運動研究
第 30 卷 第 2 期，13-24 頁（2021）

Journal of Sports Research
Vol. 30 No. 2 pp. 13-24 (2021)

Validation of Smartphone-Based Ankle-Control Assessment for Subjects With Chronic Ankle Instability

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DOI:10.6167/JSR.202112_30(2).0002
Received: August, 2019 Accepted: December, 2019

Abstract

Ankle sprains can damage ankle proprioception, causing a decrease in postural-control ability; poor postural-control ability is a risk factor in ankle sprain, which creates a vicious circle of recurrent sprains. Proper and early assessment is the key to break down this circle. With smartphones built-in sensors, utilizing smartphones as assessment tools can provide quantitative data of postural-control performance. This study aims to verify the feasibility and validity of smartphone-based ankle-control measurement for subjects with chronic ankle instability (CAI). Twelve participants were recruited. The data of ankle-control performance were simultaneously recorded using a smartphone built-in accelerometer (SBA) and a stand-alone pre-calibrated three-axial accelerometer (SPA) during a single-leg stance. The smartphone was fixed at the middle of the shin. The participants completed trials under eyes-opened (EO) and eyes-closed (EC) conditions. Each ankle was classified into healthy or unstable ankle using the Cumberland Ankle Instability Tool with 24 as the cutoff score. The average in variation of the three axial acceleration resultant was calculated as the performance index. Pearson's correlation coefficient (PCC) and independent-t test were used to analyze the data, and the statistical significance was set at $\alpha = .05$. The PCC between SBA and SPA were .960 ($p < .001$) under the EO condition and .997 ($p < .001$) under the EC condition. The distinction between the healthy and unstable ankles was also verified. Significant differences existed between the healthy and unstable ankles and also between the eyes opened condition and eyes closed condition as measured by both accelerometers. The results show that utilizing SBA to measure the ankle-control performance exhibited a similar differentiation as that using SPA in evaluating the performance of a single-leg stance test for subjects with CAI.

Keywords: mobile device, ankle sprain, ankle control

I. Introduction

Ankle sprain is one of the most common sports injuries with high prevalence (Fong, Hong, Chan, Yung, & Chan, 2007; Lambers, Ootes, & Ring, 2012). Ankle sprain is defined as an acute traumatic injury to the lateral ligament complex of an ankle resulting from inversion, plantar flexion, and internal rotation mechanism (Chu et al., 2010; Dedieu et al., 2017). After a sprain, the ankle joint proprioception is damaged. The reduction in proprioception indicates a symptom and affects the postural-control ability (Dedieu et al., 2017; Doherty et al., 2018; Kalichman, Lachman, & Freilich, 2016; Kirby, Houston, Gabriner, & Hoch, 2016; Mailuhu et al., 2018). According to the literature, the recurrent rate of ankle sprain is as high as 70% for those who have first experienced an ankle sprain. Among them, approximately 59% experience residual symptoms and functional instability, which are the main characteristics of chronic ankle instability (CAI) (Hertel, 2000).

The literature demonstrated that CAI can cause reduction in proprioception and sensorimotor function, which not only lower the sports-related performance but also damage the postural-control ability (Doherty et al., 2018; Kalichman et al., 2016; Kirby et al., 2016; Mailuhu et al., 2018). The reduced postural-control ability after ankle sprains can increase the sprain recurrent rate, creating a vicious circle (Kalichman et al., 2016). The consequence of CAI includes long-term symptoms, reduced function, higher risk of ankle sprain, and related joint arthritis (Doherty et al., 2018; Kalichman et al., 2016; Kirby et al., 2016; Mailuhu et al., 2018). Early assessment and treatment are crucial to resolve the CAI problem.

However, majority of ankle sprain sufferers are young people tend to ignore the issue after the pain or acute symptoms are gone (Doherty et al., 2018). Many patients return to the same intensity of exercise after a short rest without proper treatment. Nevertheless, the ankle ligamentous injury and proprioception reduction remain untreated. This condition can lead to a high sprain-recurrence rate, create CAI vicious circle, and worsen the instability issue. Even though some patients do seek help, they oftentimes quit before receiving complete treatment and rehabilitation, which make the ankle instability issue remain unsolved. The use of smartphones as a tool for providing ankle-control ability assessment and training may increase the level of attention for ankle instability among young subjects and can help solve the CAI problem.

