*Journal of Athletic Training* 2014;49(1):15–23
doi: 10.4085/1062-6050-48.6.09

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*original research*

# Postural-Stability Tests That Identify Individuals With Chronic Ankle Instability

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***Context:*** Chronic ankle instability (CAI) is characterized by repeated ankle sprains, which have been linked to postural instability. Therefore, it is important for clinicians to identify individuals with CAI who can benefit from rehabilitation.

***Objective:*** To assess the likelihood that CAI participants will exhibit impaired postural stability and that healthy control participants will exhibit better test performance values.

***Design:*** Case-control study.

***Setting:*** Laboratory.

***Patients or Other Participants:*** People with CAI ($n = 17$, age $= 23 \pm 4$ years, height $= 168 \pm 9$ cm, weight $= 68 \pm 12$ kg) who reported ankle "giving-way" sensations and healthy volunteers ($n = 17$, age $= 23 \pm 3$ years, height $= 168 \pm 8$ cm, weight $= 66 \pm 12$ kg).

***Intervention(s):*** Participants performed 7 balance tests: Balance Error Scoring System (BESS), time in balance, foot lift, single-legged stance on a force plate, Star Excursion Balance Test, side hop, and figure-of-8 hop.

***Main Outcome Measure(s):*** Balance was quantified with errors (score) for the BESS, length of time balancing (seconds) for time-in-balance test, frequency of foot lifts (score) for foot-lift test, velocity (cm/s) for all center-of-pressure velocity measures, excursion (cm) for center-of-pressure excursion measures, area ($cm^2$) for 95% confidence ellipse center-of-pressure area and center-of-pressure rectangular area, time (seconds) for anterior-posterior and medial-lateral time-to-boundary (TTB) measures, distance reached (cm) for Star Excursion Balance Test, and time (seconds) to complete side-hop and figure-of-8 hop tests. We calculated area-under-the-curve values and cutoff scores and used the odds ratio to determine if those with and without CAI could be distinguished using cutoff scores.

***Results:*** We found significant area-under-the-curve values for 4 static noninstrumented measures, 3 force-plate measures, and 3 functional measures. Significant cutoff scores were noted for the time-in-balance test ($\leq$25.89 seconds), foot-lift test ($\geq$5), single-legged stance on the firm surface ($\geq$3 errors) and total ($\geq$14 errors) on the BESS, center-of-pressure resultant velocity ($\geq$1.56 cm/s), standard deviations for medial-lateral ($\leq$1.56 seconds) time-to-boundary and anterior-posterior ($\leq$3.78 seconds) time-to-boundary test, posteromedial direction on the Star Excursion Balance Test ($\leq$0.91), side-hop test ($\geq$12.88 seconds), and figure-of-8 hop test ($\geq$17.36 seconds).

***Conclusions:*** Clinicians can use any of the 10 significant measures with their associated cutoff scores to identify those who could benefit from rehabilitation that reestablishes postural stability.

***Key Words:*** lower extremity, ankle sprains, Balance Error Scoring System, Star Excursion Balance Test

**Key Points**

- Chronic ankle instability has been linked to postural instability. Postural instability can be addressed with targeted interventions.
- The time-in-balance test, foot-lift test, Balance Error Scoring System total and single-limb stance on a firm surface, center-of-pressure resultant velocity, time-to-boundary anterior-posterior and medial-lateral standard deviation, Star Excursion Balance Test in the posteromedial direction, side-hop test, and figure-of-8 hop test can be used to identify people with chronic ankle instability who may benefit from rehabilitation to reestablish postural stability.

Ankle sprains are one of the most common injuries experienced by the physically active.[1–3] A single ankle sprain can lead to balance impairments, recurrent instability, and recurrent sprains.[4,5] These deficits are often grouped together and defined as *chronic ankle instability* (CAI), which is more specifically defined by a history of ankle sprains or recurrent episodes of instability or both.[6] Clinicians and researchers alike focus on identifying and correcting balance impairments because poor balance is linked to ankle sprains.[7]

A variety of postural-stability tests have been developed to identify poor balance associated with CAI[4] in both clinical and research settings. Tests include the Balance Error Scoring System (BESS), time-in-balance test, foot-lift test, force-plate measures (eg, center-of-pressure velocity, center-of-pressure area, time to boundary),[4] and functional measures (eg, Star Excursion Balance Test [SEBT],[8] side-hop test, figure-of-8 hop test).[9] Several authors[10–12] have performed receiver operating characteristic (ROC) curve analyses and established cutoff scores for a number of static postural control variables in those with ankle instability. However, no investigators to our knowledge have determined the likelihood that patients with CAI will exhibit impaired postural stability, both statically and functionally, in the same cohort.

Clinical tests focus on noninstrumented measures that quantify balance. Common static, clinician-based postural-stability tests include the BESS, time-in-balance test, and foot-lift test. Researchers[13–15] have also attempted to develop the most precise measurements of static balance using instrumented force plates. However, force plates can be expensive and may not be readily available to clinicians. Several center-of-pressure (COP) measurements have been used by investigators[13,16] to detect balance deficits associated with CAI.

Some authors[17,18] have suggested that functional tests may provide better means of identifying participants with CAI than static, single-legged balance tests because functional movements may magnify the degree to which sensorimotor deficits affect balance performance. Functional balance tests may provide an overall assessment of joint stability, strength, and sensorimotor function, which might help clinicians identify balance deficits that would be undetected with static tests.[9] Functional balance tests are often used clinically to determine readiness for returning to physical activity, but clinicians may also use established cutoff scores of functional tests to identify patients with postural instability who would benefit from rehabilitation.

