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Determining Sensitive and Accurate Measures for Detecting Balance Deficits Associated with Functional Ankle Instability

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DETERMINING SENSITIVE AND ACCURATE MEASURES FOR DETECTING BALANCE DEFICITS ASSOCIATED WITH FUNCATIONAL ANKLE INSTABILITY

A Dissertation submitted in partial fulfillment of the requirements for the degree of Doctorate of Philosophy at Virginia Commonwealth University.

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Abstract

DETERMINING SENSITIVE AND ACCURATE MEASURES FOR DETECTING BALANCE DEFICITS ASSOCIATED WITH FUNCTIONAL ANKLE INSTABILITY

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The focus of this study was to determine the balance measures most sensitive and accurate in detecting balance deficits associated with functional ankle instability (FAI). Subjects consisted of those with a history of ankle sprains and resultant symptoms of giving way (N=17; Height=167.72±9.11 cm; Mass=67.81±12.29 kg; Age=23.35±3.62 yrs) and subjects without a history of ankle injuries (N=17; Height=168.16±8.32 cm; Mass=66.22±12.35 kg; Age=23.35±3.26 yrs). Data collection consisted of each subject performing static and dynamic balance tests. Static stability was assessed with force plate measures, the Balance Error Scoring System, foot lift test, and time-in-balance test. Dynamic stability was assessed with the Star Excursion Balance Test, side hop test, and figure-of-eight hop test. Significant receiver operating characteristic curves and therefore cutoff scores were found for the foot lift test (P=0.011; cutoff=4.84 foot lifts), time-in-balance test (P=0.020; cutoff=41.23 s), center-of-pressure velocity (P=0.026; cutoff=1.56 cm/s), anterior-posterior time-to-boundary standard deviation of the minima (P=0.054; cutoff=3.72 s), posteromedial reach direction of the Star Excursion Balance Test (P=0.039; cutoff=0.91 normalized to leg length) and side hop test (P=0.044; cutoff=12.88 s). The associated positive (≥2) and negative (≤0.05) likelihood ratios with each cutoff score indicated that changes in positive and negative posttest probabilities from the pretest probability of 50% were small, yet significant. Essentially, the significant change between pretest and posttest probabilities indicates that clinically relevant information was gained by conducting these balance measure because they quantified a high proportion of individuals with a positive test who have FAI and a low proportion of individuals with a negative test who have FAI. No significance was found for the Balance Error Scoring System (P=0.249), center-of-pressure area (P=0.547), anteromedial (P=0.134) and medial (P=0.125) reach directions of the Star Excursion Balance Test, and the figure-of-eight hop test (P=0.117). In conclusion, we found the foot lift test, time-in-balance test, center-of-pressure velocity, anterior-posterior time-to-boundary standard deviation of the minima, posteromedial reach direction of the Star Excursion Balance Test, and the side hop test to be sensitive and accurate balance measures for detecting balance deficits associated with

FAI. We suggest utilizing these measures and their cutoff scores to evaluate balance deficits associated with FAI.

STATEMENT OF PROBLEM

Ankle sprains are one of the most common injuries experienced by physically active individuals. Eighteen to 42% of individuals with ankle sprains report having recurrent sprains.[1-4] Recurrent sprains and other residual symptoms, such as pain or swelling, are reported by 20-50% of those sustaining an ankle sprain.[5-7] The residual symptoms associated with repeated ankle sprains have wide ranging clinical ramifications. For example, joint disease has been linked to recurrent sprains. Specifically, osteoarthritis and articular degeneration have been related to recurrent sprains.[8, 9] In addition to the risks for joint disease, there are also occupational health considerations for recurrent ankle instability. Recurrent ankle instability prevents 6% of patients from returning to their occupation and 13-15% of patients remain occupationally handicapped from at least 9 months to 6.5 years following their injury.[10, 11]

Static single-leg balance impairments have been associated with FAI[12-19] and have predicted ankle sprain injury in physically active individuals.[20-23] More specifically, a significant association between a positive single-leg balance test and ankle sprains has been demonstrated in men's American football, men's and women's soccer, and women's volleyball at both high school and collegiate levels.[23] A positive single-leg balance test signifies that a person has poor balance. The relative risk for an ankle sprain with a positive single-leg balance test was 2.54 with a 95% confidence interval of 1.02 to 6.03.[23]

Based on these reports, it is clear that a relationship exists between balance impairments and FAI. Therefore, if a common sensitive and accurate method of balance testing were employed as a screening tool in the clinical setting it would allow clinicians to detect balance deficits in the hopes of preventing future injury, which may help minimize the risk of developing joint disease or occupational handicaps later in life. Furthermore, with increasing governmental and societal emphasis on exercise and physical activity, it is reasonable to expect that the numbers will remain constant or increase as more Americans become physically active; therefore, increasing the number of people at risk for developing FAI if not properly detected.

A variety of balance tests have been developed to differentiate subjects with stable and unstable ankles because research has shown an association between balance deficits and ankle sprain injury exists..[20, 24] Balance testing has been used in both clinical and research settings in order to assess postural instabilities associated with FAI. Tests include the Balance Error Scoring System, time-in-balance test, foot lift test, Star Excursion Balance Test, figure-of-eight hop test, side hop test, as well as force plate measures such as center-of-pressure velocity, center-of-pressure area, and time-to-boundary. However, no one study has compared these specific tests to discover which test is the most sensitive and accurate measure for detecting balance deficits associated with FAI.

Static measures of balance can be further subdivided into two categories: clinical measures and force plate measures. The Balance Error Scoring System provides a quantitative static measure of postural sway.[25] The Balance Error Scoring System attempts to challenge the sensory systems by combining a variety of stances on a firm surface as well as a more unstable surface, foam.[14] It has been shown that postural control deficits can be identified in subjects with FAI using the Balance Error Scoring System.[14] The Balance Error Scoring System identifies balance deficits associated with FAI, and can easily be employed as a clinical tool; therefore, the sensitivity and accuracy of the measure is warranted in order to determine if the use of this test in a clinical setting is valuable.

Another static balance test similar to the Balance Error Scoring System has been developed. The foot lift test, however, only uses the single-limb stance on a firm surface; making the test simpler and quicker because it does not require the use of six stances or the use of a foam pad. Although the foot lift test was originally developed for use with dancers, it has been found to detect differences between control subjects and participants with both unilateral and bilateral FAI.[16] Results have also shown that controls lifted their foot fewer times than those with FAI.[16] The foot lift test may be administered easily in the clinical setting; therefore, the sensitivity and accuracy of the measure is warranted because it could serve clinicians as a worthwhile screening tool.

A third static balance test shown to be very useful is the time-in-balance test. This test also uses only the single-limb stance on a firm surface. The difference with this test is it evaluates time not “errors”. Results have shown that a decreased standing time in the single-leg stance correlates well with conditions of functional instability following injury to the lateral ligaments of the ankle.[13] The standing time on the injured leg has shown to be significantly shorter with both eyes open and closed than the standing times both on the uninjured leg and in a control group.[13] This test also can be easily employed as a clinical tool; therefore, the sensitivity and accuracy of the measure is warranted to understand whether or not this test can be useful clinically to assess balance deficits associated with FAI.

Researchers have attempted to develop the most precise measurements of balance using force plates. Unfortunately, force plates can be expensive and therefore not readily available for the clinical setting. Laboratory research, however, has shown that basketball players with a high variation of postural sway were more likely to have an injured ankle during the season.[22] The authors suggested that this may be true because postural sway represents the ability to maintain standing balance, and a large variation of postural sway may indicate inconsistent or poor quality of performance, leading to ankle injury.[22] Potentially, a less sensitive and accurate force plate measure could fail to detect balance deficits associated with FAI; therefore leaving patients at risk for future injury.

Several center-of-pressure measurements exist in the literature. However, three measures in particular have shown strong results for detecting balance impairments associated FAI. Center-of-pressure velocity measures have been commonly used to evaluate balance deficits associated with ankle instability. An injured group has been found to have significantly higher center-of-pressure velocity values than a control group.[26] Furthermore, higher center-of-pressure velocity values have also shown to correspond with increased ankle sprain injury rates.[20] Another center-of-pressure measurement commonly used is the center-of-pressure area, which is also known as Area 95 or 95% Confidence Ellipse. It was also found that those individuals with abnormal area values ran a significantly higher risk of sustaining an ankle injury during the following season compared to players with normal area values.[21] Finally, a novel center-of-pressure measurement known as time-to-boundary has shown promise in detecting deficits in postural control related to ankle instability. A lower time-to-boundary measure indicates greater postural instability as the center-of-pressure is closer in time to reaching the boundary of the base of support.[15] In previous studies, time-to-boundary deficits have been detected in males and females with ankle instability.[15, 27] Results have shown greater effect sizes with the time-to-boundary measurement compared to center-of-pressure measurements.[15, 27] Due to the fact that the time-to-boundary measure is a relatively new calculation, yet has shown promising results suggest that the sensitivity and accuracy of this measure is warranted in order to determine if this test is better than center-of-pressure velocity or area measures.