As the technology rapidly advances, the application of smartphones as clinical assessment tools has become more common

(Abbott, Magnusson, Gibbs, & Smith, 2018; Malwade et al., 2018; Nishiguchi et al., 2016; Wenger, Williams, & Parashar, 2019). Clinical applications include goniometer (Johnson et al., 2015), gait assessment (Manor et al., 2018), balance assessment (Hsieh, Roach, Wajda, & Sosnoff, 2019; Moral-Munoz, Esteban-Moreno, Herrera-Viedma, Cobo, & Pérez, 2018; Roeing, Hsieh, & Sosnoff, 2017), etc. The literature also demonstrated that the application of smartphones for clinical assessment renders sufficient reliability and validity (Burghart, Craig, Radel, & Huisinga, 2017; Kuznetsov et al., 2018). However, an application that targets the assessment of ankle-control ability remains lacking. In addition, currently available related applications on balance assessment are few, and evidence on their reliability and validity is insufficient (Manor et al., 2018; Roeing et al., 2017).

In the present study, we develop an application to assess the ankle-control ability by recording data using the smartphone built-in accelerometer (SBA). The purpose of this study is to verify the validity of SBA by comparing the correlation between the recorded data with the stand-alone pre-calibrated three-axial accelerometer (SPA) data, verify the feasibility of the ankle-control ability assessment using smartphone, and substantiate the ability of distinguishing the ankle-control performance.

II. Methods

A. Subjects

Twelve college students volunteered for this study. The exclusion criteria are listed as follows: 1. presence of any lower extremity injuries before participation in the study, 2. underwent any operation history in the lower extremity, or 3. suffering from any neurological disease. The subjects were then classified using the score obtained by the Cumberland Ankle Instability Tool (CAIT) for each ankle. A score that was higher than 24 was considered to indicate a healthy ankle. Scores lower or equal to 24 indicated unstable ankles (Hertel, 2000; Kirby et al., 2016). This study was approved by the Institutional Review Board of National Yang-Ming University, Taipei, Taiwan.

B. Instrument

The smartphone application was developed using Android Studio v.2.6 to record the SBA data at a 100-Hz sampling rate for 30 s, and the data were exported as a text file to the smartphone internal storage. The ASUS ZenFone 3® (ASUS, Taiwan) smartphone was chosen to be used in the study trials because the accelerometer of this smartphone can stably work at a 100-Hz sampling rate. It is also a mainstream brand and in parity with other brands of smartphones in Taiwan. The SPA was

Crossbow® CXL04GP3 (Technology Inc., CA, USA). The data were processed using the data-acquisition function of the NI Hi-Speed USB Carrier NI USB-9162 (NI, USA) for signal conditioning and analog-to-digital conversion.

C. Procedures

The subjects were requested to perform a single-leg stance (SLS) with the smartphone fixed on the lower leg. The SLS position was defined with the hands of the subjects on their waist and the non-tested knee bent backward by 90°. The subjects were instructed to stand still and not to sway during the 30-s trials. They were asked to practice before the formal trial at least once and for a maximum of three times. The tests were conducted two times for each leg both under eyes-opened (EO) and eyes-closed (EC) conditions. The smartphone was fixed at the middle of the shin and facing the side, which was defined as the half-length between the fibula head to the lateral malleolus, to focus on the ankle joint. The SBA data collection was synchronized with the SPA data collection during the 30-s SLS trials to test the correlation between the recorded data of the SBA and SPA, which were used as the criterion for validity.