Researchers[9] have also suggested that functional balance tests that increase inversion torques on the ankle joint can identify performance deficits associated with CAI. Furthermore, these tests can be administered quickly and easily with minimal supplies. However, on several functional measures (ie, up-down hop, single hop,[9] triple-crossover hop for distance, and shuttle run[19]), no difference was seen between those with CAI and those with healthy ankles. Given the conflicting results in this area, functional testing warrants further investigation.

Due to the large number of balance assessments, we believe that clinicians should know the type of postural-stability tests and outcomes that are most appropriate to discriminate between those with CAI and those with stable ankles. Therefore, the purpose of our study was to assess the likelihood that CAI participants would exhibit impaired postural stability and that healthy control participants would exhibit better outcomes identified by specific cutoff values. With this information, clinicians can identify individuals who may benefit from rehabilitation that reestablishes postural stability. This finding is important because of similarities to a subgroup of patients in the anterior cruciate ligament injury literature; there are "copers" who do not demonstrate postural instability and therefore do not require rehabilitation.[20] Furthermore, clinicians can benefit from knowing minimum test performance goals for CAI patients that correspond to the cutoff points that separate those with CAI and healthy ankles.

## METHODS

### Participants

A total of 34 recreationally active volunteers agreed to participate in our study. The CAI group consisted of 17 participants who had a history of ankle sprains and symptoms of giving way (13 women, 4 men; age = 23 ± 4 years; height = 168 ± 9 cm; weight = 68 ± 12 kg; test foot = 14 right, 3 left; dominant foot = 17 right). The healthy group consisted of 17 participants with stable ankles and no history of ankle injury (13 women, 4 men; age = 23 ± 3 years; height = 168 ± 8 cm; weight = 66 ± 12 kg; test foot = 14 right, 3 left; dominant foot = 17 right). Inclusion criteria for both groups were (1) age 18 to 40 years old, (2) no current knee or hip injuries that limited function, and (3) performance of cardiovascular or resistance training for at least 1.5 hours per week. Additionally, participants with CAI had to meet the following inclusion criteria: (1) history of at least 1 significant ankle sprain, (2) self-reported sensations of giving way at least twice a year during activity, (3) Cumberland Ankle Instability Tool (CAIT) score of $\leq$27, and (4) no signs or symptoms of an acute injury. Our inclusion criteria of a history of at least 1 significant ankle sprain and self-reported sensations of giving way at least twice a year during activity are similar to those reported by Docherty et al,[21] Lee et al,[22] and Olmsted et al.[23] Hiller et al[24] reported that those with CAI should have scores of 27 or less on the CAIT. Our CAIT score for the CAI group was 19.76 ± 4.24 and for the healthy group was 29.47 ± 1.50. Participants in the healthy group had to meet the following inclusion criteria: (1) no history of ankle injury and (2) sex, height (± 10 cm), weight (± 15 kg), and age (18–29 or 30–40 years) matched to a participant with ankle instability. Exclusion criteria for all volunteers were (1) any known vision deficit other than myopia, hyperopia, or astigmatism; (2) any known vestibular deficit; or (3) any known somatosensory deficits (other than those present in the ankle for the CAI group). In participants with bilateral CAI, the more symptomatic ankle (self-reported) was chosen for study. Three participants presented with mechanical instability as measured by manual stress tests (2 on anterior drawer test, 1 on talar tilt test). All participants provided written informed consent, and the study was approved by the university's institutional review board.

### Procedures

Data for all balance measures were collected during 2 visits to the Sports Medicine Research Laboratory. The first session started with recording the participant's age, height, and weight. A single investigator who is a certified athletic trainer performed an ankle evaluation for joint laxity using the anterior drawer and talar tilt tests and completed the CAIT.

Next, the participant completed either the static or functional postural-stability tests. Testing type was counterbalanced. Each participant stood on the leg with CAI or the matched test leg. The order of testing for static balance tests was counterbalanced. For the functional testing session, the SEBT was completed first, and the order of reach directions (anteromedial, medial, posteromedial) was counterbalanced. The SEBT was performed first due to the potential fatigue from performing both the side-hop test and figure-of-8 hop test. Both hop tests were then performed, with the order of testing counterbalanced.

**Balance Error Scoring System.** The BESS provides a quantitative static measure of balance using an error score. This test attempts to challenge the postural-control system by combining a variety of stances on a firm surface and an unstable surface.[21,25] A high total error score on the BESS has identified balance deficits associated with CAI.[21]

Participants performed all 6 stances of the BESS in the following order: double legged (feet side by side) on a firm surface, double legged on a foam surface, single legged on a firm surface, single legged on a foam surface, tandem (leg with CAI or matched test leg placed directly behind the heel of the contralateral foot) on a firm surface, and tandem on a foam surface. One trial on each surface for each stance was performed. The stable surface was the floor, and the unstable surface was an Airex Balance Pad (Perform Better, Cranston, RI) that was medium-density foam (dimensions = 50.8 × 41.7 × 6.4 cm). Participants were instructed to keep their eyes closed and their hands on their hips during testing. The single-legged stances were performed with the weight-bearing leg in approximately 5° of knee flexion and the nonweight-bearing leg slightly flexed at the hip and knee.[25] Before each test, participants were instructed to remain as motionless as possible for 20 seconds and to minimize balance errors during testing. One error was recorded for any of the following: lifting hands off hips, moving the thigh into more than 30° of flexion or abduction, lifting the forefoot or heel, remaining out of the testing position for more than 5 seconds, or opening eyes.[25] Participants were given the opportunity to practice each stance on each surface once before performing each test, and they rested for 30 seconds between trials. The total number of errors committed in each individual stance and a total number for all trials were used for analysis.[25]

