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Research article

Inertial Sensor-Based Assessment of Static Balance in Athletes with Chronic Ankle Instability

Yuta Koshino ✉, Moeko Akimoto, Daiki Kawahara, Kentaro Watanabe, Tomoya Ishida, Mina Samukawa, Satoshi Kasahara and Harukazu Tohyama
Faculty of Health Sciences, Hokkaido University, Sapporo, Japan

Abstract

The Balance Error Scoring System (BESS), a subjective examiner-based assessment, is often employed to assess postural balance in individuals with chronic ankle instability (CAI); however, inertial sensors may enhance the detection of balance deficits. This study aimed to compare the BESS results between the CAI and healthy groups using conventional BESS scores and inertial sensor data. The BESS test (six conditions: double-leg, single-leg, and tandem stances on firm and foam surfaces, respectively) was performed for the CAI (n = 16) and healthy control (n = 16) groups with inertial sensors mounted on the sacrum and anterior shank. The BESS score was calculated visually by the examiner by counting postural sway as an error based on the recorded video. The root mean square for resultant acceleration (RMS_{acc}) in the anteroposterior, mediolateral, and vertical directions was calculated from each inertial sensor affixed to the sacral and shank surfaces during the BESS test. The mixed-effects analysis of variance and unpaired t-test were used to assess the effects of group and condition on the BESS scores and RMS_{acc}. No significant between-group differences were found in the RMS_{acc} of the sacral and shank surfaces, and the BESS scores ($P > 0.05$), except for the total BESS score in the foam condition (CAI: 14.4 ± 3.7, control: 11.7 ± 3.4; $P = 0.039$). Significant main effects of the conditions were found with respect to the BESS scores and RMS_{acc} for the sacral and anterior shank ($P < 0.05$). The BESS test with inertial sensors can detect differences in the BESS conditions for athletes with CAI. However, our method could not detect any differences between the CAI and healthy groups.

Key words: Wearable sensor, Balance Error Scoring System, postural control, postural stability, ankle sprain.

Introduction

Chronic ankle instability (CAI), which is a sequela of lateral ankle sprain (LAS), causes ankle recurrent sprain, the ankle giving way, and a perception of ankle instability (Gribble et al., 2013). CAI is a serious problem for athletes, owing to the high rate of recurrent sprain associated with sports activities (Roos et al., 2017). Additionally, CAI is associated with a higher risk of progression to posttraumatic ankle osteoarthritis and a decrease in the health-related quality of life (Gribble et al., 2016). An accurate understanding of its complex pathogenesis is necessary for the prevention and treatment of CAI, which is a long-term problem for patients.

The pathology of CAI is characterized by a deficit in sensorimotor function, including postural balance, proprioception and neuromuscular reflexes, and inhibition (Hertel and Corbett, 2019). Static balance is the most often assessed aspect of sensorimotor function by previous randomized controlled trials in patients with CAI (Nozu et al., 2021). Additionally, the assessment of static balance is recommended by clinical practice guidelines for CAI (Martin et al., 2021) and is considered necessary for the decision to return to sports activities (Wikstrom et al., 2020). The clinical assessment of static balance is important for individuals with CAI for rehabilitation and sports, necessitating the formulation of a valid evaluation method.

Clinically, static balance in individuals with CAI is commonly assessed using the Balance Error Scoring System (BESS) (Koshino and Kobayashi, 2023). Studies have validated the ability of BESS to identify the presence or absence of CAI (Docherty et al., 2006; Linens et al., 2014). BESS is also commonly used to assess balance in patients with concussion (Ozinga et al., 2018). This simple assessment method does not require any instruments, and can be performed anywhere. However, it is a subjective method, in which the examiner counts the number of postural sways (errors) and is therefore dependent on the examiner. Moreover, the floor and ceiling effect is a limitation of the BESS (Alberts et al., 2015). An instrumented BESS test may be useful in increasing the objectivity and efficacy of detection of balance deficits in individuals with CAI.