D. Data Processing

A total of 3,000 items of data were recorded by each axle in both accelerometers. We considered the middle 2,000 data items from the 500th to the 2,500th to avoid possible interference in the data or unstable motions detected at the beginning and near the end of the trial. We used the average of the variation in the acceleration to represent the subject performance. The variation was calculated as the absolute value of the current data minus the previous data. We then calculated the average of 1,999 items of variance data. The output data of SPA was in a voltage form. We then converted these data into acceleration. As we calculated the data variation, the initial voltage was eliminated during the process. We obtained the voltage difference between the situation where the accelerometer was located at the level surface and that upside down on the same level surface. Because the acceleration at the level surface should be $1g$ and $-1g$ when placed upside down, we obtained +0.5 and –0.5 V from SPA, which indicated that to convert the voltage to acceleration, we need to multiply the voltage by 2 × 9.8. Both the anterior–posterior and medial–lateral directions were calculated. The added data were calculated by vector addition using the following formula, where S represents the overall performance in the horizontal plane, x represents the medial–lateral direction, and z denotes the anterior–posterior direction:

$$S = \sqrt{x^2 + z^2} \qquad (1)$$

E. Data Analysis

We tested the validity of the SBA using the Pearson's correlation coefficient and compared it with the SPA. An independent *t* test was used to verify the differentiation of both the SPA and SBA between the two eye conditions and between the healthy and unstable ankles. α was set to .05.

III. Result

A. Demographic Data

Twelve subjects were recruited. The demographic data are listed in Table 1. The average age of all subjects was 24.8 ± 3.2 years old. The average body mass index (BMI) was 24.0 ± 5.0 kg/m^2. Five of the participants were male, and seven were female. Six subjects were classified to have both healthy ankles, five subjects were classified to have both unstable ankles, and one subject had one healthy and one unstable ankle. The healthy ankles scored an average of 26.8 ± 1.3 in CAIT, and the unstable ankle scored an average of 20.1 ± 3.0.

Table 1. Demographics

Demographic characteristics	Average (*SD*)
Amount of subjects	12
Average age (*SD*)	24.8 (3.2)
Gender	
Male	5
Female	7
Average of BMI (*SD*)	24.0 (5.0)
Average of CAIT score (*SD*)	
Healthy Ankle	26.8 (1.3)
Instable Ankle	20.1 (3.0)

Source: This study.

Note. BMI: body mass index; CAIT: Cumberland Ankle Instability Tool.

B. Validity

The results of the validity test are listed in Table 2. The validity test was completed by comparing the correlation between the SBA and SPA data under EC condition. The correlations were .999 (p < .001) at the medial–lateral direction, .978 (p < .001) at the anterior–posterior direction, and .997 (p < .001) in the combined two axial directions.

C. Differentiation

The results of the differentiation under the two conditions are listed in Table 3. A significant difference existed between the EO and the EC conditions as measured by the SBA or SPA.

The results of the differentiation of the healthy and unstable ankles are listed in Table 4. A significant difference existed

Table 2. Validity Results

Directions	PCC	*p*-value
ML direction	.999	< .001
AP direction	.978	< .001
Sum	.997	< .001

Source: This study.

Note. PCC: Pearson's correlation coefficient; ML: medial-lateral; AP: anterior-posterior.

Table 3.　Differentiation of Eyes Opened and Eyes Closed Conditions

Eyes opened/closed	Average (*SD*)	*p*-value
	Smartphone built-in accelerometer	
Eyes opened	0.221 (0.072)	< .001
Eyes closed	0.582 (0.468)	
	Stand-alone, pre-calibrated three axials accelerometer	
Eyes opened	0.255 (0.078)	< .001
Eyes closed	0.666 (0.510)	

Source: This study.
Note. Units: m/s^2.

Table 4.　Differentiation of Healthy Ankle and Instable Ankle

Healthy/instable ankle	Average (*SD*)	*p*-value
	Smartphone built-in accelerometer	
Healthy ankle	0.411 (0.120)	.022
Instable ankle	0.770 (0.637)	
	Stand-alone, pre-calibrated three axials accelerometer	
Healthy ankle	0.490 (0.147)	.031
Instable ankle	0.862 (0.686)	

Source: This study.
Note. Units: m/s^2.

between the healthy and unstable ankles as measured by the SBA or SPA.