**Time-In-Balance Test.** This test also uses a single-legged stance on a firm surface and assesses the amount of time that the participant can remain on a single leg without losing balance. Decreased standing time correlates well with CAI.[26] Positioning for this test was identical to that for the single-legged stance on a firm surface for the BESS. This test determined how long the participant could remain motionless in single-legged stance before moving the test foot on the floor or touching the floor with the contralateral foot. Three trials with eyes closed were collected, and the longest time trial was used for analysis.[26] The maximum length of each trial was 60 seconds.[26]

**Foot-Lift Test.** The foot-lift test is another static balance assessment that involves single-legged stance on a firm surface. This test has distinguished between participants with and without CAI by demonstrating greater frequency of test-foot lifts over a 30-second trial.[27] Positioning was single-legged stance on a firm surface as previously described. Each foot lift constituted 1 error.[27] Foot lifts were documented as any part of the foot that lost contact with the ground (eg, lifting toes from the floor).[27] Also included in this assessment was frequency of foot touches of the contralateral leg to the floor: each touch was an error, and 1 error was added for each second the foot remained on the floor.[27] The average of the 3 trials was used for analysis.[27]

**Force-Plate Measures.** Center-of-pressure velocity (COPV) measures have quantified balance deficits associated with ankle instability via a meta-analysis, which has greater statistical power than a single investigation.[4] Another type of COP measurement used is center-of-pressure area. Two such area measurements are the 95% confidence ellipse of the center-of-pressure area (COPA-95) and center-of-pressure rectangular area (COPA-r). Reports[28] have indicated improvement of COPA-95 after a balance-training intervention, yet the 95% confidence intervals were very wide. Furthermore, abnormal area values of COPA-95 have indicated ankle-sprain injury.[29] Finally, time-to-boundary (TTB) is a spatiotemporal measure that has detected deficits related to ankle instability.[30] This measure estimates how quickly the instantaneous COP would reach the boundary of the foot if it continued to move at its instantaneous velocity. Thus, lower values have indicated impaired balance associated with CAI.[30]

Data for force-plate measures were collected on an AccuSway force plate (Advanced Mechanical Technology, Inc, Watertown, MA) at a sampling rate of 50 Hz.[13] With the test foot positioned in the middle of the force plate, the participant assumed the same single-legged stance position described previously. He or she performed 1 practice trial and then completed 3 test trials lasting 20 seconds each, with 30 seconds' rest between trials. Anterior-posterior and medial-lateral center-of-pressure data were calculated using Balance Clinic Software (Advanced Mechanical Technology, Inc) and filtered with a fourth-order, zero-lag, low-pass digital filter with a cutoff frequency of 5 Hz.[13] The data were exported to spreadsheets and imported into a custom program in LabVIEW (National Instruments Corporation, Austin, TX) that computed COPV measures, COPA, and TTB measures. The COPV measures were COP resultant velocity, anterior-posterior (A-P) velocity mean, medial-lateral (M-L) velocity mean, A-P excursion mean, M-L excursion mean, A-P COP standard deviation, and M-L COP standard deviation. The COPA measures were COPA-r and COPA-95. The primary difference between these COPA measures is that COPA-r computes rectangular area by multiplying maximum A-P range by maximum M-L range, whereas COPA-95 computes an area in the shape of an ellipse. The TTB measures were A-P mean of minimum, M-L mean of minimum, A-P absolute minima, M-L absolute minima, A-P standard deviation, and M-L standard deviation. Further details of TTB measures have been described by Hertel et al.[13,30]

**Star Excursion Balance Test.** The SEBT is a dynamic test that has detected postural-control deficits associated with ankle instability: reach impairments with this test have indicated lower extremity injury.[8,31] Patients with CAI have been shown to reach less in the anteromedial, medial, and posteromedial directions when balancing on their unstable leg compared with either their uninjured leg or healthy participants.[8] Additionally, the posteromedial reach direction of the SEBT has been most predictive of dynamic balance impairments associated with CAI.[8] Therefore, researchers[8] have recommended using, at minimum, the posteromedial reach in balance assessments and adding anteromedial and medial reaches to provide more clinically relevant information.

The SEBT was performed according to the methods described by Hertel et al.[8] We also followed the recommendation by Hertel et al[8] and isolated testing to the anteromedial (SEBT-AM), medial (SEBT-M), and posteromedial (SEBT-PM) reach directions. Participants performed these reach tests while standing barefoot on the foot with CAI (or the matched test leg) at the center of a grid on the floor with 3 cloth tape measures extending at

45° angles from the center. The lines extended in the AM, M, and PM directions. Participants maintained single-legged stance with their eyes open and hands on their hips while reaching with the contralateral leg to touch as far as possible along the tape measure in the chosen direction. Reach distances were measured by a single examiner and normalized to each participant's leg length (measured from the anterior-superior iliac spine to the distal tip of the medial malleolus). Each person performed 4 practice trials in each of the 3 directions, followed by 5 minutes of rest, and then performed 3 trials in each direction on the test limb. Between trials, 10 seconds of rest were provided.