Some authors have suggested that static single-leg balance tests may not be sensitive enough to detect motor-control deficits related to balance performance, and that dynamic tests may provide better means of identifying functional deficits related to balance performance in subjects with FAI.[28-30] These tests are helpful because they combine multiple components, such as joint stability, muscular strength, and neuromuscular coordination, which could all be affected after an ankle sprain.[31] Clinically, dynamic balance tests are often used during the latter stages of rehabilitation and as criteria to determine return-to-play status.[31]

A dynamic measure of balance that is easily employed clinically is the Star Excursion Balance Test. The Star Excursion Balance Test has shown to detect functional performance deficits associated with lower extremity pathology in otherwise healthy individuals[29] and predict lower extremity injury.[24] Subjects with FAI have been shown to reach significantly less on anteromedial, medial, and posteromedial directions when balancing on involved limbs compared to their uninvolved limbs and side-match controls.[29] The posteromedial reach direction of the Star Excursion Balance Test has shown to be the most predictive of performance.[29] The Star Excursion Balance Test has detected differences between groups and can easily be administered in a clinical setting; therefore, the sensitivity and accuracy of this measure is warranted since this test is already used clinically

The side hop and figure-of-eight hop tests were originally developed for use in anterior cruciate ligament research but have both showed significant positive relationships with a questionnaire on self-reported feelings of ankle instability and detected deficits in performance.[31] These dynamic balance tests that place lateral or rotational stress on the ankle reveal performance deficits in participants with FAI. In addition, both of these tests have the advantage of being quickly and easily administered in the clinical setting. Due to the ease of administration in a clinical setting, significant relationships with an ankle instability questionnaire and ability to detect performance deficits, the sensitivity and accuracy of the measures are warranted in order to determine if one hop test is better than the other and/or the Star Excursion Balance Test, which occupies more of a clinician's time employing.

In summary, no one study has compared these specific static and dynamic measures to discover which test is the most sensitive and accurate measure for detecting balance deficits associated with FAI. A clear answer as to whether a static or dynamic measure of balance would better identify those with FAI cannot be found in the literature. This may be due to the fact that the most sensitive and accurate measure for detecting balance deficits associated with FAI has not been identified for static or dynamic tests individually. Furthermore, there is no standard found in the literature as to whether a clinical or force plate static balance measure is more appropriate for identifying those with FAI. It would be important to determine the most sensitive and accurate measure for detecting balance deficits associated with FAI, whether it be static or dynamic, in hopes of better serving athletes by identifying those who may need ankle rehabilitation.

Research Questions

R_1: What is the most sensitive and accurate static clinical balance measure for detecting balance deficits associated with FAI?

R_2: What is the most sensitive and accurate static force plate measure for detecting balance deficits associated with FAI?

R_3: What is the most sensitive and accurate dynamic balance measure for detecting balance deficits associated with FAI?

R_4: What is the most sensitive and accurate static or dynamic balance measure for detecting balance deficits associated with FAI?

Research Hypotheses

H_1: The foot lift test will be the most sensitive and accurate static clinical balance measure for detecting balance deficits associated with FAI compared to the Balance Error Scoring System and time-in-balance test.

H_2: The time-to-boundary standard deviation of minima in the anterior-posterior direction will be the most sensitive and accurate static force plate balance measure for detecting balance deficits associated with FAI compared to center-of-pressure velocity and center-of-pressure area.

H_3: The Star Excursion Balance Test, specifically in the posteromedial direction will be the most sensitive and accurate dynamic balance measure for detecting balance deficits associated with FAI compared to the anteromedial and medial reach directions of the Star Excursion Balance Test, figure-of-eight hop test, and side hop test.

H_4: The Time-to-Boundary standard deviation of minima in the anterior-posterior direction will be the most sensitive and accurate static or dynamic balance measure for detecting balance deficits associated with FAI.

Operational Definitions

Static Stability: maintaining a stable center of gravity within a fixed base of support.

Dynamic Stability: maintaining a moving center of gravity within a fixed base of support.

Center-of-pressure Velocity: measurement of the total distance traveled divided by the length of time of the trial.

Center-of-pressure Area: determined by calculating the 95th percentile ellipse, which by definition encompassed 95% of the data points.

Time-to-Boundary: estimated the time it would take for the center-of-pressure to reach the boundary of the base of support if the center-of-pressure was to continue on its trajectory at its instantaneous velocity.

Dominance: the limb chosen to kick a ball

Sensitivity: the probability that participants with FAI were correctly identified as having FAI.

Specificity: the probability that participants with stable ankles were correctly identified as not having FAI.

Clinical Significance

The focus of this study was to determine the balance measure most sensitive and accurate in detecting balance deficits associated with functional ankle instability. Discovering the most sensitive and accurate measure has implications for improving balance testing related to ankle instability research and improving screening tools for ankle instability in the clinical setting. The employment of a common method of balance testing during research will allow future studies to be compared between populations as well as the removal of insensitive and inaccurate tests utilized in future research. Clinically, balance testing with a sensitive and accurate measure will allow therapists to detect balance deficits in the hopes of correcting these impairments to prevent future ankle injury.

REVIEW OF LITERATURE

Functional Ankle Instability

Ankle sprains are one of the most common injuries experienced by physically active individuals. Specifically, ankle sprains account for 10-54% of injuries in physically active populations.[32-43] Eighteen to 42% of individuals with ankle sprains report having recurrent sprains.[1-4] Functional ankle instability (FAI) is a residual symptom of ankle sprains. FAI was first described as a disability in which patients refer when they mention that their foot tends to "give way".[7] FAI has been further characterized as joint motion that does not normally exceed a person's normal range of motion, but is beyond volitional control.[44, 45] Some researchers believe that FAI is a subjective complaint of instability in the absence of mechanical disruption.[46] These residual symptoms are reported by 20-50% of those sustaining an ankle sprain.[5-7] The clinical significance of ankle sprains is that joint disease as well as other associated injuries have been linked to recurrent sprains. Osteoarthritis and articular degeneration have been related to recurrent sprains.[8, 9] More specifically, a retrospective study of thirty-five chronically unstable ankle patients revealed that 57% had spurs and/or loose bodies.[47] The incidence of spurs in this chronically unstable patient population was 3.37 times higher than in a comparable adult population.[47] Furthermore, numerous associated injuries were discovered, in a study of sixty-one patients undergoing a primary lateral ankle ligament reconstruction for chronic instability.[48] The researchers found that 77% of patients also had peroneal tenosynovitis, 67% of patients also had anterolateral impingement lesions, 26% of patients also had an intra-articular loose body, 25% of patients also had a peroneus brevis tear, and 23% of patients had an osteochrondral lesion of the talus.[48] In addition to the risks for joint disease and numerous associated injuries, there are also occupational health considerations for recurrent ankle instability. Recurrent ankle instability prevents 6% of patients from returning to their occupation and 13-15% of patients remain occupationally handicapped from at least 9 months to 6.5 years following their injury.[10, 11]

A current problem in the literature concerning FAI is not only the various definitions utilized by researchers, but the use of the term chronic ankle instability (CAI). CAI has gained a lot of use in the ankle instability literature and has been defined in several ways. CAI has been defined as a subjectively reported phenomenon and has been described as a tendency to "give way" during normal activity. CAI has also been considered comparable with the giving way phenomenon that occurs in an unstable knee joint.[49] Another researcher describes CAI as altered mechanical joint stability due to repeated disruptions to ankle integrity with resultant perceived and observed deficits in neuromuscular control.[50] And yet another researcher describes CAI as simply as the occurrence of repetitive bouts of lateral ankle instability, resulting in numerous ankle sprains.[51] While there is not a standardized definition of CAI, many researchers, however, do agree that CAI is independent of the severity of the original injury and the treatment received.[3, 52-54] With the numerous definitions of CAI and the overlapping descriptions between CAI and FAI, the need becomes apparent for agreement on which term to utilize when and where, as well for understanding that CAI and FAI cannot necessarily be used interchangeably.

Anatomy

The anatomy of the ankle complex seems complicated yet bony and muscular anatomy is well understood. However, the ligamentous support of the ankle complex is incredibly complicated and therefore will have more detailed descriptions. The ankle complex is comprised of three articulations: the talocrural joint, the subtalar joint, and the distal tibiofibular joint. The talocrural joint is formed by the articulation of the dome of the talus, the medial malleolus, the tibial plafond, and the lateral malleolus.[51] This joint is commonly known as the "mortise" joint and is considered a hinge type joint that allows the motions of dorsiflexion and plantar flexion.[51] When the ankle complex is fully loaded, the articular surfaces are the primary stabilizers against excessive translation and talar rotation[55]; however talocrural joint stability is dependent upon ligamentous support.[51] The talocrural joint receives ligamentous support from a joint capsule and several ligaments, including the anterior talofibular ligament (ATFL), calcaneofibular ligament (CFL), posterior talofibular ligament (PTFL), and deltoid ligament. The ATFL, CFL, and PTFL support the lateral aspect of the ankle, while the deltoid ligament provides medial support to the talocrural joint.[51]

The ATFL lies on the dorsolateral aspect of the foot and courses from the lateral malleolus anteriorly and medially toward the talus.[56] The ligament infringes to some extent on the entrance to the tarsal tunnel in order for the ligament to stabilize the talus.[57] The ATFL is an average of 7.2 mm wide and 24.8 mm long.[56] The ATFL prevents anterior displacement of the talus from the mortise and excessive internal rotation of the talus on the tibia and excessive inversion.[55, 58-61] The ATFL becomes increasingly taut as the ankle moves from dorsiflexion into plantar flexion.[60] The ATFL is the most frequently injured of the lateral ligaments[62] which could in part be explained by its decreased tensile strength compared to the PTFL, CFL, anterior inferior tibiofibular ligament, and deltoid ligament.[63]