A previous study suggested that the quantification of BESS using inertial sensors can overcome this limitation (Alberts et al., 2015). The BESS with inertial sensors reportedly enables superior detection of balance impairments in patients with concussion compared to conventional BESS without sensors (Doherty et al., 2017; King et al., 2014; King et al., 2017). The inertial sensors are easily applicable in the clinical setting since they are portable and inexpensive. However, no study has examined whether BESS with inertial sensors is more useful than the conventional examiner-based BESS score in individuals with CAI. Therefore, the present study aimed to compare the inertial sensor-based and conventional BESS scores between the CAI and healthy groups, and determine the assessment method with the superior ability to detect between-group differences. We hypothesized that inertial sensor-based BESS assessment would detect more differences between participants with CAI and healthy controls compared to the conventional BESS score.

Methods

Participants

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The present study enrolled 16 college athletes with CAI and 16 college athletes without CAI (healthy controls), who engaged in regular sports (basketball, soccer, lacrosse, tennis, and badminton). An *a priori* power analysis was performed using the total BESS errors reported in a previous study (Docherty et al., 2006), which required 16 participants in each group to achieve adequate statistical power ($\alpha = 0.05$, $1 - \beta = 0.80$).

The definition of CAI was based on the following recommendations provided by the International Ankle Consortium (Gribble et al., 2013): (i) a history of at least one LAS, (ii) the initial sprain must have occurred over 1 year ago, (iii) a history of at least two instances of the affected joint "giving way" within the past 6 months and/or recurrent LAS, and (iv) a Cumberland Ankle Instability Tool (CAIT; Japanese version) score ≤25 (Kunugi et al., 2017). This questionnaire assesses ankle instability during activities of daily living and sports and is valid and reliable for determining the presence of CAI. (Kunugi et al., 2017). Participants with a negative history of lower extremity or trunk injury and a CAIT score ≥ 28 were designated as the healthy control group. The exclusion criteria that were common to all participants included a history of lower limb surgery and fracture, and lower limb injury, including LAS within 3 months, and neurological findings. The CAI and control groups were matched for the dominance of the test limb. The participants' demographic data are presented in Table 1. This study was approved by our university's ethics committee and all participants provided written informed consent for participation.

Table 1. Demographic data.

	CAI	Control	*P* value
Male/female, n	12/4	12/4	
Age, years	19.9 (1.2)	20.3 (1.5)	0.52
Height, cm	169.5 (0.1)	170.2 (0.9)	0.81
Mass, kg	64.8 (8.0)	63.2 (9.7)	0.62
BMI, kg/m^2	22.5 (1.6)	21.5 (1.9)	0.19
Sports participation, h/week	12.7 (3.4)	11.2 (3.1)	0.17
Number of previous ankle sprains	3.1 (1.3)	0	
CAIT score	21.5 (2.8)	29.6 (0.6)	< 0.001

Mean (standard deviation). Abbreviations: BMI, body mass index; CAI, chronic ankle instability; CAIT, Cumberland Ankle Instability Tool.

Instrumentation

Inertial sensors (SS-MS-HMA5G3, Sports Sensing Co., Ltd., Fukuoka, Japan) with a tri-axial accelerometer (± 5 g), gyroscope (± 300 dps) and magnetometer (± 10 Gauss) were affixed to the sacrum (level of the posterior superior iliac spine) and anterior surface of the shank (mid-height level of the lateral malleolus and fibula head), respectively (Figure 1) (Chiu et al., 2017; Doherty et al., 2017). Data were acquired at a sampling frequency of 100 Hz.

Procedures

BESS is used to assess static postural balance (Docherty et al., 2006; Riemann et al., 1999). The BESS consists of three standing conditions with two floor conditions, with a total of six conditions (Figure 2): double-leg stance on a firm surface (DLSfi), single-leg stance on a firm surface (SLSfi), tandem stance on a firm surface (TSfi), double-leg stance on a foam surface (DLSfo), single-leg stance on a foam surface (SLSfo), and tandem stance on a foam surface (TSfo). The Airex Balance-pad Elite (Airex AG, Sins, Switzerland) was used as the foam surface. In all conditions, participants stood barefoot with the eyes closed, with both hands placed on the iliac crest. The order of the six conditions was random and one trial was conducted for each condition. The participants were instructed to hold their posture for 20 s without moving as much as possible and return to the original posture as quickly as possible when they lost their posture (Riemann et al., 1999). All trials were recorded using a video camera (HDR-680; SONY, Tokyo, Japan).