**Side-Hop Test.** The side-hop test has been positively correlated with answers to questions on self-reported feelings of ankle instability: greater instability was related to increased time to complete this test.[9] Methods described by Docherty et al[9] were used for this test. Participants performed this test barefoot on the CAI leg (or matched test leg). They were instructed to hop laterally 30 cm and back medially 30 cm for 10 repetitions.[9] The total time taken to complete 10 repetitions was recorded by 1 examiner with a handheld stopwatch to the nearest 0.01 second. The test was completed twice, and the best (shortest) time was used for analysis.[9]

**Figure-of-8 Hop Test.** The figure-of-8 hop test has also been positively correlated with answers to questions on self-reported feelings of ankle instability, indicating that greater instability is related to increased time to complete this test (ie, performance deficits).[9] Methods described by Docherty et al[9] were also used for this test. Participants performed this test barefoot on a 5-m course outlined by cones in a figure-of-8 pattern. They were instructed to hop as quickly as possible on the CAI leg (or matched test leg) twice in a figure-of-8 pattern. The total time was recorded by 1 examiner with a handheld stopwatch to the nearest 0.01 second. Participants completed the test twice, and the best (shortest) time was used for analysis.[9]

### Statistical Analysis

We used SPSS software (version 18.0; SPSS Inc, Chicago, IL) for the statistical analyses. Means and standard deviations were calculated for all dependent measures. Effect size values between groups were calculated with the Cohen d, and values of 0.20, 0.50, and 0.80 were defined as low, medium, and high, respectively.[32] Sensitivity and 1–specificity values were calculated for each significant dependent measure across the range of possible scores to compute ROC curves. Area under the curve (AUC) and asymptotic significant values were then calculated ($\alpha = .05$). The AUC is an indicator of the overall value of the variable for accurate discrimination among all possible cutpoints for dichotomous categorizations of cases. Next, cutoff scores were computed with the Youden index [([sensitivity + specificity] − 1) × 100].[33] Positive and negative likelihood ratios were calculated from the sensitivity and specificity values. Then odds ratios were used to determine if a specific cutoff score could distinguish individuals with and without CAI (positive likelihood ratio divided by negative likelihood ratio).[34] We selected the odds ratio as an outcome variable because it is an indicator of the discriminatory power of the variable being analyzed and provides the magnitude of association with a classification of having or not having CAI.[34] If the variable of interest is worse in those with CAI versus stable ankles, the odds ratio will exceed 1.[34] Furthermore, the higher the odds ratio, the greater the association with CAI. Finally, we used a 1-tailed Fisher exact test to determine the statistical significance of the selected cutoff score for each dependent measure as a way to identify a substantial deviation from the expected frequencies of occurrence that would result from chance ($\alpha = .05$).[35] The smaller the *P* value, the stronger the evidence that the 2 proportions are truly different.[35]

## RESULTS

Group means, standard deviations, and effect sizes for each dependent measure are reported in Table 1. All diagnostic values (AUC, *P* values, cutoff scores, sensitivity, 1–specificity, positive and negative likelihood ratios, odds ratios, Fisher exact test results, and the Youden index) for each dependent measure are presented in Table 2. Four static, clinician-based measures (BESS single limb on a firm surface, BESS total, time-in-balance test, and foot-lift test), 5 force-plate measures (COP resultant velocity, A-P COP velocity mean, A-P TTB mean of minimum, A-P COP standard deviation, and M-L COP standard deviation), and 5 functional measures (SEBT-AM, SEBT-M, SEBT-PM, side-hop test, and figure-of-8 hop test) had significant AUC values. Five static, clinician-based measures (BESS single-legged stance on a firm surface, BESS tandem stance on a foam surface, BESS total, time-in-balance test, and foot-lift test), 8 force-plate measures (M-L COP standard deviation, A-P COP standard deviation, A-P TTB mean of minimum, A-P COP velocity mean, COPA-95, COP resultant velocity, A-P COP excursion mean, and A-P COP standard deviation), and 3 functional measures (SEBT-PM, side-hop test, figure-of-8 hop test) had significant cutoff scores and odds ratios.

## DISCUSSION

Our most important finding was that some postural-stability measures were better than others at identifying individuals who need balance rehabilitation. We specifically identified particular postural-stability tests that reflected deficits commonly associated with CAI. Odds ratios were then calculated to determine if a specific cutoff score could distinguish individuals with and without CAI.

### Static Clinician-Based Measures

An individual with CAI will lift the foot 5 or more times during the foot-lift test. Our results support the previous finding[27] that healthy participants with no history of ankle sprain lifted the foot fewer times than those with a history of ankle sprain. Furthermore, our results support a recent meta-analysis[4] that showed the foot-lift test had a larger standard difference of the mean than all other measures. One reason the foot-lift test is potentially one of the most useful indicators of CAI is the specific focus on the foot. Instability at the ankle may cause individuals to use a hip strategy over an ankle strategy to maintain single-legged balance, and the foot lifts may be a response to the hip strategy[27]; that is, the foot lifts correct for the excessive movement at the hip. Individuals with stable ankles may