IV. Discussion

A. Validation and Differentiation

In this study, we validated the SBA and verified the Pearson correlation between the SBA and SPA. The result showed that the correlation between the two types of accelerometers was high, which demonstrated that the SBA was valid and stable. Slight discrepancies were observed between the two acceleration datasets, which may due to the unclear exact position of the embedded accelerometer in the smartphone. The slight difference in the position of these two accelerometers resulted in data discrepancy. However, the correlation was sufficiently high for us to conclude that a high consistency in the data collection between these two accelerometers was achieved, which sufficiently validated the SPA.

The literature has proven that utilizing the built-in sensors of smartphones achieves a good correlation with the results using clinical assessment tools in recording the center of pressure movement (Hsieh et al., 2019; Moral-Munoz et al., 2018; Roeing et al., 2017). In 2014, Chung, Soangra, &

Lockhart (2014) explored the possibility of using smartphones with built-in sensors as substitutes for force plates. His application recorded the postural-sway data using a built-in accelerometer at a frequency of 30 Hz. The subjects completed a 1-min static double-leg stance where the smartphone was fixed to the pelvis, and the force plate data were simultaneously collected. The correlation between the center-of-gravity displacement from the force plate and acceleration from the smartphone was compared. The results showed that the measurement from the built-in sensor in the smartphone was similar to that in the force plate, which proved that smartphones with built-in sensors have a similar ability of differentiation as the triaxle force plate. In 2019, Hsieh et al. (2019) utilized the built-in sensors of smartphones for postural stability assessment to distinguish the fall risk among the elderly. Thirty old adults completed seven balance tests by holding the smartphones against their chests while simultaneously collecting data from the force plate to establish the validity of SBA. The result showed that the smartphone provided a valid measurement of postural stability and was capable of distinguishing fall-risk stratification in older adults. Smartphones can thus potentially offer objective fall-risk assessments in older adults.

We also verified the differentiation ability of the smartphone-based assessment using a smartphone fixed at the middle shin for ankle-control ability. The results showed that SBA can identify the difference between the EO and EC conditions and between healthy and unstable ankles. In the EC condition, the literature proved that the postural performance would significantly decrease with no visual input (Linens, Ross, Arnold, Gayle, & Pidcoe, 2014). The literature also proved that subjects with ankle instability would significantly perform worse in the SLS balance test compared with healthy subjects (Doherty et al., 2018; Kalichman et al., 2016; Kirby et al., 2016; Mailuhu et al., 2018). Our result agreed with previous studies, thus showing that the smartphone-based assessment can detect the difference in the ankle-control performance under different situations.

B. Fixation of Smartphones

In previous studies (Chung et al., 2014; Hsieh et al., 2019), smartphones were usually fixed near the center of gravity, such as in the waist, L2 lumbar spine, or chest, to assess the whole-body balance performance. In research that focused on ankle function, Shah, Aleong, and So (2016) verified the validity of the self-developed “myAnkle” application. Three smartphones were simultaneously positioned above the malleolus and patella of the participants and at the umbilicus level to verify the most sensitive position for detecting the performance. The difficulty ranking of the eight balance tasks was compared by experts using the data collected by SBA. The results showed that the degree of task difficulty in terms of the magnitude from the accelerometer data was correlated to the difficulty of the expert ranking, which proved that this mobile application could achieve expert validity performance. The results of the study suggested that the knee location was the most sensitive in detecting the differences among the tasks, which might be due to the different strategies used by the subjects in the different tasks. However, by fixing the smartphone above the patella, the recorded data included the motion of not only the ankle but also the knee joint, which could not directly represent the ankle-control performance. Thus, we modified the suggested location in fixing the smartphone in our study.

In the present study, our main goal was to design a smartphone-based assessment, especially for subjects with CAI. Because the subjects were proven to have poor postural-control ability due to the proprioception reduction caused by an initial ankle sprain, instead of fixing the smartphone near the center of pressure, we located the smartphone at the middle of the shin to directly assess the ankle-control ability. In fixing the smartphone at the middle of the shin, it detected the motion of the ankle and foot joint under a closed chain condition during the ankle-control performance in the SLS balance test. Our previous study provided preliminary data that proved that when the smartphone was fixed at the middle of the shin, the collected acceleration data can identify the difference between healthy and unstable ankles even at a 10-Hz sampling rate only (Chiu, Tsai, Lin, Hou, & Sung, 2017). In the present study, we upgraded the assessment application to a higher sampling rate (100 Hz) and adjusted the smartphone placement to face the side to minimize interference from the muscle contraction, especially the tibialis anterior muscle, to ensure that the tasks could be normally performed.