Figure 1. Location of the inertial sensors on the sacrum (a) and shank (b).

Data analysis

The traditional BESS score is based on the recorded video, which is obtained by counting the following errors: (1) moving the hands off the hips; (2) opening the eyes; (3) stepping, stumbling, and falling; (4) moving hip abduction or flexion > 30°; (5) lifting the forefoot or heel; and (6) staying out of the test position for > 5 s (Docherty et al., 2006; Doherty et al., 2017; Riemann et al., 1999). The maximum number of errors for each condition was set as 10.

This study utilized three-axis acceleration data obtained from the inertial sensor during the BESS test. Data were filtered using a fourth-order low-pass Butterworth filter with a cut-off frequency of 4 Hz (Alberts et al., 2015; Doherty et al., 2017). We calculated the root mean square (RMS) of acceleration using MATLAB R2021b (MathWorks, Natick, MA, USA) according to the method described by Whitney et al. (Whitney et al., 2011). RMS values are commonly used in populations with concussion and have been reported to be more sensitive to postural balance changes than the BESS score (Baracks et al., 2018; King et al., 2014; King et al., 2017; Parrington et al., 2020). The RMS of the acceleration measured by the inertial sensor bears a significant correlation with the center-of-gravity acceleration measured by the motion capture system and center-of-pressure (COP) acceleration measured by the force plate, respectively (Alberts et al., 2015; Neville et al., 2015). Additionally, the test-retest reliability of RMS for postural balance measures has been shown to be good to excellent (Mancini et al., 2012). The RMS for resultant acceleration ($\mathrm{RMS}_{\mathrm{acc}}$) in the anteroposterior, mediolateral, and vertical directions was calculated using the following formula:

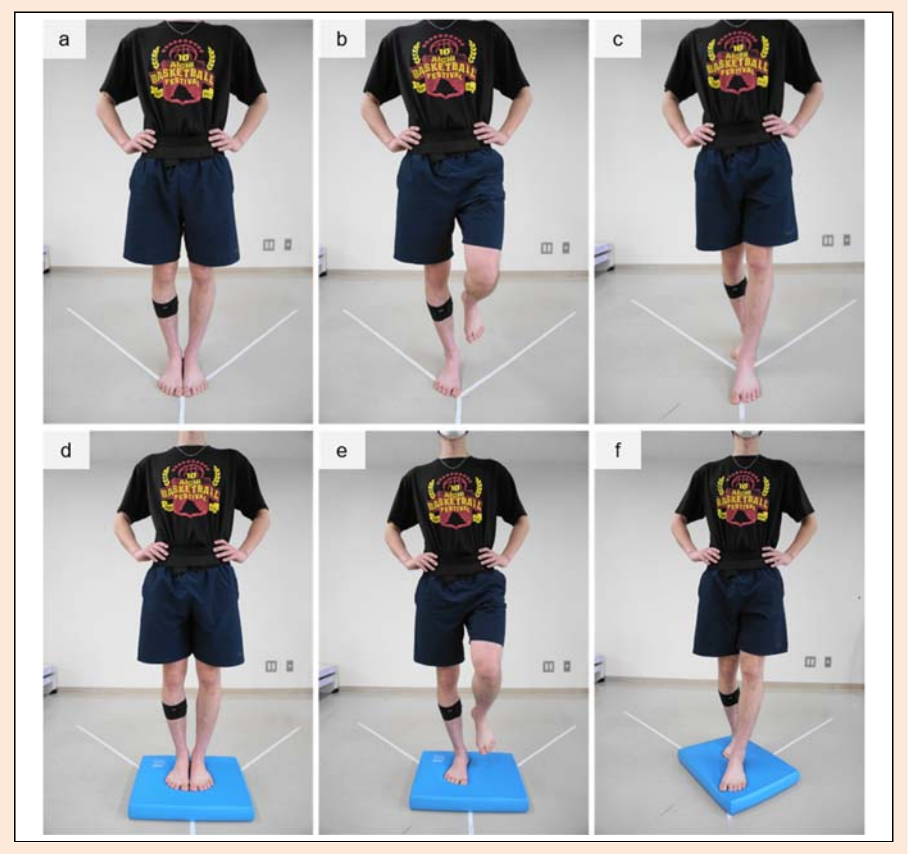

Figure 2. Balance Error Scoring System (a) double-leg stance on a firm surface (DLSfi); (b) single-leg stance on a firm surface (SLSfi); (c) tandem stance on a firm surface (TSfi); (d) double-leg stance on a foam surface (DLSfo); (e) single-leg stance on a foam surface (SLSfo); (f) tandem stance on a foam surface (TSfo).

$$RMS_{acc} = \sqrt{\frac{\sum_{i=1}^{N}(x_i - x_{avg})^2 + \sum_{i=1}^{N}(y_i - y_{avg})^2 + \sum_{i=1}^{N}(z - z_{avg})^2}{N}}$$

where N represents the number of data point, and x_i, y_i, *and* z_i are the instantaneous acceleration data in the vertical, mediolateral, and anteroposterior directions, respectively. The average values across the time-series acceleration data were represented as x_{avg}, y_{avg}, and z_{avg}, respectively.

Statistical analysis

IBM SPSS Statistics version 26 (IBM, Chicago, IL, USA) was used for all statistical analyses. The demographic data of the CAI and control groups were compared using unpaired t-tests.

For each of the BESS and RMS_{acc} values of the sacral and shank sensors, a mixed-effects analysis of variance was used to evaluate the main effects and interactions between the condition and group. The within-subject factor consisted of six conditions in the BESS (double-leg, single-leg, and tandem stances on firm and foam surfaces), and the between-subjects factor consisted of the two groups (CAI and control). When a significant main effect or interaction was observed, comparisons between groups or conditions were performed using the Bonferroni correction. Statistical significance was set at $P < 0.05$.

We calculated the total BESS score (sum of errors for all six conditions), score on the firm surface (sum of errors for the three firm surface conditions), and score on the foam surface (sum of errors for the three foam surface conditions) (Khanna et al., 2015). Similarly, the total RMS_{acc}, value was calculated for all six conditions: three conditions for the firm surface and three conditions for the foam surface. These variables were compared between the CAI and control groups using the unpaired t-test ($P < 0.05$).

Results

Demographic data

Demographic data, including age, height, weight, and body mass index, did not differ significantly between the CAI and control groups. The participation time in sports activities did not differ significantly between the groups. The CAIT scores were significantly lower in the CAI group than those in the control group. These results are shown in Table 1.

BESS scores

For the BESS scores, we found a significant main effect of condition ($P < 0.001$, partial $\eta^2 = 0.761$) but no significant main effect of group ($P = 0.457$, partial $\eta^2 = 0.019$) or interaction ($P = 0.089$, partial $\eta^2 = 0.068$). No significant group differences were found in any of the conditions ($P > 0.05$).

The error counts were significantly lower in the DLSfi condition compared to the other conditions ($P < 0.005$), except for the DLSfo condition ($P = 0.160$). The error counts in the DLSfo condition were significantly fewer than those in the SLSfi, SLSfo, and TSfo conditions

($P < 0.01$). The error counts were significantly fewer in the SLSfi condition than those in the SLSfo and TSfo conditions ($P < 0.001$). The error counts were significantly higher in the SLSfo condition than those in the other conditions ($P < 0.001$), except for the TSfo condition ($P = 1.000$). The error counts were significantly fewer in the TSfi condition than those in the SLSfo and TSfo conditions ($P < 0.001$). The frequency of errors in the TSfo condition was significantly higher than that in the SLSfo condition ($P < 0.001$) for all conditions, except the SLSfo condition ($P = 1.000$). The errors in all conditions are shown in Figure 3a.

