J. Phys. Ther. Sci. 35: 553–558, 2023

The Journal of Physical Therapy Science

Review Article

Reliability and validity of quantitative evaluation of anticipatory postural adjustments using smartphones

Ryo Onuma, PhD, PT[1, 2)*], Fumihiko Hoshi, PhD, PT[3)], Ryosuke Tozawa, PhD, PT[4)], Yuki Soutome, MSc, PT[5)], Tomoko Sakai, PhD, MD[2)], Tetsuya Jinno, PhD, MD[2, 6)]

[1)] *Faculty of Health Science, Mejiro University: 320 Ukiya, Saitama-shi, Saitama 339-850, Japan*
[2)] *Department of Rehabilitation Medicine, Tokyo Medical and Dental University Graduate School, Japan*
[3)] *Graduate School of Health and Social Services, Saitama Prefectural University, Japan*
[4)] *Faculty of Health Science, Ryotokuji University, Japan*
[5)] *Department of Physical Medicine and Rehabilitation, Geriatric Health Services Facility, Caretown Yuyu, Medical Corporation Meikeikai, Japan*
[6)] *Department of Orthopaedic Surgery, Dokkyo Medical University Saitama Medical Center, Japan*

Abstract. [Purpose] This study aimed to investigate the reliability and validity of the quantitative evaluation of anticipatory postural adjustments using smartphones. [Participants and Methods] The study included 10 young control participants who underwent a one-legged stance with an accelerometer and a smartphone that were simultaneously attached to their lower back (L5). Acceleration was measured as the mediolateral component of the lumbar movement toward the stance side. The peak value of the time (peak latency) and the amount of displacement (peak magnitude) in the stance side direction of the lumbar acceleration were analyzed as anticipatory postural adjustment features. Intra-rater reliability was calculated for both accelerometer and smartphone measurements, while inter-rater reliability was calculated for smartphone measurements by two examiners. Validity was determined for both accelerometer and smartphone measurements. [Results] In this study, the intra-rater reliability of the peak latency and peak magnitude in accelerometer and smartphone measurements was confirmed, as was the inter-rater reliability in smartphone measurements. The intra-rater reliability was confirmed through re-testing, while the validity of the accelerometer and smartphone measurements was also confirmed. [Conclusion] The findings of this study suggest that the use of smartphones to measure anticipatory postural adjustments is highly reliable and valid, making it a useful clinical balance index. The method is simple and can be used for continuous patient monitoring.

Key words: Smartphone, Postural control, Reliability and validity

(This article was submitted Mar. 16, 2023, and was accepted Apr. 16, 2023)

INTRODUCTION

Measurement of balance function is important for clinical evaluation, treatment effect judgment, and fall prediction. Balance function is divided into proactive, predictive, and reactive control mechanisms from the viewpoint of time series related to the three interactions of tasks: environment, physical function, and fall avoidance[1)]. Anticipatory postural adjustments (APA) in predictive control mechanisms are postural adjustments that act as feed-forwards before initiating movement[2, 3)]. APA is included as an item of the balance evaluation systems test (BESTest), which is widely used in clinics for balance-function evaluation, as the score of the respective item is highly related to falls and is important for the clinical evaluation of

*Corresponding author. Ryo Onuma (E-mail: r.onuma@mejiro.ac.jp)

balance function and fall prediction[4, 5]. The quantification of APA through kinematic analysis can provide important information for understanding balance control mechanisms in clinical settings[6]. Previous studies have reported that APA induces the activation of the tibialis anterior and suppression of the soleus at the start of gait, as well as changes in the posterolateral shift of the center of pressure (COP) of the stance leg[7–10]. In addition, APA takes place until the trajectory of the COP shifts from the center of both soles to the rear of the swing side and the rear of the stance side, and the relationship between this COP movement and the lumbar acceleration is high[11–13]. Moreover, it has been reported that the mediolateral acceleration of the lumbar region during one-leg stance (OLS) movement is highly correlated with the Mini-BESTest[14]. To measure these predictive posture controls, it takes time to prepare and measure equipment such as stabilometers and accelerometers. Thus, it is necessary to be able to measure easily and within a small space in clinical practice.