**Table 1. Dependent Measures**

| Dependent Measure | Dependent Measure Category | Group (Mean ± SD) Chronic Ankle Instability (n = 17) | Control (n = 17) | Effect Size |
|---|---|---|---|---|
| Balance Error Scoring System Total, errors | Static | 13.59 ± 4.00 | 11.06 ± 3.01 | 0.71 |
| Single-limb stance on firm surface | Static | 2.53 ± 2.37 | 1.29 ± 1.05 | 0.68 |
| Single-limb stance on foam surface | Static | 6 ± 1 | 5.59 ± 1.33 | 0.35 |
| Double-limb stance on firm surface | Static | 0 | 0 | 0 |
| Double-limb stance on foam surface | Static | 0.06 ± 0.24 | 0.11 ± 0.33 | 0.17 |
| Tandem stance on firm surface | Static | 1.29 ± 1.53) | 1 ± 1.17 | 0.21 |
| Tandem stance on foam surface | Static | 3.71 ± 1.65 | 3.06 ± 1.48 | 0.41 |
| Time-in-balance test, s | Static | 28.99 ± 17.30 | 46.01 ± 19.64 | 0.92 |
| Foot-lift test, lifts | Static | 5.57 ± 2.38 | 3.20 ± 2.68 | 0.94 |
| Center of pressure | | | | |
| Resultant velocity, cm/s | Force plate | 1.81 ± 0.38 | 1.61 ± 0.40 | 0.51 |
| Anterior-posterior velocity mean, cm/s | Force plate | 1.83 ± 0.43 | 1.65 ± 0.52 | 0.38 |
| Medial-lateral velocity mean, cm/s | Force plate | 1.91 ± 0.42 | 1.82 ± 0.40 | 0.22 |
| Anterior-posterior excursion mean, cm | Force plate | 0.38 ± 0.05 | 0.38 ± 0.10 | 0 |
| Medial-lateral excursion mean, cm | Force plate | 0.33 ± 0.05 | 0.32 ± 0.06 | 0.18 |
| Anterior-posterior standard deviation, cm | Force plate | 0.48 ± 0.07 | 0.47 ± 0.11 | 0.11 |
| Medial-lateral standard deviation, cm | Force plate | 0.39 ± 0.06 | 0.39 ± 0.07 | 0 |
| Rectangular area, $cm^2$ | Force plate | 22.57 ± 4.42 | 22.56 ± 9.14 | 0.001 |
| Area 95% confidence ellipse, $cm^2$ | Force plate | 3.50 ± 0.68 | 3.50 ± 1.41 | 0 |
| Time to boundary, s | | | | |
| Anterior-posterior mean of minimum | Force plate | 6.14 ± 1.12 | 7.02 ± 1.34 | 0.71 |
| Medial-lateral mean of minimum | Force plate | 2.17 ± 0.39 | 2.29 ± 0.41 | 0.30 |
| Anterior-posterior absolute minima | Force plate | 1.05 ± 0.27 | 1.10 ± 0.49 | 0.13 |
| Medial-lateral absolute minima | Force plate | 0.48 ± 0.09 | 0.49 ± 0.09 | 0.11 |
| Anterior-posterior standard deviation of minimum | Force plate | 3.65 ± 0.40 | 3.99 ± 0.38 | 0.87 |
| Medial-lateral standard deviation of minimum | Force plate | 1.55 ± 0.22 | 1.68 ± 0.13 | 0.72 |
| Star Excursion Balance Test, cm/leg length | | | | |
| Anteromedial reach direction | Functional | 0.85 ± 0.08 | 0.90 ± 0.09 | 0.59 |
| Medial reach direction | Functional | 0.87 ± 0.08 | 0.92 ± 0.09 | 0.59 |
| Posteromedial reach direction | Functional | 0.88 ± 0.09 | 0.95 ± 0.12 | 0.66 |
| Side-hop test, s | Functional | 16.76 ± 8.30 | 12.20 ± 5.39 | 0.65 |
| Figure-of-8 hop test, s | Functional | 16.88 ± 4.52 | 14.92 ± 3.48 | 0.49 |

use an ankle strategy to control their balance, which allows them to maintain the foot in contact with the ground. Therefore, clinicians should expect those with CAI to lift the foot more often than those who have never sprained their ankle. The BESS single-limb stance on a firm surface is very similar to the foot-lift test. Both tests require the same positioning and the same type of testing surface. However, the BESS single-limb stance on a firm surface is different in that it focuses on the eyes, hips, and hands and not the small movements of only the foot. Also, data are collected for only 20 seconds, whereas foot-lift test data are collected for 30 seconds. Because of the similarities in the tests, we were not surprised that both measures were significant. Clinicians can use the cutoff score of $\geq$3 with the BESS single-limb stance on a firm surface to identify individuals with CAI who can benefit from balance rehabilitation.

The time-in-balance test had an odds ratio greater than 1 and a significant AUC value. This finding indicates that the time-in-balance measure can be included in a balance assessment with a cutoff score of $\leq$25.89 seconds. Conclusions similar to those from the foot-lift test can be drawn for the time-in-balance test: using a hip strategy may create a tipping moment that is too large when the center-of-mass shifts excessively to the limits of stability. Chronic ankle instability may prevent individuals from developing a stabilizing moment and can lead to foot lifts or touching the floor with their nonweight-bearing leg, resulting in less time balancing on a single leg. Our results agree with those previously reported[26] in which participants without a history of ankle injury were able to stand on a single leg with their eyes closed longer than those with CAI. Additionally, our results support those of a recent balance meta-analysis in which the time-in-balance test outperformed all static and functional balance measures except for the foot-lift test.[4]