Data of the inertial sacral sensor

We found a significant main effect of condition on the RMS_{acc} ($P < 0.001$, partial $\eta^2 = 0.656$), but no significant main effect of group ($P = 0.215$, partial $\eta^2 = 0.051$) and no significant interaction ($P = 0.112$, partial $\eta^2 = 0.069$). We found no significant group differences in any of the conditions ($P > 0.05$). The RMS_{acc} values for the sacral sensor under all conditions are shown in Figure 3b.

The RMS_{acc} was significantly smaller in the DLSfi condition than that in all other conditions ($P < 0.05$). The RMS_{acc} was significantly smaller in the DLSfo condition than that in all conditions, except the TSfi condition ($P < 0.001$). The RMS_{acc} was significantly smaller in the SLSfi condition than that in the SLSfo and TSfo conditions ($P < 0.001$). RMS_{acc} in the SLSfo condition was larger than that in all conditions ($P < 0.05$). The RMS_{acc} was smaller in the TSfi condition than that in the SLSfi, SLSfo, and TSfo conditions ($P < 0.005$). The RMS_{acc} was significantly smaller in the TSfo condition than that in the SLSfo condition ($P = 0.044$).

Data of the inertial shank sensor

A significant main effect of condition was found for the RMS_{acc} of the sensors on the shank ($P < 0.001$, partial $\eta^2 = 0.663$). However, the main effects of group ($P = 0.478$, partial $\eta^2 = 0.017$) and interaction (RMS_{acc}: $P = 0.675$, partial $\eta^2 = 0.015$) were not significant. There were no significant differences in any conditions between the CAI and control groups. The RMS_{acc} of the shank sensor under all conditions is shown in Figure 3c.

In the DLSfi condition, the RMS_{acc} was significantly smaller than that in all conditions ($P < 0.05$). The RMS_{acc} in the DLSfo condition was significantly smaller than that in the SLSfi, SLSfo, and TSfo conditions ($P < 0.001$). The RMS_{acc} of the SLSfi condition was significantly smaller than that of the SLSfo and TSfo conditions ($P < 0.001$). The RMS_{acc} in the SLSfo condition was larger than that in all conditions ($P < 0.001$), except for the TSfo condition ($P = 1.000$). The RMS_{acc} in the TSfi condition was smaller than that in the SLSfo and TSfo conditions ($P < 0.001$). The RMS_{acc} in the TSfo condition was larger than that in all conditions ($P < 0.001$), except for the SLSfo condition ($P = 1.000$).