The CFL and the PTFL are the other two ligaments providing lateral support to the "mortise" joint. The CFL courses from the lateral malleolus posteriorly and inferiorly to the lateral aspect of the calcaneus.[64] This ligament is an average of 5.3mm wide and 35.8 mm long.[64] The CFL restricts excessive supination of both the talocrural and subtalar joint;[51] and furthermore, restricts excessive internal rotation of the rearfoot and inversion.[55] The CFL is most taut when the ankle is in a dorsiflexed position.[55, 59] Of the lateral talocrural ligaments, the CFL is the second most often injured.[65] The PTFL runs from the lateral malleolus posteriorly to the posterolateral aspect of the talus.[51] The anterior-posterior diameter of the PTFL averaged 10.1 mm and the proximal-distal diameter averaged 6.9 mm.[64] The width of the PTFL, however, varies greatly with foot position and therefore an average has not be estimated in the literature.[64] The PTFL provides restriction of both internal rotation and inversion of the loaded talocrural joint.[55] Of the lateral talocrural ligaments, the PTFL is the least commonly sprained.[65]

The second articulation of the ankle complex is the subtalar joint; which is formed by the articulation between the talus and the calcaneus. This joint allows the motions of pronation and supination and consists of a complicated structure with two separate joint spaces, posterior and anterior.[51] The posterior subtalar joint is formed between the inferior posterior facet of the talus and the superior posterior facet of the calcaneus.[66] The anterior subtalar joint is formed by the head of the talus, the anterior-superior facets, the sustentaculum tali of the calcaneus, and the concave proximal surface of the tarsal navicular.[51] The posterior and anterior subtalar joints have separate ligamentous joint capsules and are separated from each other by the canalis tarsi and sinus tarsi.[67] The ligamentous support of the subtalar joint is complicated and not well understood.[51] Discrepancies exist in the literature regarding the terminology for the individual ligaments and the functions they serve.[67, 68] Basically, the lateral ligaments may be separated into three groups: 1) deep ligaments, 2) peripheral ligaments, and 3) retinacula.[67, 69]

The deep ligaments consist of the cervical and interosseous ligament.[51] Together these ligaments stabilize the subtalar joint and divide it into the anterior and posterior joint capsules.[51] These ligaments, have been described as the “cruciate ligaments” of the subtalar joint due to their positioning; they cross obliquely through the canalis tarsi.[67] The cervical ligament is positioned anterior and lateral to the interosseous ligament and runs from the cervical tubercle of the calcaneus anteriorly and medially to the talar neck.[51] The cervical ligament lies within the sinus tarsi and has been shown to provide support to both of the capsules.[70] It resists supination and is the strongest of the subtalar ligaments.[61, 67, 68] The interosseous ligament lies just posterior to and courses more medially than the cervical ligament.[51] The interosseous ligament originates on the calcaneus just anterior to the posterior subtalar joint capsule and runs superiorly and medially to its insertion on the talar neck.[51] Because of its oblique fiber arrangement and diagonal orientation, portions of the ligament are taut throughout supination and pronation.[61, 67, 68] The interosseous ligament is also referred to as the ligament of the canalis tarsi.[61]

The peripheral ligaments of the subtalar joint include the CFL, lateral talocalcaneal (LTCL), and fibulotalocalcaneal (FTCL) ligaments.[51] The CFL is integral in preventing excessive internal rotation of the calcaneus in relation to the talus and excessive inversion.[58, 61, 62] The CFL does not normally connect the calcaneus and the talus, but various attachments of the anterior aspect of the CFL to the talus have been reported.[69] The LTCL courses anterior yet parallel to the CFL, but only crosses the posterior subtalar joint.[51] The LTCL is smaller and weaker than the CFL but aids in preventing excessive supination of the subtalar joint.[61, 64, 67] The LTCL averaged 26.5 mm in length and 4.4 mm in width.[64] The FTCL runs from the posterior surface of the lateral malleolus to the posterolateral surface of the talus and then courses to the posterolateral calcaneus.[51] It lies posterior to the CFL and aids in resisting excessive supination.[67] The FTCL is also known as ligament of Rouviere.[51]

Fibers of the inferior extensor retinacula (IER) have also been purported to provide support to the lateral aspect of the subtalar joint.[69] Three roots of the IER have been discovered within the sinus tarsi: lateral, intermediate, and medial.[51] However, only the lateral root of the IER has been shown to significantly affect subtalar joint stability.[67]

The bifurcate ligament also deserves mentioning as a static support to the lateral ankle complex.[51] The bifurcate ligament originates from the anterior surface of the calcaneus and divides anteriorly into the calcaneocuboid branch and the calcaneonavicular branch.[66] The calcaneocuboid branch attaches to the dorsal aspect of the cuboid. The calcaneonavicular branch attaches to the lateral aspect of the navicular. Due to the positioning of these two braches the bifurcate ligament it is also called the "Y-shaped" ligament.[66] This ligament resists supination of the midfoot and is commonly injured in combination with hypersupination mechanisms related to lateral ankle sprains.[62]

The third joint of the ankle complex is the distal articulation between the tibia and fibula. The distal tibiofibular joint is a syndesmosis type joint that allows minimal movement between the two bones.[71] However, gliding at this joint has been shown to be critical in order for normal mechanics to occur throughout the entire ankle complex.[71] The distal tibiofibular joint is stabilized by a thick interosseous membrane and the anterior and posterior inferior tibiofibular ligaments.[51] The anterior inferior tibiofibular ligament is often injured in conjunction with eversion injuries.[72] Weakness of the static stabilizing structures and/or mal-alignments of bony anatomy could predispose or be a result of a person developing FAI.

Muscles and their tendons must also be mentioned because of their role in dynamic protection of the ankle joint.[51] While the talocrural joint is often considered the "true ankle joint," it is important to recognize that the subtalar joint is critical to the mechanics of ankle instability. In general, the orientation of the tendons of the extrinsic muscles to the subtalar joint determines the movements the muscles are capable of producing.[66]

Basically, the muscles medial to the subtalar joint axis are supinators and the muscles lateral to the subtalar joint axis are pronators.

The tibialis anterior muscle is a weak supinator. The reason why this muscle provides a weak supination force is because it has a small lever arm due to the tendon's proximity to the subtalar axis. In contrast to the tibialis anterior, the tibialis posterior lever arm is rather long; therefore, it can exert a strong supination force upon the subtalar joint. The flexor hallucis longus and flexor digitorum longus muscles also supinate the subtalar joint; however, they differ in the amount of assistance provided to the supination force. The flexor hallucis longus is a weak supinator despite its long lever arm, because it passes the subtalar joint axis at an angle less than perpendicular; therefore resulting in decreased efficiency. While the flexor digitorum longus muscle is a stronger supinator due to its long lever arm which is aligned in a more efficient manner. The triceps surae group is also a supinator of the subtalar joint, because of the group's distal insertion which passes medial to the axis of motion. The extensor hallucis longus tendon, while positioned medially, it is nearly parallel to the subtalar joint axis; therefore, provides no assistance to pronation or supination of the subtalar joint.[66]

The pronators of the subtalar joint are the muscles lateral to the joint axis.[66] The muscles in the antero-lateral aspect are the extensor digitorum longus and peroneus tertius. The lever arm of the extensor digitorum longus is large and has the assistance of peroneus tertius muscle. The muscles of the postero-lateral aspect are the peroneus longus and brevis. The peroneus longus passes posterior to the lateral malleolus and inferior to the peroneal tubercle. The distance between the tendon and the subtalar axis is great;

therefore, the muscle is able to produce a strong pronation force. Likewise, the lever arm of the peroneus brevis muscle is long allowing it to produce a strong pronation force of the subtalar joint as well.[66]

In addition to the roles mentioned above, the peroneals, the tibialis anterior, the extensor digitorum longus, and the extensor digitorum brevis may also contribute to the dynamic stability of the lateral ankle complex by contracting eccentrically during forced supination of the rearfoot.[51] Specifically, these muscles may be able to slow the plantar flexion component of supination and thus prevent injury to the lateral ligaments.[73] In addition to ligamentous laxity or bony incongruence, muscular imbalances and/or weakness across the ankle complex could also predispose or be a result of a person developing FAI.