Contrary to our results, previous investigators[21] found that total error score on the BESS identified balance deficits associated with CAI. Our AUC value for the total BESS score was not significant (0.126). However, we identified significant cutoff scores for 2 BESS variables (BESS total $\geq$14, single-limb stance on a firm surface $\geq$3) with odds ratios greater than 1 (6.67 and 5.25, respectively). We believe the ease of completing the double-limb stance on the firm and foam surfaces may have contributed to the lack of significant findings with these stances. Participants in both groups had little difficulty completing these 2 stances, which led to almost no variability in the dataset. Therefore, the entire BESS test need not be performed by those with

**Table 2. Diagnostic Values**

| Dependent Measure | Category | Area Under the Curve | Asymptotic Significance | Cutoff Score | Sensitivity | 1–Specificity | Likelihood Ratio Positive | Likelihood Ratio Negative | Odds Ratio | 95% Confidence Interval | Fisher Exact Test *P* Value | Youden Index |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Balance Error Scoring System | | | | | | | | | | | | |
| Total | Static | 0.62 | 0.126 | 14 | 0.47 | 0.12 | 4.00 | 0.60 | 6.67 | 1.15, 38.60 | .03[a] | 35.29 |
| Single-limb stance on firm surface | Static | 0.66 | 0.12 | 3 | 0.53 | 0.18 | 3.00 | 0.57 | 5.25 | 1.09, 25.21 | .04[a] | 47.06 |
| Tandem stance on firm surface | Static | 0.55 | 0.62 | 1 | 0.65 | 0.53 | 1.22 | 0.75 | 1.63 | 0.41, 6.46 | .36 | 11.80 |
| Tandem stance on foam surface | Static | 0.60 | 0.32 | 5 | 0.29 | 0.06 | 4.98 | 0.75 | 6.67 | 0.69, 64.77 | .09 | 23.50 |
| Time-in-balance test | Static | 0.73 | 0.010[a] | 25.89 | 0.82 | 0.35 | 2.33 | 0.27 | 8.56 | 1.74, 42.17 | .006[a] | 47.06 |
| Foot-lift test | Static | 0.76 | 0.005[a] | 5 | 0.76 | 0.53 | 1.44 | 0.50 | 11.20 | 2.20, 56.93 | .002[a] | 52.94 |
| Center of pressure | | | | | | | | | | | | |
| Area 95% confidence ellipse | Force plate | 0.56 | 0.57 | 3.05 | 0.82 | 0.53 | 1.56 | 0.37 | 4.15 | 0.86, 19.92 | .07 | 29.50 |
| Rectangular area | Force plate | 0.56 | 0.28 | 15.39 | 0.94 | 0.06 | 1.23 | 0.27 | 4.92 | 0.49, 49.61 | .17 | 17.28 |
| Resultant velocity | Force plate | 0.72 | 0.015[a] | 1.56 | 0.76 | 0.35 | 2.17 | 0.36 | 5.96 | 1.33, 26.66 | .02[a] | 41.18 |
| Anterior-posterior velocity mean | Force plate | 0.65 | 0.14 | 1.41 | 0.88 | 0.59 | 1.50 | 0.29 | 5.25 | 0.90, 30.62 | .06 | 35.30 |
| Medial-lateral velocity mean | Force plate | 0.55 | 0.62 | 1.86 | 0.53 | 0.35 | 1.50 | 0.73 | 2.06 | 0.52, 8.17 | .25 | 17.60 |
| Anterior-posterior excursion mean | Force plate | 0.54 | 0.67 | 0.34 | 0.88 | 0.59 | 1.50 | 0.29 | 3.27 | 0.67, 15.82 | .13 | 29.40 |
| Medial-lateral excursion mean | Force plate | 0.56 | 0.52 | 0.30 | 0.82 | 0.59 | 1.40 | 0.13 | 2.38 | 0.52, 9.99 | .23 | 23.60 |
| Anterior-posterior standard deviation | Force plate | 0.53 | 0.77 | 0.42 | 0.88 | 0.65 | 1.36 | 0.33 | 4.09 | 0.69, 24.24 | .11 | 29.40 |
| Medial-lateral standard deviation | Force plate | 0.54 | 0.69 | 0.33 | 0.94 | 0.77 | 1.23 | 0.23 | 3.43 | 0.32, 36.83 | .30 | 17.60 |
| Time to boundary | | | | | | | | | | | | |
| Anterior-posterior mean of minimum | Force plate | 0.67 | 0.10 | 7.10 | 0.83 | 0.53 | 1.56 | 0.38 | 4.15 | 0.86, 19.92 | .07 | 29.50 |
| Medial-lateral mean of minimum | Force plate | 0.58 | 0.42 | 2.48 | 0.82 | 0.71 | 1.17 | 0.60 | 1.94 | 0.38, 9.88 | .34 | 11.80 |
| Anterior-posterior absolute minimum | Force plate | 0.47 | 0.77 | 1.53 | 0.94 | 0.82 | 1.14 | 0.34 | 3.42 | 0.32, 36.83 | .30 | 11.70 |
| Medial-lateral absolute minimum | Force plate | 0.52 | 0.88 | 0.57 | 0.88 | 0.77 | 1.15 | 0.50 | 2.30 | 0.36, 14.72 | .33 | 11.70 |
| Anterior-posterior standard deviation | Force plate | 0.69 | 0.05[a] | 3.78 | 0.71 | 0.29 | 2.40 | 0.42 | 5.77 | 1.32, 25.19 | .02[a] | 41.20 |
| Medial-lateral standard deviation | Force plate | 0.71 | 0.03[a] | 1.56 | 0.65 | 0.18 | 3.68 | 0.43 | 8.56 | 1.74, 42.17 | .007[a] | 47.10 |
| Star Excursion Balance Test | | | | | | | | | | | | |
| Anteromedial reach direction | Functional | 0.65 | 0.07 | 0.86 | 0.76 | 0.47 | 1.63 | 0.44 | 3.66 | 0.84, 15.91 | .08 | 29.41 |
| Medial reach direction | Functional | 0.65 | 0.07 | 0.91 | 0.59 | 0.29 | 2.00 | 0.58 | 3.43 | 0.83, 14.21 | .08 | 29.41 |
| Posteromedial reach direction | Functional | 0.71 | 0.02[a] | 0.91 | 0.65 | 0.29 | 2.20 | 0.5 | 4.4 | 1.04, 18.60 | .04[a] | 35.29 |
| Side-hop test | Functional | 0.70 | 0.02[a] | 12.88 | 0.65 | 0.18 | 3.67 | 0.43 | 8.56 | 1.74, 42.17 | .006[a] | 47.06 |
| Figure-of-8 hop test | Functional | 0.66 | 0.06 | 17.36 | 0.47 | 0.12 | 4.00 | 0.60 | 6.67 | 1.15, 38.60 | .03[a] | 35.29 |