To address these problems, we focused on measuring APA using smartphones. Smartphones are owned by many people in modern society, have low operational difficulty, and have the advantage of being simple and easy to use. Recent advancements have provided the accelerometers built into smartphones with sufficient inspection and measurement capabilities. Many previous studies have already reported on its application in digital health, including studies on the reliability and validity of the Timed Up and Go test (TUG) using smartphones[15–17]. In addition, setting the movement task to OLS is highly useful for fall prevention as it allows clinicians to easily measure the APA of patients with balancing issues in various settings, such as laboratories, hospitals, and at home, enabling them to make quantitative evaluations. However, no reports quantify APA in OLS movements using a smartphone and verify its reliability and validity.

This study aimed to measure the APA in the OLS movement using a smartphone and examine the intra-rater reliability, inter-rater reliability, and validity. We examined whether simple and highly accurate measurements are possible for clinical balance-function evaluation. We hypothesize that the measurement of APA using a smartphone as a clinical balance-function evaluation provides high intra-rater reliability, inter-rater reliability, and validity.

PARTICIPANTS AND METHODS

The participants were 10 healthy controls (mean ± standard deviation: 28.4 ± 6.2 years). The examiners were two physiotherapists. Individuals with motor disorders due to illness, difficulty understanding the study task, and visual disorders were not included. Table 1 presents the background of the participants.

This study was conducted under the approval of the Research Ethics Committee of the Tokyo Medical and Dental University Graduate School (M2021-064) after obtaining written and verbal consent from the participants.

The equipment used in this study includes an accelerometer (AMWS020, ATR Co. Ltd, Kyoto, Japan), a smartphone (iPhone X, Apple Co., Ltd, Cupertino, CA, USA), and a free smartphone application (Phyphox, RWTH Aachen University, Aachen, NRW, Germany). Acceleration during single-leg standing motion was measured using a smartphone and an accelerometer and recorded at a sampling frequency of 100 Hz. These devices were managed with a personal computer (PC) to synchronize the trigger signal for starting the measurement from the smartphone and the trigger signal for starting the measurement from the accelerometer.

All participants wore a smartphone and an accelerometer with a belt on their pelvis (L5) and assumed a standing posture facing a PC display. The participants put their hands on their waists, and their heels were aligned with the width of the pelvis. When the controller is pressed, the measurement of the smartphone and the accelerometer starts. Five seconds later, the left or right arrow is displayed as the OLS starts sending signals to the PC screen (Fig. 1). At the start of the OLS movement, the examiner verbally instructed participants to follow the visual cue on the PC display, saying, “When the cue appears on the screen, raise your leg in the direction of the arrow and keep it there”. By specifying the left and right conditions of the leading leg, the subjects were not allowed to anticipate the weight shift before OLS. A total of four OLS motion tasks were performed, two on each of the left and right sides. The participants finished the OLS by maintaining the lifted leg posture for 20 seconds before returning their lifted leg to the ground.

Table 1. Participant characteristics (n=10)

Variable	Control (n=10)
Age (years)	28.4 (6.2)
Gender (Male/Female)	5/5
Height (cm)	164.7 (8.6)
Weight (kg)	56.3 (7.7)
PL (s)	Right 0.61 (0.07) /Left 0.60 (0.07)
PM (mG)	Right 125.1 (44.9) /Left 120.6 (32.7)
OLS (s)	20 (0.0)

Values are mean (standard deviation) or number of participants. PL: Peak latency; PM: Peak magnitude; OLS: one-leg stance.

The acceleration data was analyzed for the mediolateral component of the lumbar (L5). We analyzed the acceleration data for two seconds after the start of the OLS movement and normalized the time axis with the start signal of the task[18]. As APA features, we analyzed the time (peak latency (PL)) and the amount of displacement (peak magnitude (PM)) to the peak value in the stance side direction of the lumbar acceleration[6, 13]. Smartphones were also analyzed using the same method as for accelerometer (Fig. 2A).