Mechanical Instability

Another debate in the FAI literature is the presence or absence of mechanical instability (MI). MI has been defined as ligament elongation or rupture.[3, 74, 75] Some researchers believe that FAI occurs in the absence of MI and others believe they occur in conjunction with one another, but is dependent on the definition of FAI employed by the researcher. Research has shown that MI occurs as a result of anatomic changes after an initial ankle sprain, which leads to insufficiencies that predispose the ankle to further episodes of instability.[51] These anatomic changes include: pathologic laxity, impaired arthrokinematics, synovial changes, and the development of degenerative joint disease. These changes may occur in combination with one another or in isolation. Ligamentous injury often results in pathologic laxity, thus causing joints to be mechanically unstable. Pathologic laxity can result in joint instability when the ankle is put in susceptible positions during activity.[51] Ligamentous laxity may be assessed clinically with physical examination, stress radiography,[76] or instrumented arthrometry.[77, 78] Pathologic laxity most often occurs in the talocrural and subtalar joints following a lateral ankle sprain.[76]

Another potential contributing factor of mechanical instability of the ankle is impaired arthrokinematics at any joint of the ankle complex.[51] One arthrokinematic restriction related to repetitive ankle sprains involves a mal-alignment at the inferior tibiofibular joint.[51] Mulligan[71] has suggested that individuals may have an anteriorly and inferiorly displaced distal fibula; therefore, leaving the ATFL in more slack while in its resting position. Thus, when the rearfoot begins to supinate, the talus may go through a greater range of motion before the ligament becomes taut. This may result in episodes of recurrent instability.[51]

Mechanical instability of the ankle complex may also occur due to insufficiencies caused by synovial hypertrophy and impingement.[51] Synovial inflammation has been shown in the talocrural and posterior subtalar joint capsules. Patients with synovial inflammation often report frequent episodes of pain and recurrent ankle instability. It has been found that anterolateral impingement syndrome of the talocrural joint is present in 67% and talocrural synovitis is present in 49% of patients requiring surgery for lateral instability.[48] Synovitis of the lateral aspect of the subtalar joint has also been found to often occur as a result of repetitive instances of ankle instability.[79]

In addition, mechanical instability has been related to degenerative changes in the ankle complex.[8] One study found more osteophytes and subchondral sclerosis in volleyball players with a history of repetitive ankle sprains compared with a group of healthy controls.[9] As mentioned earlier, individuals undergoing surgery for ankle ligament repair were 3.37 times more likely to have osteophytes, or loose bodies, than those with asymptomatic ankles.[47] However, it is unclear whether this is a developmental change in response to numerous instances of ankle instability or a structural predisposition to recurrent ankle sprains.[51] Due to the numerous possible causes of MI and the symptoms reported by those that repeatedly sprain their ankles are incredibly varied, the results of research can be confounded. Again this research demonstrates the need for a standardized definition of FAI and more specifically agreement on whether MI is a component of FAI or not.

Quantification

FAI is often quantified through the use of questionnaires. However, there is no gold standard for which researchers or clinicians can employ in their respective practices. The Foot and Ankle Ability Measure (FAAM) was developed as a region specific instrument to comprehensively asses physical performance among individuals with a range of leg, foot, and ankle musculoskeletal disorders.[80] The measure is divided into two separately scored subscales, the 21-item activities of daily living and the 8-item sports subscales. Items are scored using a Likert response format, with higher scores representing higher levels of ability. Decisions regarding changes in individuals' scores and status can be interpreted by using the minimally detectable change (MDC) that is calculated at the 95% confidence level and the minimal clinically important difference (MCID) values. The MCID values have been found to be 8 points for the activities of daily living subscale and 9 points for the sports subscale. This measure has shown good test retest reliability for both subscales, 0.89 for the activities of daily living and 0.87 for the sport subscale.[80]

Another common questionnaire utilized in the quantification of FAI is the Ankle Joint Functional Assessment Tool (AJFAT).[81] This measure is comprised of 12 questions related to ankle pain, ankle swelling, ability to walk on uneven surfaces, overall feeling of stability, overall ankle strength, ability to descend stairs, ability to jog, ability to change directions when running, overall activity level, ability to sense a "rollover" event, ability to respond to a "rollover" event, and ability to return to activity following a "rollover" event. Participants are instructed to choose the answer that best describes their ankle using the following scale: much less than the other ankle, slightly less than the other ankle, equal in amount to the other ankle, slightly more than the other ankle, or much more than the other ankle. These answers are scored from 0 to 4, with a maximum score of 48. A higher score indicates greater functional limitations. A cutoff score of greater than or equal to 26 has been shown to discriminate between subjects with FAI and subjects with stable ankles. The AJFAT has been shown to have even greater test retest reliability (0.94) than the FAAM.[81]

The Functional Ankle Disability Index (FADI) is another commonly used questionnaire.[82] The FADI consists of two components, the FADI and the FADI-Sport. The FADI is comprised of 26 items each scored from 0 (unable to do) to 4 (no difficulty at all). However, the 4 pain items are scored from 0 (unbearable) to 4 (none). The maximum score is 104 points. Each component is scored separately as percentages, with 100 percent representing no dysfunction. The FADI-Sport was designed to detect deficits in higher functioning subjects to prevent ceiling effects when using many subjective reports of function that are designed to be used among older populations or populations with limitations in the performance of activities of daily living.[83] The sport component is comprised of 8 items also scored with the same method as the FADI.[82] The maximum score for the sport component is 32 points.[82] Both components have been shown to be reliable in detecting functional limitations in subjects with ankle instability, sensitive to differences between healthy subjects and those with ankle instability, and responsive to improvements in function following rehabilitation in subjects with ankle instability.[83] Furthermore, both components have been shown to be reliable over 1 week (0.85) and 6 weeks (0.93) when used with subjects with ankle instability.[83]

A fourth commonly employed questionnaire is the Cumberland Ankle Instability Tool (CAIT).[16] This tool was developed to determine severity of functional ankle instability and is comprised of 9 items with a maximum score of 30. To be considered to have a highly stable ankle joint a score greater than or equal to 28 is necessary. To be considered at least moderately unstable a score of less than or equal to 24 is necessary.[16] The CAIT has been significantly correlated with the Lower Extremity Functional Scale and the Visual Analog Scale.[84] Excellent test retest reliability (0.96) has been shown for the CAIT.[84]

The Lower Extremity Functional Scale (LEFS) which has been significantly correlated with the CAIT measures lower extremity function across a wide range of lower limb disability levels and conditions, yet is not specific to the ankle.[84] However, the LEFS has shown to be a valid and reliable tool to use in rehabilitation settings and is sensitive to changes in lower limb function.[85] This questionnaire consists of 20 items that specifically address the areas of activity and participation. Items are scored using a Likert response format, with a higher score representing a higher level of ability.[85]

A less commonly known questionnaire that could prove useful is the Sports Ankle Rating System (SARS).[86] This questionnaire is intended for use in assessing functional outcomes of athletes with ankle injuries. It was developed at West Point Military Academy and consists of three outcome measures: Quality of Life Measure, Clinical Rating Score, and Single Assessment Numeric Evaluations. SARS includes both patient-based (self-administered) and process-based (clinician administered) assessments to provide the clinician with a more complete evaluation of an athlete's ankle related health status.[86] A comparison between these questionnaires is warranted in order to discover the most useful tool in which to quantify functional ankle instability allowing for improved evaluation of research subjects and patients.

Strength

Strength training has become an important component of the rehabilitation process following a lateral ankle sprain, because lateral ankle instability is often assumed to be associated with peroneal muscle weakness.[87] However, results of strength testing are equivocal. If strength deficits do exist after ankle sprains, the mechanism of such deficits are not completely understood.

Two distinct theories regarding the relationship between muscle weakness and FAI have been proposed. The first theory suggested that the evertors must be strong enough to counter the inversion mechanism associated with a lateral ankle sprain.[87] This theory can be explained by when the foot and ankle are suddenly forced into inversion a strong concentric response on the part of the evertors must resist the inversion lever and prevent the sprain.[87] However, recent research fails to report weakness in the muscles that evert the foot.[52, 88-92] The second theory involves eccentric control of the ankle invertors in an attempt to counter the lateral displacement of the lower leg during closed chain activities.[44, 93] Further research in this area is necessary.

Early research concerning strength and FAI were first conducted using manual muscle testing. It was reported that peroneal weakness was the most significant factor contributing to recurrent ankle sprains, in a follow-up study of 133 ankle sprains.[94] Manual muscle tests were performed on the peroneal muscles in a 15 year follow-up study of 51 ankles and some degree of weakness was found in 43% of the symptomatic ankles.[75] The same researchers later studied 27 ankles having immediate surgery for ruptures of the fibular collateral ligaments.[74] On follow-up, peroneal muscle weakness and some form of functional instability were present in three patients several months after surgery. All three patients recovered fully following a period of continued manual resistance exercise intended to strengthen the peroneal muscles.[74] However, the problem with these early studies was the use of manual muscle testing which are highly subjective and less accurate.[87]

To combat the subjectivity of manual muscle testing, Tropp[45] was the first to examine isokinetic strength and FAI as he measured peak torque with an isokinetic dynamometer. A significant difference in peak torque for pronation was evident between ankles with and without FAI.[45] Further research also employed the use of isokinetic testing following Tropp's study. Isokinetic strength testing have revealed strength deficits among subjects with FAI.[45, 52, 95]; there have been reports of decreased strength in both eversion[45, 95, 96] and inversion[52, 96], but reports of no deficits in strength can also be found.[88-91] Eversion muscle strength was found to be significantly lower in an instability group compared to a control group.[97] None the less, several studies found no significant differences in eversion strength between limbs of a unilateral FAI group and/or between a FAI group and control group.[88-90] Inversion strength was also discovered to be significantly lower in the functionally unstable ankles compared to their opposite healthy ankles.[98] To the contrary, inversion strength deficits were not found between sides of an unilateral FAI group in another study.[88] Conflicting results have also been found for deficits in plantar flexion strength.[99-102] Plantar flexion strength was found to be decreased in those with FAI compared to a healthy control group[100] and in an injured limb compared to the opposite ankle in subjects with unilateral FAI.[102] However, no differences in plantar flexion strength in those with FAI compared to a healthy control group have also been reported.[101] Due to the equivocal results throughout the history of strength research an underlying problem may exist. The problem may be the definition of FAI employed by the researchers and therefore the specificity of inclusion criteria for FAI subjects. Again this demonstrates the need for a standardized definition of FAI and a standardized set of criteria used for inclusion of FAI subjects in ankle instability research.