[a] Statistically significant at $\leq .05$.

ankle instability and could be simplified. Further research is warranted to confirm this contention.

## Force-Plate Measures

We included 3 types of force-plate measures: COPV, COPA, and TTB. One COPV measure had a significant AUC value: COP resultant velocity = 0.72. If clinicians elect to use COP resultant velocity for a postural-stability assessment, a cutoff score of $\geq$1.56 cm/s distinguishes between individuals with and without CAI. In addition, COP resultant velocity had an odds ratio of 5.96. Our COP resultant velocity results support those of previous authors who found higher COP resultant velocity values in an injured group than in a control group[30] and noted that COP resultant velocity discriminated between those with a history of CAI and those with stable ankles.[12] We believe that a clinical strength of our COP resultant velocity findings is that most clinical balance force-plate software computes this measure.

Clinical balance software, however, has not provided a simple computation for TTB measures. We expected several TTB measures to identify postural-stability insufficiencies based on data reported in literature.[17,19] Significant AUC values and cutoff scores were found for 2 TTB measures (A-P and M-L TTB standard deviations). Odds ratios greater than 1 were also seen for both TTB variables (A-P TTB standard deviation = 5.77, M-L TTB standard deviation = 8.56). The TTB measures estimate how quickly the instantaneous center of pressure would reach the boundary of the foot if it continued to move at its instantaneous velocity.[13] The calculation of this measure is inherently linked to COPV measures because it is included in the equation to calculate TTB. According to Hertel and Olmsted-Kramer,[13] TTB may be a better balance measure for assessing deficits because it includes only data nearest the boundary of the foot (ie, position of instability), whereas COP velocity includes all data (both stable and unstable). Conversely, Knapp et al[11] and Wikstrom et al[10] found that neither the A-P nor M-L TTB standard deviation achieved statistical significance to determine CAI status. Our effect sizes for differences between group means (A-P TTB standard deviation = 0.87, M-L TTB standard deviation = 0.72) were much larger than the effect sizes (A-P TTB standard deviation = 0.13, M-L TTB standard deviation = 0.04) reported by Knapp et al.[11] We speculate these differences in reported effect sizes may be due to different testing procedures. One main variation was that Knapp et al[11] completed testing using only a 10-second, single-legged stance, whereas we collected 20 seconds of data. A shorter timeframe might have resulted in less variability among the participants with CAI. Another difference in testing procedures was that our participants were not wearing shoes during testing, whereas those in the Wikstrom et al[10] study did wear shoes. This could be a significant contributing factor in their lack of asymptotic significance given the sensitivity of this measure.

Neither COPA measure had a significant AUC value, cutoff score, or odds ratio. Previous investigators[4,36] reported that COPA-95 did not identify balance deficits associated with CAI; therefore, we were not surprised by our results. Other authors[37,38] have shown improvement in COPA-95 measurements after a balance-training intervention, which was why we included this measure in our data collection. We could not calculate an effect size for our COPA-95 data because the group means were not different, although others have found differences between group means with an effect size of 0.35 in Knapp et al[11] and 0.70 in Ross et al.[39] We believe that these differences in effect sizes are consistent with the literature on COPA-95 because a larger variance is associated with this measure, making it difficult to detect ankle group differences.[4] We did not find a significant cutoff score for COPA-r. Ross et al[12] noted differences between group means for COPA-r with an effect size of 0.60, whereas we found an effect size of 0.001. The large difference in effect sizes again can be due to differences in testing methods: Ross et al[12] tested their participants with eyes open and wearing shoes. Both COPA-95 and COPA-r assess excursion but do not evaluate a time component such as COPV or TTB. Thus, the important factor may not be the actual area that CAI participants travelled but the time required to make a postural correction compared with those who have stable ankles.