In the examination of inter-rater reliability, the participants were assessed by two physiotherapists. In addition, the intra-rater reliability was re-tested after three days by the same physiotherapist as the first time.

We used SPSS Statistics ver.19 (IBM, Chicago, IL, USA) for the analysis. For the smartphone and accelerometer data, a total of four PL and PM values were obtained for each participant, and the average value was used as the representative value for each participant. For statistical processing, the inter-rater reliability and intra-rater reliability were calculated using the intraclass correlation coefficients (ICCs) for the PL and PM results in accelerometer and smartphone measurements. For inter-rater reliability and re-test, the average value was used as a representative value. We also examined the relevance and degree of agreement between the measurements of PL and PM in accelerometers and smartphones, using Pearson's product-moment correlation coefficient and Bland-Altman analysis. If a systematic error was found in the Bland-Altman analysis, the

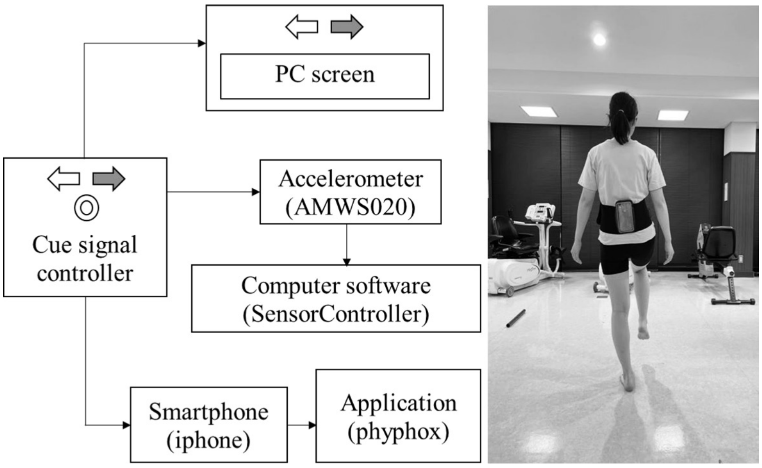

Fig. 1. Experimental set-up.
A signal in the left or right direction was displayed on the PC screen, indicating which leg should be raised.

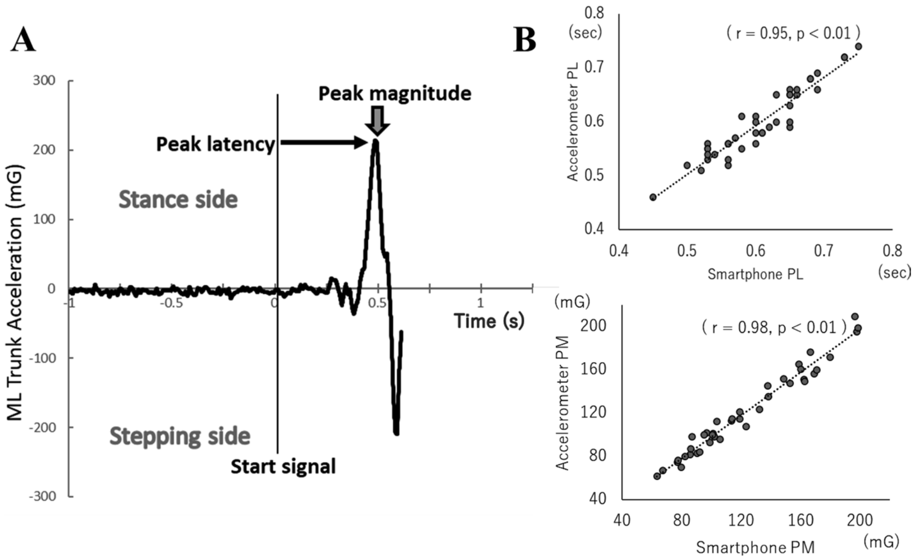

Fig. 2. Typical example of mediolateral acceleration in each group during one-leg stance (OLS) movement.
(A) The displacement in the acceleration of a healthy control is shown. The arrows show the peak latency (PL) and peak magnitude (PM).
ML: Mediolateral.
(B) Correlation of peak latency (PL) and peak magnitude (PM) in accelerometer and smartphone measurement results.

limit of agreement (LOA) was calculated. If no systematic error was found, 95% confidence intervals of minimal detectable change (MDC_{95}) were calculated. The level of significance was set at 5%.