Neuromuscular Control

Neuromuscular control deficits have been proposed to be a cause of FAI. However, there have been conflicting theories in the ankle literature on the mechanism of neuromuscular control which actually causes FAI. Neuromuscular control deficits were first described by Freeman and colleagues in 1965.[7] They proposed a theory that neuromuscular control deficits, after joint injuries, were attributable to damage to the articular nerve fibers of the mechanoreceptors located within the injured ligaments and joint capsule. This was believed because the tensile strength of these nerve fibers is less than the collagen fibers within which they are embedded and therefore must be disrupted when ankle ligaments and capsules are torn or stretched.[7] These mechanoreceptors provide afferent impulses regarding position and joint movement as well as contributing to a complex reflex system, which acts to maintain the body's equilibrium.[28] As a result, proprioceptive inputs from the ankle joint could be reduced.[103] Proprioception is the cumulative neural input to the central nervous system, from mechanoreceptors in the joint capsules, ligaments, muscles, tendons and skin.[28] The proprioceptive information conveyed to the spinal cord eventually results in excitation or inhibition of motor neurons.[28] Subsequently, Freeman theorized that disruption of these mechanoreceptors results in decreased sensory input to the central nervous system; which consequently, may lead to faulty positioning and diminished reflex responses, thus leading to an increased incidence of recurrent ankle sprains.[28] Freeman's theory was termed "articular deafferentation" and went generally accepted for more than two decades.[104]

Even though Freeman's original theory is still cited in the literature today, there are reasons why researchers do not fully accept his theory. The first reason is that studies that have sought to anesthetize the lateral ankle ligaments, and thus directly impair the function of the ligamentous and capsular mechanoreceptors, have failed to consistently show deficits in measures of postural control[105-107] or proprioception[105, 106, 108] Specifically, no significant differences were found for joint reposition sense between subjects in the non-anesthetized and anesthetized conditions, regardless of whether one or two ligaments were anesthetized.[105] The authors attributed their results to the adequate amount of afferent feedback from the skin, muscles, and other joint receptors for their positioning task and that ligament mechanoreceptors contribute little to ankle joint proprioception.[105] Furthermore, it has been reported that following an injection of either saline or anesthetic into the ankle joint, tibialis anterior and peroneal muscle activity were equally depressed compared with baseline measures while running.[109] This finding suggested to the authors that any adverse effects may be due to edema in the ankle joint rather than actual deafferentation of the lateral ligaments.[109] Researchers believe the lack of considerable changes despite lateral ankle ligament anesthetization is most likely due to the overlap of sensory information available from other receptors.[104]

Proprioception is a key component of neuromuscular control, and allows for the sensation of body movement and position in space; proprioception is a purely afferent phenomenon.[104] The assessment of joint proprioception can primarily be divided into two components, kinesthesia and joint position sense.[110] Kinesthesia is measured by assessing the threshold-to-detection of passive motion (TTDPM),[111] while joint position sense is measured by assessing the reproduction of passive and active joint positioning.[110] Deficits in the TTDPM have been demonstrated in several studies of individuals who have unilateral CAI. Research has shown deficits in the detection of passive plantar flexion[111, 112] and inversion[90] within an injured ankle joint when compared to the non-injured ankle joint. However, other studies have shown no deficits in the ability to detect passive plantar flexion, dorsiflexion, inversion or eversion of subjects with FAI.[113-115] In the area of joint position sense, one researcher found that recurrent lateral ankle sprains had no significant effect on judgments of joint position either actively or passively.[116] However, other researchers have reported deficits in active replication of joint position in the inversion range of motion[117] and deficits in passive replication of joint position in the plantar flexion range of motion[118] in subjects that have experienced recurrent lateral ankle sprains.

In recent years, a new area of proprioception has emerged in the ankle instability literature, force sense.[104] Force sense represents the ability of an individual to recreate specific force outputs in particular muscle groups. Poor force sense is believed to be caused by proprioceptive deficits caused by dysfunction of the muscle spindles and Golgi tendon organs that cross an injured joint.[104] In subjects who had unilateral FAI, diminished eversion force sense has been reported between involved and uninvolved ankles.[119] In addition, a significant relationship between FAI status and eversion force sense has been identified.[120] The proprioceptive deficits identified in kinesthesia, joint position sense and force sense, indicate that it is likely that there are afferent proprioceptive deficits associated with ankle instability.[104] Unfortunately, the research is inconclusive whether deficits in these proprioceptive measures related to ankle instability represent a peripheral mechanism dysfunction, a central nervous system alteration at the spinal or supraspinal levels, or both[104]

A second limitation to Freeman's theory is it assumes only a feedback model of neuromuscular control. Efferent motor control deficits emerge only after the damaged afferents fail to perceive that the ankle is moving toward or is in a potentially harmful position, in a feedback only model.[104] Furthermore, the feedback only model does not include the feedforward role of the gamma motoneuron pool system or the influence of chronic adaptations in the alpha motoneuron pool excitability.[104] It has been well recognized that there is a sizeable increase in lower leg muscle activity before initial contact of the foot with the ground during gait and jump landings; and furthermore, that the peroneal muscles cannot respond quickly enough to prevent a lateral ankle sprain if they operate in a feedback only manner.[121] Therefore it has been said that accounting for feedforward mechanisms of motor control is vital.[104] The depression of alpha motoneuron pool excitability of the peroneal muscles during rest among individuals with FAI[122] also casts substantial doubt on the feedback only model of neuromuscular control.[104]

To discuss alpha motoneuron pool excitability more in-depth, an understanding of arthrogenic muscle inhibition is warranted. Arthrogenic muscle inhibition has been defined as a continuing reflex reaction of the musculature surrounding a joint after swelling or damage to the structures of that joint.[123] Arthrogenic muscle inhibition is measured by evaluating motoneuron pool excitability of a specific muscle group. The test is an estimation of how much of the alpha motoneuron pool for a specific muscle group is available, rather than a direct measure of muscle contraction force. Arthrogenic muscle inhibition is measured by the H-reflex and M response.[123] Diminished H-reflex/M response ratios have been found in the peroneus longus and soleus muscles of individuals who have FAI.[122] However, what may be more interesting in the autogenic muscle inhibition literature is that inhibition of the quadriceps and increased alpha motoneuron pool excitability of the hamstring muscles have also been reported among those who have CAI.[124] All of these findings provide evidence of altered motoneuron pool excitability not only in muscles that cross the ankle joint but also in proximal leg muscles of those with CAI.[104] These differences indicate that spinal level motor control deficits are associated with ankle instability.[104] Due to the research presented above, a theoretic model that encompasses both feedback and feedforward mechanisms of motor control deficits related to ankle instability seems more useful and has been theorized by current researchers.[104] Direct evidence of mechanoreceptor deficits following a lateral ankle sprain remains missing; however, by exploring the vast array of sensorimotor deficits identified with ankle instability a clearer understanding of the scope of this condition appears. The initial ligamentous injury clearly results in immediate deficits in integrated sensorimotor function, ankle proprioception, and efferent muscle activity. The presence of bilateral postural control deficits with FAI provides obvious evidence of central changes in neuromuscular control.[104] For example, increased center of pressure excursion velocity measures, on not only the limb with an acutely sprained ankle, but also on the contralateral uninjured limb has been discovered.[125] Furthermore, significant decreases in vibration perception and significant delays in gluteus maximus muscle recruitment during hip extension has also been found in those who suffered a severe unilateral ankle sprain.[126] These examples suggests that unilateral ankle sprains result in not only local sensorimotor deficits, but also centrally mediated impairments.[125, 126] This information combined with evidence of altered alpha motoneuron pool excitability of proximal muscles in individuals who have FAI indicates that spinal level motor control mechanisms are clearly altered.[104]

Balance

Single-leg balance impairments have been associated with FAI[12-19] and have predicted ankle sprain injury in physically active individuals.[20-23] More specifically, a significant association between a positive single-leg balance (SLB) test and ankle sprains has been demonstrated in men's American football, men's and women's soccer, and women's volleyball at both high school and collegiate levels.[23] The relative risk for an ankle sprain with a positive SLB test was 2.54 with a 95% confidence interval of 1.02 to 6.03.[23] Research has also shown that basketball players with a high variation of postural sway were more likely to have an injured ankle during the season.[22] The authors suggested that this may be true because postural sway represents the ability to maintain standing balance, and a large variation of postural sway may indicate inconsistent or poor quality of performance, leading to ankle injury.[22] As a result of this association between balance deficits and ankle sprain injury, balance testing has been used in both clinical and research settings in order to assess postural instabilities associated with FAI.

There are numerous ways in which to test balance, there are static, dynamic and/or functional methods. The first clinical measure of balance was the Rhomberg test which was developed in 1851 as a test of a person's stationary balance.[127] However, this test does not provide a quantitative measure of the magnitude of body sway during quiet stance.[127] The Balance Error Scoring System (BESS) is a valid and reliable static measure of postural sway,[25] but was originally used in the assessment of mild head injuries.[128] The BESS attempts to challenge the sensory systems by combining a variety of stances on a firm surface as well as a more unstable surface, foam.[14] The addition of the foam surface increases the difficulty of the task more than the traditional Rhomberg test, but does so with equipment readily available to clinicians. During each trial the evaluator records one error for each time any of the following are observed: 1) lifting hands off iliac crests; 2) opening eyes; 3) stepping, stumbling, or falling; 4) moving the hip into more than 30 degrees of flexion or abduction; 5) lifting the forefoot or heel; 6) remaining out of the testing position for more than five seconds. The total number of errors are calculated for each individual condition and then summed to produce a total BESS score. It has been shown that postural control deficits can be identified in subjects with FAI using the BESS. Specifically, more errors are committed during single-limb stance on firm surface, tandem stance on foam surface, single-limb stance on foam surface, and total score.[14]

A less common but promising test, somewhat similar to the BESS test, is the foot lift test of balance.[16] Participants stand barefoot on one leg in a standardized position with the non-stance foot touching the stance calf, arms by the side, and looking straight ahead. When participants feel steady they close their eyes and maintain their balance without using their arms or other leg. The number of times a part of the foot is lifted during the thirty seconds is recorded. A "part foot lift" is defined as any part of the foot, such as the toes or metatarsal heads, lifting from the floor. If the contralateral foot touches the floor, one count is added and an extra count for each second it remains on the floor. The test-retest reliability has shown to be good (0.78) for the foot lift test. Results have also shown that controls lifted their foot fewer times than those with FAI.[16] Another advantage of this test is the ease of use in the clinical setting.

