unipodal support tasks showed excellent inter-day reliability, whereas feet parallel with eyes open demonstrated good inter-day reliability. Except for semi-tandem with eyes closed, all other tasks exhibited a CV% close to 10%, implying a relatively low degree of variability across days (**table I**). Although the task semi-tandem with eyes closed showed a good ICC, the CV% was significantly greater than 10%, indicating a high relative variability between days. In general, these results align with previous research that demonstrated the reliability of measurements obtained from smartphone for assessing static postural balance (9). The authors reported moderate to high within-session reliability in tasks with eyes open and closed performed on firm and compliant superficies. The current study extends these findings by examining the reliability of smartphone measurements across different days and demonstrating their valuable utility in monitoring postural control over time.

A strength of the present study lies in the use of smartphones as a practical and accessible tool for postural balance assessment, which provides some advantages. Specifically, smartphones with built-in accelerometers are widely available and relatively affordable compared to traditional laboratory equipment, such as force plates (8). This accessibility makes smartphone-based assessments more feasible for widespread implementation in clinical settings, enabling the large-scale screening and monitoring of postural balance. Additionally, the portability of smartphones allows for convenient data collection in various environments, including home-based assessments and remote monitoring scenarios (20). In clinical practice, smartphones have demonstrated their utility in several other domains. For instance, smartphone applications have been employed for measuring dorsiflexion range of motion (21, 22), tracking step counts and providing feedback to promote daily physical activity (23), as well as offering break reminders to encourage physical activity among office employees (24).

Limitations and future perspectives

The current study has some limitations. Firstly, our sample comprised young and healthy individuals, which does limit the extent to which we can extrapolate our findings to more diverse groups with varying health conditions. Individuals with lower functional status, such as the elderly, orthopedics, or with other clinical conditions, may exhibit different responses and outcomes; thus, caution should be taken when applying these findings to such populations. Second, the reliability and sensitivity of the device used in this study were specific to the five static balance conditions evaluated. The applicability of these results to a broader range of postural balance assessments such as dynamic tasks remain uncertain. Finally, because we rely on the magnitude of acceleration from the three axes to assess postural balance, it is not possible to discern whether certain tasks have a greater acceleration in a specific direction. Considering these limitations, future studies should aim to address these issues and expand our understanding of fall prevention and postural balance, particularly in diverse and clinically relevant populations, including the elderly and orthopedic patients. These future investigations could focus on optimizing the signal processing to obtain instantaneous results, adapting them for dynamic tasks, and exploring the aspects of postural balance for a more comprehensive perspective on fall prevention and rehabilitation in these specific groups.

CONCLUSIONS

In conclusion, this study demonstrated that smartphones may provide reliable and sensitive measurements when it comes to evaluating postural balance across tasks of differing complexity. These findings underscore the potential of smartphone as a cost-efficient and practical instrument for assessing postural balance, carrying significant implications for enhancing fall prevention strategies and monitoring of postural stability in clinical settings. Incorporating smartphone-based assessments into fall prevention programs could improve their effectiveness by offering a practical and accessible means of tracking postural balance, thereby enabling the identification of individuals at risk and implementing targeted interventions.

FUNDINGS

None.

DATA AVAILABILITY

Data are available under reasonable request to the corresponding author.

CONTRIBUTIONS

JCSA: design, data collection, signal processing, analysis and interpretation of data, writing – original draft, writing – review & editing. CTL, SCS, TL: design, analysis and interpretation of data, writing – review & editing.

CONFLICT OF INTERESTS

The authors declare that they have no conflict of interests.

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