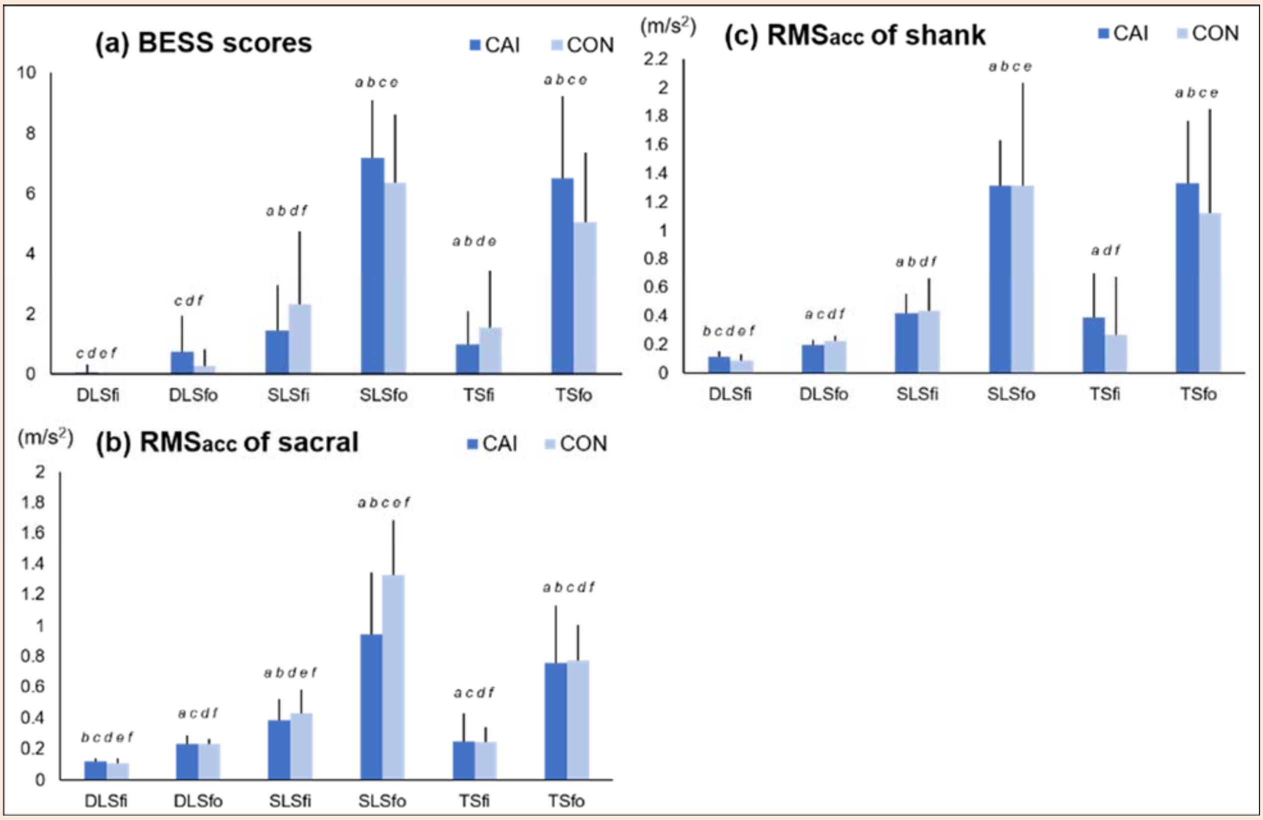

Figure 3. Mean BESS score (a) and mean RMS_{acc} of sensors mounted on the sacrum (b) and shank (c) in all conditions The error bars indicate standard deviation. ^{a} significantly different from DLSfi, ^{b} significantly different from DLSfo, ^{c} significantly different from SLSfi, ^{d} significantly different from SLSfo, ^{e} significantly different from TSfi, ^{f} significantly different from TSfo. BESS, Balance Error Scoring System; CAI, chronic ankle instability; CON, control; DLSfi, double-leg stance on firm surface; DLSfo, double-leg stance on foam surface; SLSfi, single-leg stance on firm surface; SLSfo, single-leg stance on foam surface; TSfi, tandem stance on firm surface; TSfo, tandem stance on foam surface.

Table 2. Total error scores and total RMS_{acc} data of sacral and shank.

	CAI	Control	*P* value
Visual assessment, errors			
Total BESS score	16.9 (4.5)	15.6 (5.8)	0.457
Firm BESS score	2.5 (2.0)	3.9 (3.9)	0.227
Foam BESS score	14.4 (3.7)	11.7 (3.4)	0.039*
Accelerometer assessment, m/s^2			
Total RMS_{acc} of sacral	2.68 (0.56)	3.11 (1.23)	0.215
Firm RMS_{acc} of sacral	0.75 (0.25)	0.78 (0.42)	0.814
Foam RMS_{acc} of sacral	1.93 (0.54)	2.33 (0.94)	0.151
Total RMS_{acc} of shank	3.76 (1.29)	3.46 (1.11)	0.478
Firm RMS_{acc} of shank	0.93 (0.52)	0.79 (0.26)	0.366
Foam RMS_{acc} of shank	2.84 (1.12)	2.67 (0.94)	0.641

Mean (standard deviation). CAI: chronic ankle instability, RMS: root mean square.
* significant difference between the CAI and control groups.

Total BESS scores and total RMS values of acceleration

The total BESS score (sum of errors during all six conditions) and firm surface score (sum of errors during three firm surface conditions) did not differ significantly between the CAI and control groups (Table 2). We observed a significant difference in the foam surface score (sum of errors during the three foam surface conditions) between the CAI and control groups (Table 2).

The total, firm total, and foam total values of the RMS_{acc} of the sacral and anterior shank surfaces did not differ significantly between the CAI and control groups (Table 2).