Time-in-balance is yet another test that could be easily administered in the clinical setting.[13] This test is also a measure of static single-leg balance, but for time. The test is performed barefooted and moving the test foot or touching the floor with the non-stance foot is not allowed. The test is performed with both eyes open and eyes closed. Each trial lasts for a maximum of sixty seconds. Legs are tested alternately, each side three times. The best test result, meaning the longest time trial with the eyes open and the longest time trial with the eyes closed are registered. One study has revealed that those individuals with instability had a reduced test result (shorter time-in-balance) on the affected leg, as compared with the unaffected leg and the control group.[13] Reliability of this measure needs to be studied.

Some authors have suggested that static SLB tests may not be sensitive enough to detect motor-control deficits related to balance performance, and that dynamic tests may provide better means of identifying functional deficits related to balance performance in subjects with FAI.[28] A dynamic measure of balance that is easily employed clinically is the Star Excursion Balance Test (SEBT). Numerous studies have been conducted on the

SEBT, which has been purported to detect functional performance deficits associated with lower extremity pathology in otherwise healthy individuals.[29] The SEBT consists of a series of lower extremity reach tasks in eight directions that challenge subjects' postural control, strength, range of motion, and proprioceptive abilities. The farther a subject can reach with one leg while balancing on the opposite leg, the better functional performance they are assessed to have.[29] The ability to reach farther with a limb requires a combination of better balance, strength, flexibility, and motion on the contralateral stance limb.[129] Reach distance is often normalized to subjects' leg length. Six practice trials were originally granted for each direction, but four practice trials have been shown to be sufficient.[130] Furthermore, the original SEBT procedure was to reach in eight directions, but has been shown that three reach directions (anteromedial, medial, and posteromedial) are sufficient.[130] Intra-tester and inter-tester reliability has been established to be moderate to excellent (0.67 to 0.96) depending on the reach direction.[129, 131]

The results utilizing this test are equivocal. CAI subjects have displayed significantly smaller reach distances and knee flexion angles for three reaching directions (anterior, medial, posterior) compared with the uninjured side and the healthy group.[132] Subjects with CAI reached significantly less on anteromedial, medial, and posteromedial directions when balancing on involved limbs compared to their uninvolved limbs and the side-match controls.[29] In a similar study, subjects with CAI reached further while standing on the uninvolved limb in the posteromedial, posterolateral, and lateral directions when compared to the involved limb.[82] In a study in which reach distance from all eight directions were averaged together, deficits accompanied by reduced knee and hip motion, but not ankle motion in the sagittal plane was found suggesting to the authors that CAI may be related to performance deficits in an entire affected extremity.[133] It is believed that the SEBT is sensitive in detecting reach deficits both between and within athletes with unilateral CAI.[133] Furthermore, reach deficits have also been shown to be exacerbated between subjects with and without CAI after lower extremity fatiguing exercise.[132] To the contrary, no significant reach distance differences between individuals with recurrent ankle sprains and those without have been found as well.[134] The problem with the results in addition to being variable is how in which the researchers classified their subjects. Some subjects had CAI and some had recurrent ankle sprains. More consistent inclusion/exclusion criteria could lead to less variable results.

More functional tests have been utilized in the literature such as the side hop, figure-of-eight hop, up-down hop, single hop for distance, shuttle run, agility hop test, lateral hop, forward hop, and triple crossover hop for distance. The side hop and figure-of-eight hop tests both showed significant positive relationships with the researchers' questionnaire on self-reported feelings of instability.[31] During the side hop subjects are instructed to hop laterally 30 cm and back for a total of 10 repetitions. During the figure-of-eight hop test a 5 m course is outlined by cones and subjects are instructed to hop as quickly as possible twice through the course. Both tests are completed barefooted and are evaluated by length of time to complete task.[31] The up-down hop and single hop for distance test both showed no relationship with that same questionnaire.[31]

The shuttle run is a task in which subjects must complete four consecutive 6.1 m lengths for a total of 24.4 m; similar to the side hop and figure-of-eight hop, this test is evaluated based on length of time to complete task.[49, 135] The agility hop test requires a subject to hop in many different directions and return to a stable, balanced position between each hop. Scoring is based on an error rating scale and a total score is tallied.[49] The shuttle run and agility hop test have both been unable to detect differences between subjects with stable or unstable ankles.[49, 135] However, further research using these tests is being conducted to verify findings.

Three different hop tests are evaluated for distance: the lateral hop, forward hop, and triple crossover hop. The lateral hop and forward hop were both found to be significant factors that predict individual's subjective score on the SARS questionnaire.[86] During the triple crossover hop test subjects hop three times in a zigzag fashion with the distance from the start line to where the toe landed on the third hop is recorded with a standard tape measure. This hop test like the up-down hop test and single hop for distance test, it did not detect functional deficits despite subjects' self-report scores indicating functional impairments.[135]

In addition to the battery of static clinical tests and more dynamic functional tests to assess balance; laboratory or static force plate balance measures are employed by researchers. These static measures include: center of pressure, center of pressure velocity, center of balance, sway index, stability index, postural sway, area 95, modified equilibrium score, and ground reaction. Center of pressure (COP) has been defined as the single point location of the ground reaction force vector.[136] It is a summary measure representing the movements of all of the body segments while a subject attempts to remain upright.[137] Conflicting results using this measure have been found. Subjects with recurrent ankle sprains demonstrated significantly greater excursion of the COP in static balance testing, in one study.[134] However, another study found no significant difference in mean COP distribution between healthy subjects and those with sprained ankles.[138]

Center of pressure velocity (COPV) is the resultant velocity of the COP. COPV is calculated by taking the total distance traveled and dividing it by the time of the trial.[137] One study found that at baseline, no statistically significant differences were detected in COPV between subjects with CAI and those without CAI when standing on the involved limb or the uninvolved limb with the eyes open or closed.[82] However, a CAI group was found in another study to have significantly higher COPV values than the control group.[26] Furthermore, higher COPV values have shown to correspond with increased ankle sprain injury rates.[20] Subjects, high school basketball players, who demonstrated greater COPV values had nearly seven times as many ankle sprains as subjects who had lower COPV values.[20]

Center of balance is another static measure that is described as the point on the foot at which the body weight is equally distributed between the medial-lateral (ML) and anterior-posterior (AP) quadrants and is recorded in centimeters.[139] Center of balance does not seem to be sensitive to foot type because no difference was found between pronators and supinators.[139] A related laboratory measure is the sway index. The sway index is a numerical value of the standard deviation of the distance the subject spent away from his/her center of balance.[140] No significant differences were found for sway index of those with FAI participating in coordination training and those not participating.[140] Another related static laboratory measure to center of balance is the stability index. The stability index is the mean deviation in sway around the center of balance.[139] The stability index was found to be sensitive to foot type.[139] Stability index measures were greater in pronators than in supinators, but neither group was different from those with a neutral foot type.[139] None of these three measures seem to demonstrate enough positive evidence to promote their use.

Postural sway has been expressed as the maximum sway distance recorded in the AP or ML sway in relation to the theoretical limits of stability.[139] However, postural sway is also expressed by another researcher by a transverse sway value obtained during single limb stance on a force plate.[17] Furthermore, this same researcher found increased postural sway in subjects with FAI. Yet when comparing ML and AP mean sway values between the FAI and stable ankle groups they were not significantly different.[30] Another study found that high variation of postural sway in both AP and ML directions corresponded to occurrences of ankle injuries.[22] The effect of foot type on the measure of postural sway has been researched as well and no difference was found as a function of foot type, meaning pronator or supinator.[139]

Area 95 was first described as the total force acting on the force plate, which is the result of gravity and accelerations of body segments, together with isometric muscle contractions. The force plate measures both gravity forces and forces caused by the person to keep the center of gravity within the area of support. The coordinates of the intersection between the line of action of the force and the surface of the plate are calculated and then mean value of the coordinates with its standard deviation are calculated. The degree of variation in coordinates is given as the area of the two-dimensional confidence ellipse for the mean at level 1/√e (=61%).[141] The area is a statistical measurement of the total sway amplitude which takes a possible correlation between the x and y components into account.[142] More simply, area 95 is a measure of the area that the COP traverses.[137] It is determined by taking the radius of the major and minor axes and then fitting an ellipse that would include 95% of the points.[137] Area 95 is usually measured in millimeters squared (mm^2),[142] and is also known as the 95% Confidence ellipse area.[137] It was found that those individuals with abnormal area values ran a significantly higher risk of sustaining an ankle injury during the following season compared to players with normal area values.[21]