C. Advantage of Using a Smartphone as a Postural-Control Assessment Tool

In this study, we utilized SBA to assess the ankle-control ability. Accelerometers were used as a balance or postural-control assessment tool in the past. Kamen, Patten, Du, and Sison (1998) utilized the accelerometer as a balance assessment tool and demonstrated that the accelerometer could differentiate among the balance tasks and differentiate healthy older adults from elderly who are prone to fall. The literature proved that accelerometers can be used as a balance assessment tool, which provides objective data to reflect the balance performance (Moe-Nilssen & Helbostad, 2002; Wong & Wong, 2008). Today, almost all smartphones have accelerometers as one of their built-in sensors. Thus, almost all smartphones meet the basic requirement for performing the assessment tasks presented in this study.

Traditionally, detecting body motion using SPA requires many data-acquisition processes, signal conditioning, and analog-to-digital conversion devices that work together to acquire the required data. With many wire and devices, the assessment setting is usually complex and difficult to use. In contrast, smartphones equipped with built-in sensors and powerful computing ability require no other devices or wires. With just one smartphone, the same SPA function under a complex setting can be achieved. The convenience of smartphone use makes assessment of the ankle-control ability easier, which may help increase the accessibility of ankle-control assessment and training. Furthermore, the elevated accessibility may change the level of attention for ankle sprain sufferers, particularly the young people, because the smartphone penetration rate is high among them. The more attention they paid on the CAI issue, the lesser is the CAI burden.

D. Limitation

Only one smartphone was used as a tool for the validation test. Validation may be needed for re-evaluation if other smartphone brand or model is used.

V. Conclusion

The results of our study showed that the utilization of the built-in accelerometer in smartphones could apply in detecting ankle-control ability for patients with ankle instability.

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運動研究
第 30 卷 第 2 期，13-24 頁（2021）

Journal of Sports Research
Vol. 30 No. 2 pp. 13-24 (2021)

應用智慧型手機評估慢性足踝不穩患者足踝控制之效度驗證

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DOI:10.6167/JSR.202112_30(2).0002
投稿日期：2019 年 8 月　接受日期：2019 年 12 月

摘　要

足踝扭傷會導致本體感覺受損，造成姿勢控制能力的下降，而較差的姿勢控制能力是足踝扭傷的危險因子，形成一個惡性循環。適當且即時的評估，將可協助制定復健計畫並降低反覆扭傷的風險。智慧型手機內建感測器已被證實為方便且有效的姿勢控制評估工具，然而針對足踝不穩患者的足踝控制評估仍相當稀少。本研究目的為驗證智慧型手機內建感測器作為足踝控制評估之效度。共招募 12 位受試者，以智慧型手機內建加速規及市售三軸加速規同步收集開眼及閉眼單腳站測試數據，以皮爾森相關係數分析市售三軸加速規與手機加速規之校標效度。並依康柏蘭足踝不穩工具分數 24 分作為切點，將受試者雙足分為健康足與不穩足以驗證兩種加速規之鑑別力。結果顯示市售三軸加速規與手機內建加速規量測到之數據相關性在開眼情境下為 .960 ($p <$ .001)、閉眼情境下為 .997 ($p <$ .001)。且兩種加速規之鑑別力結果顯示在量測健康足與不穩足間之差異以及開眼與閉眼情境之差異皆有達統計學上的顯著差異。故使用智慧型手機內建加速規進行足踝控制評估與市售三軸加速規量測結果具高度相關性，且具備鑑別健康足與不穩足之能力，有潛力成為臨床足踝控制表現評估工具。

關鍵詞：行動裝置、足踝扭傷、足踝控制