RESULTS

For intra-rater reliability in the measurement of PL with the accelerometer, ICC (1,1) was 0.65, and ICC (1,4) was 0.88. For intra-rater reliability in the measurement of PM, ICC (1,1) was 0.78, and ICC (1,4) was 0.93 (Table 2). For intra-rater reliability in the measurement of PL with a smartphone, ICC (1,1) was 0.65, and ICC (1,4) was 0.88. For intra-rater reliability in the measurement of PM, ICC (1,1) was 0.71, and ICC (1,4) was 0.91 (Table 2).

For the inter-rater reliability in the measurement of PL with a smartphone, ICC (2,1) was 0.74, whereas, in the measurement of PM, ICC (2,1) was 0.93 (Table 3).

Three days later, in the intra-rater reliability of the measurement of PL with a smartphone, ICC (1,1) was 0.82, whereas, in the measurement of PM, ICC (1,1) was 0.94 (Table 3).

The correlation coefficient between the measurement of the acceleration and the measurement of the smartphone was $r=0.95$ ($p<0.01$) for PL and $r=0.98$ ($p<0.01$) for PM (Fig. 2B). In addition, the average (standard deviation) of the accelerometer and smartphone was 0.61 (0.07) s and 0.60 (0.07) s for PL, 122.8 (38.9) milli-Gal (mG) and 120.9 (39.4) mG for PM. As a result of the Bland-Altman analysis, a fixed error was found in PL, and the Limits of Agreement (LOA) ranged from −0.02 s to 0.04 s. No systematic error was observed in PM, and MDC95 was 13.7 mG.

DISCUSSION

In this study, we examined the reliability and validity of APA acceleration measurements using a smartphone and an accelerometer. The PL and PM measurements on the accelerometer and smartphone showed high intra-rater reliability, inter-rater reliability, and validity.

For intra-rater reliability in the measurement of PL with the accelerometer, ICC (1,1) was 0.65, and ICC (1,4) was 0.88. In addition, in the intra-rater reliability in the measurement of PM with the accelerometer, ICC (1,1) was 0.78, and ICC (1,4) was 0.93. In previous studies, ICC was considered almost perfect at 0.81 or higher[19)]. In this study, when measuring PL and PM of OLS movement using an accelerometer, the ICC was 0.81 or higher after about four measurements, the desired number of measurements. Even in the smartphone measurement, the ICC was extremely similar to the accelerometer measurement. From these results, we thought that when measuring with a smartphone, it is desirable to measure PL and PM the same number of times and in the same manner as accelerometers.

For the inter-rater reliability in the measurement of PL with a smartphone, ICC (2,1) was 0.74; in the measurement of PM, ICC (2,1) was 0.93. From this result, it was clarified that PL and PM on a smartphone were measured four times and averaged to show a high value in inter-rater reliability, and any examiner could obtain a highly reliable value. A study investigating the inter-rater reliability of gait spatiotemporal parameters in patients with Parkinson's disease through inertial measurement

Table 2. Intra-rater reliability of peak latency (PL) and peak magnitude (PM) in accelerometer and smartphone measurements

	Intra-rater reliability						
	Single measures				Average measures		
		95% Confidence interval				95% Confidence interval	
	ICC (1, 1)	Lower bound	Upper bound	Cronbach's alpha	ICC (1, 4)	Lower bound	Upper bound
Accelerometer PL	0.65	0.36	0.88	0.88	0.88	0.69	0.97
Accelerometer PM	0.78	0.56	0.93	0.94	0.93	0.84	0.98
Smartphone PL	0.65	0.36	0.88	0.88	0.88	0.69	0.97
Smartphone PM	0.71	0.43	0.90	0.90	0.91	0.75	0.97