The modified equilibrium score is a unitless measure of the actual AP or ML sway in relation to the theoretical limits of stability.[140] The theoretical limit of stability is a center of gravity sway angle and is based on height and weight. Scores near 100 percent indicate little sway, where scores of 0 mean complete loss of stability. A touch down of the non-stance foot would be recorded as a zero.[140] One study found that balance and coordination training improved modified equilibrium scores for those with FAI compared to those with FAI who did not participate and compared to all pre-test scores.[140]

Ground reaction forces are also used as laboratory measures to assess balance. The foot-ground reaction force in the AP and ML directions are monitored for each foot when being tested.[143] These are the tangential components of the force signal responsible to maintain equilibrium during standing and exerted by the body at the foot level. Time variation in these forces reflects swaying motion of the body in the horizontal plane. One study found the foot-ground reaction forces in both AP and ML directions to be the same in normal and sprained ankles of each subject while standing with either eyes open or eyes closed. However, standing with closed eyes, irrespective of ankle status, always produced significantly higher reaction forces than those obtained with eyes open.[143]

A most recent meta-analysis of the balance literature found that ankles with FAI had poorer balance performance than stable ankles across numerous measurements.[144] Even though previous balance literature has been found to be equivocal,[145] the results of the meta-analysis clearly indicate that balance is impaired.[144] Furthermore, time-in-balance and foot lift tests were both shown to have very strong results and have the advantage of being easily employed in the clinical setting.[144] A study containing a healthy population and a FAI population, with specifically defined inclusion and exclusion criteria, that compares results of the BESS test, SEBT, time-in-balance test, foot lift test, COPV, and Area 95 to determine if a particular test best predicts group membership is warranted.

METHODS

Overview

Thirty-four subjects were recruited for this study, seventeen subjects with a history of ankle instability and seventeen subjects without a history of ankle instability. Subjects reported to the Virginia Commonwealth Sports Medicine Research Laboratory for data collection on two occasions. Data collection consisted of each subject performing either static or dynamic balance measures on one day and the second type of balance testing on a subsequent day.

Subjects

All subjects were recruited from the general student population of Virginia Commonwealth University. Children under the age of 18 were excluded. Since an "ankle sprain" in the skeletally immature may be due to growth plate injury, this represents a potentially confounding factor that cannot be controlled for in this study. While controls were matched to FAI participants with regard to sex, height, weight, age, and dominance of tested foot, none of these factors was anticipated to be potential confounders in the data analysis.

The inclusion criteria for all subjects were as follows: 1) age ranging from 18 to 40 years old; 2) no current knee or hip injuries that limit function; 3) perform cardiovascular or resistance training for at least 1.5 hours per week. Exclusion criteria for all subjects were as follows: 1) any known vision deficits (any deficits other than myopia, hyperopia, or astigmatism); 2) any known vestibular deficits; 3) any known somatosensory deficits (other than those present in the ankle). Inclusion criteria specific to those with ankle instability were: 1) history of at least one significant ankle sprain; and 2) self-report sensations of "giving way" at least twice a year in the ankle joint during activity. Exclusion criteria specific to those with ankle instability included: any signs or symptoms of an acute injury (swelling, redness, heat, pain, or loss of function). Inclusion criteria specific to those without ankle instability: 1) no history of ankle injury and 2) sex, height (± 10cm), weight (± 15kg), and age (18-29 and 30-40) matched to subject with ankle instability.

Instrumentation

The AccuSway force plate (AMTI, Corp., Watertown, MA) was used to collect the center-of-pressure data at a sampling rate of 50 Hz. Data was then transferred to a personal computer for processing.

Procedure

Subjects received an orientation to the testing protocol and read a consent form that was approved by The Committee for the Protection of the Rights of Human Subjects at Virginia Commonwealth University. Any potential subject who did not meet the inclusion criteria was excluded from participation. Subjects meeting the inclusion criteria signed the consent form and the testing session continued. The subject's height, weight, and age were all recorded. Subjects then underwent an ankle evaluation for joint laxity utilizing the anterior drawer and talar tilt tests. Subjects then either completed static or dynamic balance tests. Static balance tests were counterbalanced (Table 3). During dynamic balance testing, the Star Excursion Balance Test was completed first, with reach directions counterbalanced (Table 4), followed by the side hop test and figure-of-eight hop test with their testing order counterbalanced (Table 5).

Static Balance Testing

Balance Error Scoring System

Subjects performed the Balance Error Scoring System on a stable and unstable surface (foam) using three different stances: double-limb stance (feet side by side), single-limb stance (standing on only injured leg), and tandem stance (the injured foot was placed directly behind the heel of the uninjured foot). One trial on each surface for each stance was performed. Stable surface condition was tested on the laboratory floor first, followed by the unstable surface condition on a 50.8 x 41.7 x 6.4cm block of medium-density foam (Perform Better, Airex Balance Pad, Craston, RI). The stances were ordered from double-limb stance, followed by single-limb stance, and then tandem stance. Subjects were instructed to keep their eyes closed while standing. Their hands were on their iliac crests and during the single-limb stance the non-weight bearing leg was slightly flexed at the hip and knee. The weight-bearing test leg was in approximately 0-5° of knee flexion. Subjects were instructed to remain as motionless as possible for 20 seconds. Subjects were asked to minimize balance errors during testing. One error was recorded for any of the following:

1) lifting hands off hips; 2) moving the thigh into more than 30 degrees of flexion or abduction; 3) lifting the forefoot or heel; 4) remaining out of the testing position for more than 5 seconds; and 5) opening eyes. Hopping resulted in a mistrial and resulted in a re-test. Subjects were given the opportunity to practice each stance on each surface once and then performed each task one time. Subjects rested 30 seconds in between all trials. The total number of errors committed on all trials was used for analysis.

Time-in-balance Test

Positioning was the same as for the Balance Error Scoring System except only the single-limb stance on a stable surface was used. This test was used to determine how long a subject could remain in the test position before moving the test foot or touching the floor with the contralateral foot. Three trials with eyes closed were collected and the longest time trial was used for analysis. The maximum length of each trial was 60 seconds.

Foot Lift Test

Positioning was also the same as for the Balance Error Scoring System except only the single-limb stance on a stable surface was used. During this test the number of times a part of the foot was lifted during the 30 second trial was counted as an error. A “part foot lift” was defined as any part of the foot, such as toes or metatarsal heads, lifting from the floor. If the contralateral foot touched the floor, one more error was added and an extra error for each second it remained on the floor. The average of the three trials was used for analysis.

Force Plate Measures

Force plate measures were collected on an AccuSway force plate (AMTI, Corp., Watertown, MA). Force plate sampling rate was 50 Hz.[15] Subjects' test foot was positioned in the middle of the force plate and same as single-limb stance of the Balance Error Scoring System. Three trials with eyes closed for 20 seconds were completed. Subjects rested 30 seconds between trials. After data collection, force plate data was filtered with a low pass digital filter with a cutoff frequency of 5 Hz.[15] Then, center-of-pressure anterior-posterior and medial-lateral were calculated using Balance Clinic Software (AMTI, Corp., Watertown, MA), exported into spreadsheets and saved on a personal computer.

Dynamic Balance Testing

Star Excursion Balance Test

The Star Excursion Balance Test was performed with the subject standing barefoot at the center of a grid laid on the floor with 3 lines extending at 45° angles from the center of the grid. The length and width of the stance foot will be measured and the foot will be meticulously placed so that the geometric center of the foot aligns with the center of the grid. Subjects maintained a single-leg stance while reaching with the contralateral leg to touch as far as possible along the chosen line. The lines were made of cloth tape-measures using centimeter measurements. The examiner recorded the distance touched along the tape measure. Subjects then returned to a bilateral stance while maintaining their equilibrium. Reach distances were normalized to subjects' leg length, which was measured from the anterior superior iliac spine to the distal tip of the medial malleolus. The stance foot could not move from its starting position for a valid trial; but, if this did occur then the stance foot would be repositioned at the center of the grid prior to the next trial. Testing took place with no visual references. Three surrounding walls were bare and painted white and the fourth wall was a white sheet hung from ceiling to floor.

The 3 lines were named according to the direction of reach in relation to stance leg: anteromedial (AM), medial (MD), and posteromedial (PM). The order of reach directions was counter-balanced to avoid order effects from contaminating the data (Table 4). Each subject performed 4 practice trials in each of the 3 directions followed by 5 minutes of rest before recording began. Subjects then performed 3 trials in each direction on test limb. Ten seconds of rest were provided between individual reach trials.

Figure-of-Eight Hop Test

Subjects performed this test barefoot on a 5 m course outlined by cones in a figure 8 pattern. Subjects were instructed to hop as quickly as possible twice through the course. The total time was recorded with a hand-held stopwatch to the nearest 0.01 second. Subjects completed the test a total of two times. The best (shortest) time trial was used for analysis. Due to the potential fatigue while performing both hop tests, this test was performed following the Star Excursion Balance Test and counter-balanced with the side hop test (Table 5).

Side Hop Test

Subjects performed this test barefoot, and were instructed to hop laterally 30 cm and back for a total of 10 repetitions. The total time was recorded with a hand-held stopwatch to the nearest 0.01 second. Subjects completed the test a total of two times. The best (shortest) time trial was used for analysis. Due to the potential fatigue while performing both hop tests this test was performed following the Star Excursion Balance Test and counter-balanced with the figure-of-eight hop test (Table 5).