## Functional Measures

Two functional measures had significant AUC values, but 3 had significant cutoff scores and odds ratios greater than 1. Clinicians can use the cutoff scores associated with the SEBT-PM, side-hop test, and figure-of-8 hop test to identify those who can benefit from rehabilitation. Our SEBT results support those of previous researchers[8] who found the PM reach direction demonstrated balance differences between group means of those with and without ankle instability. Therefore, we were not surprised that the PM reach direction was a sensitive measure for identifying postural-stability deficiencies. The PM reach direction has been reported to be the most representative of the overall performance of the SEBT in limbs with or without ankle instability.[8] Furthermore, participants with CAI reached during the SEBT with less hip flexion than did participants with stable ankles.[39] Greater hip flexion has permitted individuals to reach further in the PM direction.[40] Thus, we speculate that our CAI participants might have reached with less hip flexion than those with stable ankles, resulting in the PM reach direction being most sensitive. Unlike the PM direction, the AM and M reach directions did not have significant AUC values or cutoff scores. Furthermore, the degree of knee flexion influences reach distance for the AM and M reach directions.[39,40] Thus, our CAI participants might have used a similar knee kinematic pattern as stable participants, which could explain why the AM and M reach directions failed to discriminate as well between groups.

The side-hop test had a significant AUC value and an odds ratio greater than 1. The cutoff score of greater than 12.88 seconds discriminates between people with and without postural instability. Thus, individuals taking longer than 12.88 seconds to complete 10 repetitions can be categorized as having postural instability and could benefit from rehabilitation. Our side-hop test results support the previous positive relationship found between feelings of ankle instability and performance deficits on this test[9] but are contrary to other findings[41,42] of no differences among those with CAI, copers, and healthy controls. Performance on the side-hop test has been suggested to be related to feelings of instability because static and dynamic stabilizers of the ankle are forced to restrain excessive joint motion during the medial-to-lateral hopping.[9] In addition, hopping and landing require plantar flexion of the foot, which is an unstable joint position that tends to tax the anterior talofibular ligament and foot evertor muscles. Researchers[9] speculated that the lateral movement during this test would excessively stress the lateral ankle stabilizers because the foot moves into hypersupination, which is the injury mechanism for lateral ankle sprains. Thus, we believe that our findings support this contention[9] and could explain why this test identified participants with postural instability.

Our figure-of-8 hop test results did not have a significant AUC value but had an odds ratio greater than 1 and a significant Fisher exact test. These values indicate that the figure-of-8 hop test was able to identify participants who could benefit from rehabilitation using the cutoff score of $\geq$17.36 seconds. Similar to our AUC results, Wikstrom et al[42] were unable to identify a difference between CAI participants and healthy controls. A possible explanation for this lack of significance is the variation in hop distances used by participants. Some could have taken longer hops (more like a leap), whereas others took much shorter hops (more "bunny like"). Keeping hopping techniques consistent among participants and studies may be necessary to reach consensus. Future researchers should continue to examine this test and its associated cutoff scores to identify those with postural insufficiencies.

Static single-legged postural-stability tests may not be sensitive enough to detect sensorimotor deficits associated with balance; functional tests may be more sensitive and specific for identifying those with CAI.[17,18] Contrary evidence, however, indicates that static testing is as effective as or more effective than functional testing at identifying participants with CAI.[4,12] One group[12] found that the M-L ground reaction force standard deviation for static single-legged balance was more accurate than functional measures of balance in discriminating between CAI and stable ankles. In a recent meta-analysis,[4] investigators reported that no difference was evident between static and functional measures of balance for discriminating between CAI and stable ankles, yet the significance value was low ($P$ = .063). The authors suggested that, because their statistical analysis was conservative, a difference between static and functional balance tests might indeed exist, with static measures actually outperforming functional measures. Again, the results were not statistically significant and therefore warrant further research, yet our findings further support the suggestion that results on static tests outperform those on functional postural-stability measures. The measures with asymptotic significance, largest odds ratios, and significant Fisher exact tests include 2 static clinician-based measures (time-in-balance test and foot-lift test) and 1 static force-plate measure (M-L TTB standard deviation).

### Limitations

As mentioned previously, a possible limitation of our study was that 2 trials of the BESS were easy for both healthy participants and those with CAI: the double-limb stance on firm and foam surfaces. Another limitation previously mentioned was the differences in hop length on the figure-of-8 hop test. Some participants took large leaps, whereas some took very small hops. More specific instructions or standardization of the protocol could correct this limitation in future studies. Finally, participants in our study with no history of ankle injury could have had poor balance, potentially inhibiting our ability to detect group differences or a cutoff score that identified CAI.

## CONCLUSIONS

The purpose of our study was to determine which postural-stability tests best identify postural instability associated with CAI and to determine the best cutoff score of these measures. Clinicians can use the following postural-stability tests and their associated cutoff scores to identify postural instabilities: BESS single-limb stance on a firm surface ($\geq$3 errors), BESS total ($\geq$14 errors), time-in-balance test ($\leq$25.89 seconds), foot-lift test ($\geq$5 lifts), COP resultant velocity ($\geq$1.56 cm/s), A-P TTB standard deviation ($\leq$3.78 seconds), M-L TTB standard deviation ($\leq$1.56 seconds), SEBT-PM ($\leq$0.91), side-hop test ($\geq$12.88 seconds), and figure-of-8 hop test ($\geq$17.36 seconds). Thus, clinicians can use multiple tests with specific cutoff scores to identify individuals with CAI who may benefit from rehabilitation that reestablishes postural stability. Furthermore, clinicians can benefit from knowing minimum test performance goals for CAI patients that correspond to the cutoff points separating those with CAI and those with healthy ankles. Future investigators should determine which combination of postural-stability tests could be used or which tests could be streamlined to best identify those with CAI and create a prediction guide.

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