Table 3. Inter-rater reliability and intra-rater reliability (re-test) of peak latency (PL) and peak magnitude (PM) in smartphone measurements

	Inter-rater reliability				Intra-rater reliability (re-test)			
	Single measures				Single measures			
		95% Confidence interval				95% Confidence interval		
	ICC (2, 1)	Lower bound	Upper bound	Cronbach's alpha	ICC (1, 1)	Lower bound	Upper bound	Cronbach's alpha
Smartphone PL	0.74	0.28	0.93	0.85	0.82	0.44	0.95	0.90
Smartphone PM	0.93	0.77	0.98	0.96	0.94	0.77	0.98	0.97

units reported reliability of ICC 0.9 or higher in the measurements of researchers and clinicians[20]. In the present study as well, the results were measured by two professionals, and high reliability was obtained as in previous studies.

For intra-rater reliability in the measurement of PL with a smartphone three days later, ICC (1,1) was 0.82; in the measurement of PM, ICC (1,1) was 0.94. Previous studies have reported that re-testing is highly reproducible in gait analysis using mobile applications[21], and the results of this study revealed that the measurement reproducibility is high in the APA evaluation of OLS movement using a smartphone.

The correlation coefficient in the measurement results between the accelerometer and the smartphone was r=0.95 for PL and r=0.98 for PM, indicating that accelerometer and smartphones are almost completely relative to each other, and both PL and PM are highly valid based on accelerometers. Based on the Bland–Altman analysis, it was clarified that the smartphone shows a slightly higher value than the accelerometer because a fixed error was found for PL. In addition, the LOA of PL is from −0.02 s to 0.04 s, and the MDC95 of PM is 13.7 mG; this range is included as an error, and if a change exceeding this is generated, it can be regarded as a true change. These values are approximately 10% of each measured average value as the error range and are considered to be within the allowable range of error.

A limitation of this study is that it has not been conducted for older adults and patients with balancing issues, such as those with Parkinson's disease, who are more likely to fall. Future studies must focus on these populations.

To summarize, it was clarified that the measurement of APA using a smartphone has high reliability and validity and is a clinically practical evaluation method. Thus, using smartphone applications is as valid for assessing APAs as the instruments for kinematic analysis, and it is a cost-effective alternative for the assessment. Balance evaluation, such as BESTest, which is commonly used in clinical evaluation, takes much time[22]. However, the measurement in this study takes less than five minutes, due to which there is little burden on the patients. The measurement method in this study enables a simple quantitative evaluation of APA and has the potential to contribute to patient monitoring and telemedicine for continuous fall prevention. In conclusion, the quantitative evaluation method of APA using a smartphone is simple and convenient for clinical balance-function evaluation and enables highly accurate measurements.

Funding and Conflict of interest

None.

ACKNOWLEDGMENT

We thank the staff of the medical corporation Meikeikai for participating in this study.