Discussion

The present study assessed the BESS for the CAI and control groups using conventional scores obtained from the examiner's visual assessment and RMS values of acceleration data obtained from the inertial sensors attached to the sacrum and shank. We found significant differences in the BESS scores obtained on the foam surface between the CAI and control groups, but no significant group differences in the inertial sensor-based assessment of the sacrum or tibia. Therefore, our hypothesis that the inertial sensor BESS assessment would detect more group differences than those with the BESS score was disproved.

In the present study, static postural balance assessment using inertial sensors failed to detect significant differences in individuals with CAI and healthy controls. Previous studies have successfully detected differences in static postural balance assessment using inertial sensors in patients with concussion, even when the BESS score showed no difference (Doherty et al., 2017; King et al., 2014). Some studies have reported higher BESS scores in individuals with CAI in the single-leg stance condition or in the total score (Dobo et al., 2015; Docherty et al., 2006; Linens et al., 2014), whereas another study showed no significant difference in the BESS score in the single-leg stance condition between the CAI and healthy groups (Kwon, 2018). In addition, a limitation of the BESS score is the floor and ceiling effect (Alberts et al., 2015). Therefore, we considered that assessment using the BESS score alone may not be sufficient to detect the impairment in static balance in the CAI group, and investigated the utility of evaluation using inertial sensors with reference to studies on concussion. However, the inertial sensor-based BESS assessment for individuals with CAI was not found to be more useful than the traditional BESS score.

The failure of the inertial sensor-based BESS in detecting the deficit in postural balance in the CAI group could be attributed to the following potential causes. Although the BESS errors obtained on the foam surface were significantly greater in the CAI group than those in the healthy group, the other scores were not significantly different. Overall, the BESS scores of the healthy group in this study (total score: 15.6 ± 5.8) seemed to be higher than those in previous studies, where the total scores ranged from 8.4 to 13.5 (Docherty et al., 2006; King et al., 2014; Linens et al., 2014; McCrea et al., 2003; Riemann and Guskiewicz, 2000). The BESS score of the healthy group in our study exceeded the reported cut-off value of the BESS score for the diagnosis of CAI, which was 14 points (Linens et al., 2014). We were unable to fathom why the BESS errors were relatively high in healthy college athletes in our study; however, this finding may explain the near lack of significant between-group differences in this study. Previous studies using a force plate have shown that the sway area and velocity of the COP were larger in the CAI group, which required a shorter time to reach the balance boundaries during the single-leg stance compared to healthy individuals (Hertel and Olmsted-Kramer, 2007; Mohamadi et al., 2020; Wikstrom et al., 2010). The postural balance of individuals with CAI may be better suited for the assessment of the velocity and area of the sway, and time to boundary rather than acceleration. Additionally, the definition of CAI in the present study was based on the International Ankle Consortium’s recommendations; therefore, the presence or absence of mechanical ankle instability was not included in the criteria (Gribble et al., 2013). However, a previous study reported that the balance in the single-leg stance decreased in patients with mechanical instability, and balance did not decrease when mechanical instability was absent in the CAI population (Chen et al., 2014). In the future, new insights may be obtained by assessing postural balance using inertial sensors, including CAI with mechanical instability.

The RMS acceleration of the inertial sensors placed on the sacrum and shank differed significantly between the conditions in the BESS. The trends in the differences between the RMS_{acc} conditions were similar to those of the BESS scores (Figure 3). The RMS_{acc} and BESS scores were high under the single-leg and tandem stance conditions on the foam surface, which is considered a difficult task. These results suggest that the $\mathrm{RMS}_{\mathrm{acc}}$ in the present study was able to assess postural sway while maintain standing posture.

Inertial sensors were placed on the sacrum and shank based on previous studies (Chiu et al., 2017; Doherty et al., 2017). However, no significant group differences were detected in either placement. Previous studies suggest that data from head-mounted sensors are most consistent with the BESS scores (Brown et al., 2014), and that thigh-mounted sensors are best able to detect changes in acceleration between balance task conditions (Shah et al., 2016). Future studies are needed to examine whether balance impairment in the CAI group can be detected by sensors mounted on the head or thigh.