REFERENCES

1) Huxham FE, Goldie PA, Patla AE: Theoretical considerations in balance assessment. Aust J Physiother, 2001, 47: 89–100. [Medline] [CrossRef]
2) Belen'kiĭ VE, Gurfinkel' VS, Pal'tsev EI: [Control elements of voluntary movements]. Biofizika, 1967, 12: 135–141 (in Russian). [Medline]
3) Stuart DG: Integration of posture and movement: contributions of Sherrington, Hess, and Bernstein. Hum Mov Sci, 2005, 24: 621–643. [Medline] [CrossRef]
4) Horak FB, Wrisley DM, Frank J: The Balance Evaluation Systems Test (BESTest) to differentiate balance deficits. Phys Ther, 2009, 89: 484–498. [Medline] [CrossRef]
5) Miyata K, Kaizu Y, Usuda S: Prediction of falling risk after discharge in ambulatory stroke or history of fracture patients using Balance Evaluation Systems Test (BESTest). J Phys Ther Sci, 2018, 30: 514–519. [Medline] [CrossRef]
6) Onuma R, Masuda T, Hoshi F, et al.: Measurements of the centre of pressure of individual legs reveal new characteristics of reduced anticipatory postural adjustments during gait initiation in patients with post-stroke hemiplegia. J Rehabil Med, 2021, 53: jrm00211. [Medline] [CrossRef]
7) Elble RJ, Moody C, Leffler K, et al.: The initiation of normal walking. Mov Disord, 1994, 9: 139–146. [Medline] [CrossRef]
8) Brenière Y, Cuong Do M, Bouisset S: Are dynamic phenomena prior to stepping essential to walking? J Mot Behav, 1987, 19: 62–76. [Medline] [CrossRef]
9) Crenna P, Frigo C: A motor programme for the initiation of forward-oriented movements in humans. J Physiol, 1991, 437: 635–653. [Medline] [CrossRef]
10) Winter DA: Human balance and posture control during standing and walking. Gait Posture, 1995, 3: 193–214. [CrossRef]
11) Sun R, Guerra R, Shea JB: The posterior shift anticipatory postural adjustment in choice reaction step initiation. Gait Posture, 2015, 41: 894–898. [Medline] [CrossRef]
12) Rocchi L, Mancini M, Chiari L, et al.: Dependence of anticipatory postural adjustments for step initiation on task movement features: a study based on dynamometric and accelerometric data. Conf Proc IEEE Eng Med Biol Soc, 2006, 2006: 1489–1492. [Medline] [CrossRef]
13) Onuma R, Masuda T, Hoshi F, et al.: Separated center-of-pressure measurements reveal new characteristics of reduced anticipatory postural adjustments during gait initiation in patients with Parkinson's disease. Physiother Theory Pract, 2022, 38: 2544–2553. [Medline]
14) Bonora G, Mancini M, Carpinella I, et al.: Investigation of anticipatory postural adjustments during one-leg stance using inertial sensors: evidence from subjects with parkinsonism. Front Neurol, 2017, 8: 361. [Medline] [CrossRef]
15) Yamada S, Aoyagi Y, Yamamoto K, et al.: Quantitative evaluation of gait disturbance on an instrumented timed up-and-go test. Aging Dis, 2019, 10: 23–36. [Medline] [CrossRef]
16) Ishikawa M, Yamada S, Yamamoto K, et al.: Gait analysis in a component timed-up-and-go test using a smartphone application. J Neurol Sci, 2019, 398: 45–49. [Medline] [CrossRef]

17) da Costa Moraes AA, Duarte MB, Ferreira EV, et al.: Validity and reliability of smartphone app for evaluating postural adjustments during step initiation. Sensors (Basel), 2022, 22: 2935. [Medline] [CrossRef]

18) Schlenstedt C, Mancini M, Nutt J, et al.: Are hypometric anticipatory postural adjustments contributing to freezing of gait in Parkinson's disease? Front Aging Neurosci, 2018, 10: 36. [Medline] [CrossRef]

19) Landis JR, Koch GG: The measurement of observer agreement for categorical data. Biometrics, 1977, 33: 159–174. [Medline] [CrossRef]

20) Esser P, Dawes H, Collett J, et al.: Validity and inter-rater reliability of inertial gait measurements in Parkinson's disease: a pilot study. J Neurosci Methods, 2012, 205: 177–181. [Medline] [CrossRef]

21) Clavijo-Buendía S, Molina-Rueda F, Martín-Casas P, et al.: Construct validity and test-retest reliability of a free mobile application for spatio-temporal gait analysis in Parkinson's disease patients. Gait Posture, 2020, 79: 86–91. [Medline] [CrossRef]

22) Franchignoni F, Horak F, Godi M, et al.: Using psychometric techniques to improve the Balance Evaluation Systems Test: the mini-BESTest. J Rehabil Med, 2010, 42: 323–331. [Medline] [CrossRef]