The present study had several limitations. First, only healthy controls were included in the control group. Inclusion of a control group consisting of copers with a history of ankle sprain but without CAI could have enabled detection of the difference in postural balance compared to the CAI group (Kwon, 2018). Second, we do not know whether postural balance was impaired during the single-leg standing in participants with CAI. It is also possible that the postural balance in the healthy group was relatively poor. The assessment of postural balance using a force plate, the most commonly used objective evaluation method, was probably necessary to verify these results. Finally, BESS assessment with inertial sensors in a population with concussion was captured for 30 s, instead of the standard BESS measurement time of 20 s (Baracks et al., 2018; King et al., 2014; Parrington et al., 2020). We measured the inertial sensor data for 20 s, which may have influenced the results of this study.

Conclusion

In the present study, we compared BESS assessment for RMS values of acceleration obtained from inertial sensors fixed to the sacral and shank with the conventional BESS scores in the CAI and healthy groups. Comparisons between the two groups showed no significant differences in any variable, except for the total BESS score in the foam condition. Significant main effects of stance and the floor conditions were found for the BESS scores and RMS values of acceleration for the sacrum and shank. BESS testing with inertial sensors for individuals with CAI could detect differences in the BESS conditions but could not detect impairment in balance due to CAI.

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Key points

- This study compared the Balance Error Scoring System (BESS) for the chronic ankle instability (CAI) and control groups using conventional scores obtained from the examiner's visual assessment and RMS values of acceleration data obtained from the inertial sensors attached to the sacrum and shank.
- Significant differences were found in the BESS scores obtained on the foam surface between the CAI and control groups
- No significant group differences in the inertial sensor-based assessment of the sacrum or tibia.
- For the BESS scores and RMS values of acceleration data, we found a significant main effect of condition in the BESS.
- Our hypothesis that the inertial sensor BESS assessment would detect more group differences than those with the BESS score was disproved.

AUTHOR BIOGRAPHY

Yuta KOSHINO

Employment

Faculty of Health Sciences, Hokkaido University

Degree

PhD

Research interests

Rehabilitation for sports injuries and musculoskeletal disorders

E-mail: y-t-1-6@hs.hokudai.ac.jp

Moeko AKIMOTO

Employment

Faculty of Health Sciences, Hokkaido University

Degree

MSc

Research interests

Balance assessment for ankle instability

E-mail:

gn-m0799b@frontier.hokudai.ac.jp

Daiki KAWAHARA

Employment

Faculty of Health Sciences, Hokkaido University

Degree

MSc

Research interests

Biomechanics for ankle instability

E-mail:

hokusa9ra4ake@frontier.hokudai.ac.jp

Kentaro WATANABE
Employment
Faculty of Health Sciences, Hokkaido University
Degree
MSc
Research interests
Rehabilitation for ankle instability
E-mail: wataken_0121_soccer@eis.hokudai.ac.jp

Tomoya ISHIDA
Employment
Faculty of Health Sciences, Hokkaido University
Degree
PhD
Research interests
Rehabilitation and prevention for sports injuries.
E-mail: t.ishida@hs.hokudai.ac.jp

Satoshi KASAHARA
Employment
Faculty of Health Sciences, Hokkaido University
Degree
PhD
Research interests
Rehabilitation for neurological disease and motor control for aged adults
E-mail: kasahara@hs.hokudai.ac.jp

Mina SAMUKAWA
Employment
Faculty of Health Sciences, Hokkaido University
Degree
PhD
Research interests
Effects of therapeutic exercises and prevention for sports injuries.
E-mail: mina@hs.hokudai.ac.jp

Harukazu TOHYAMA
Employment
Faculty of Health Sciences, Hokkaido University
Degree
PhD
Research interests
Rehabilitation for sports injuries and exercise therapy for musculoskeletal disorders.
E-mail: tohyama@med.hokudai.ac.jp

🖂 **Yuta Koshino, PhD, PT**
Faculty of Health Sciences, Hokkaido University, West 5, North 12, Kita-ku, Sapporo 060-0812, Japan.