Data Collection and Reduction

Center-of-pressure resultant velocity and area were calculated by Balance Clinic Software. COP coordinates were saved in spreadsheets and then imported into LabVIEW 8.5 (National Instruments, Corp, Austin, TX) for data reduction and analysis. A custom software program using LabVIEW was used to calculate center-of-pressure resultant velocity, center-of-pressure area, and anterior-posterior time-to-boundary standard deviation of the minima. See Table 1 for detailed calculations.

For this study, greater values for our dependent measures indicated balance impairments associated with FAI. This presented a problem for time-in-balance, anterior-posterior time-to-boundary, and Star Excursion Balance Test measures because lesser values are used traditionally to identify balance deficits. To make greater values indicative of balance impairments for the aforementioned measures, we found the median scores and then found the absolute difference between the median score and subjects' scores. We then added that difference to the median score for subjects with FAI and subtracted that difference from the median score for subjects with stable ankles.

Statistical Analysis

Means (SD) were calculated for subject demographics. A one-way ANOVA was calculated in order to determine that our groups were not statistically different by age, height, or weight. An alpha level of 0.05 was set a priori. Means (SD) were calculated for dependent measures. Diagnostic parameters were calculated to determine static and dynamic balance measures that discriminated balance deficits between FAI and stable ankles. Sensitivity and specificity values for each dependent measure across the range of possible scores to compute receiver operating characteristic (ROC) curves and the area under the curve (AUC) was calculated. The AUC of the curve was used to determine the accuracy of each balance measure. A traditional academic point scale was used to classify the accuracy, or performance, of a measure based on the AUC (0.90-1.00 = excellent; 0.80-0.89 = good; 0.70-0.79 = fair; 0.60-0.69 = poor; 0.50-0.59 = fail).[146-148] To determine the best cutoff score we established the score with the greatest sensitivity and the lowest false-positive score (i.e., 1-specificity). Then, posttest probabilities and likelihood ratios were used to determine the meaningfulness of cutoff scores. The meaningfulness of likelihood ratios are listed in Table 6. Clinically meaningful cutoff scores indicated that posttest probabilities changed significantly from pretest probabilities (i.e., prevalence). Only those dependent measures with asymptotic significance ≤ 0.05 had a cutoff score calculated (asymptotic significance level for the AUC was set at P ≤0 .05). SPSS software (version 16.0; SPSS Inc, Chicago, IL) was used for statistical analyses.

Table 1. Force Plate Measure Calculations

Force-plate Measure	Equation	
Center-of-pressure Velocity Resultant	$R_{xy_i} = \sqrt{(x_i^2 + y_i^2)}$ $COPVR = \frac{\sum_{i=1}^{n} \left\| \frac{R_{xy,i+1} - R_{xy,i-1}}{2\Delta t} \right\|}{n-1}$	This calculation is for the mean center-of-pressure resultant velocity.
Center-of-pressure Area	$A = 2.0 \cdot \pi \cdot F \cdot \sqrt{x_{sd} \cdot y_{sd} - \sigma_{xy}}^{2}$	F statistic at confidence level of 1-α, where α = .05 F = 3
Time-to-boundary	$TTB_{AP_i} = \frac{\left(\frac{L}{2} + COP_i\right)}{COPV_i}$	L = length of foot Will calculate standard deviation of minima.

Table 2. Testing Type Order

Subject #	Testing Day 1	Testing Day 2
1	Static	Dynamic
2	Dynamic	Static
3	Static	Dynamic
4	Dynamic	Static
5	Static	Dynamic
6	Dynamic	Static
7	Static	Dynamic
8	Dynamic	Static
9	Static	Dynamic
10	Dynamic	Static
11	Static	Dynamic
12	Dynamic	Static
13	Static	Dynamic
14	Dynamic	Static
15	Static	Dynamic
16	Dynamic	Static
17	Static	Dynamic

Table 3. Static Balance Measures Testing Order

Subject #	First Static Test	Second Static Test	Third Static Test	Fourth Static Test
1	BESS	TIB	FL	FP
2	BESS	FL	FP	TIB
3	BESS	FP	TIB	FL
4	TIB	FL	FP	BESS
5	TIB	FP	BESS	FL
6	TIB	BESS	FL	FP
7	FL	FP	BESS	TIB
8	FL	BESS	TIB	FP
9	FL	TIB	FP	BESS
10	FP	BESS	TIB	FL
11	FP	TIB	FL	BESS
12	FP	FL	BESS	TIB
13	BESS	TIB	FL	FP
14	BESS	FL	FP	TIB
15	BESS	FP	TIB	FL
16	TIB	FL	FP	BESS
17	TIB	FP	BESS	FL

BESS: Balance Error Scoring System
TIB: time-in-balance test
FL: foot lift test
FP: force plate measures

Table 4. Star Excursion Balance Test Reach Direction Order

Subject #	1st Reach Direction	2nd Reach Direction	3rd Reach Direction
1	AM	M	PM
2	M	PM	AM
3	PM	AM	M
4	AM	M	PM
5	M	PM	AM
6	PM	AM	M
7	AM	M	PM
8	M	PM	AM
9	PM	AM	M
10	AM	M	PM
11	M	PM	AM
12	PM	AM	M
13	AM	M	PM
14	M	PM	AM
15	PM	AM	M
16	AM	M	PM
17	M	PM	AM

AM: anteromedial direction
M: medial direction
PM: posteromedial direction

Table 5. Hop Measures Testing Order

Subject #	Second Dynamic Test	Third Dynamic Test
1	F8H	SH
2	SH	F8H
3	F8H	SH
4	SH	F8H
5	F8H	SH
6	SH	F8H
7	F8H	SH
8	SH	F8H
9	F8H	SH
10	SH	F8H
11	F8H	SH
12	SH	F8H
13	F8H	SH
14	SH	F8H
15	F8H	SH
16	SH	F8H
17	F8H	SH

F8H: figure-of-eight hop test
SH: side hop test

Table 6. Meaningfulness of Likelihood Ratios

+ LR	Significance	- LR
2-5	Small	0.5-0.1
5-10	Moderate	0.1-0.2
>10	Large	< 0.1-0.2

RESULTS

Means and Standard Deviations

Data were collected from thirty-four subjects. Subjects were tested on their unstable ankle or their test matched ankle. Table 7 reports the subject characteristics including age, height, weight, gender, dominance, and ankle tested. The groups were not found to be statistically different from each other (age: $F_{(1,32)}=0.001$, $P=1.000$; height: $F_{(1,32)}=0.022$, $P= 0.882$; weight: $F_{(1,32)}=0.142$, $P=0.709$). Table 8 reports the means and standard deviations of each dependent measure for subjects with FAI and subjects with stable ankles.

ROC Curves

Figures 1-11 display ROC curves for all dependent measures. Table 9 reports the AUC values and asymptotic significance for all dependent measures. The foot lift test, time-in-balance test, center-of-pressure resultant velocity, Star Excursion Balance Test in posteromedial reach direction, and side hop test had “fair” accuracy for discriminating between ankle groups. Anterior-posterior time-to-boundary standard deviation of the minima, the Balance Error Scoring System, anteromedial and medial reach directions of Star Excursion Balance Test, and figure-of-eight hop test had “poor” accuracy for discriminating between ankle groups. Finally, the center-of-pressure area “failed” to accurately discriminate between ankle groups.

Cutoff Scores

Table 10 reports the diagnostic parameters for the center-of-pressure resultant velocity. The cutoff score of 1.56 cm/s had the greatest sensitivity and least false positive scores. The center-of-pressure resultant velocity cutoff score of ≥ 1.56 cm/s identified balance deficits associated with FAI. The positive and negative likelihood ratios were greater than and less than 2 and 0.5, indicating that the posttest probability changed significantly from the prevalence, respectively.

Table 11 reports the diagnostic parameters for the anterior-posterior Time-to-Boundary standard deviation of the minima. The cutoff score of 3.72 s had the greatest sensitivity and least false positive scores. The anterior-posterior Time-to-Boundary standard deviation of the minima cutoff score of ≥ 3.72 s identified balance deficits associated with FAI. The positive and negative likelihood ratios were greater than and equal to 2 and 0.5, indicating that the posttest probability changed significantly from the prevalence, respectively.

Table 12 reports the diagnostic parameters for the foot lift test. The cutoff score of 4.84 foot lifts had the greatest sensitivity and least false positive scores. The foot lift test cutoff score of ≥ 4.84 foot lifts identified balance deficits associated with FAI. The positive and negative likelihood ratios were greater than and less than 2 and 0.5, indicating that the posttest probability changed significantly from the prevalence, respectively

Table 13 reports the diagnostic parameters for the time-in-balance test. The cutoff score of 41.23 s had the greatest sensitivity and least false positive scores. The time-in-balance test cutoff score of ≥ 41.23 s identified balance deficits associated with FAI. The positive and negative likelihood ratios were greater than and less than to 2 and 0.5, indicating that the posttest probability changed significantly from the prevalence, respectively.

Table 14 reports the diagnostic parameters for the Star Excursion Balance Test posteromedial reach direction. The cutoff score of 0.91 (normalized to leg length) had the greatest sensitivity and least false positive scores. The posteromedial reach direction of the star excursion balance test cutoff score of ≥ 0.91 (normalized to leg length) identified balance deficits associated with FAI. The positive and negative likelihood ratios were greater than and equal to 2 and 0.5, indicating that the posttest probability changed significantly from the prevalence, respectively.

Table 15 reports the diagnostic parameters for the side hop test. The cutoff score of 12.88 s was chosen because this score had the greatest sensitivity and least false positive scores. The side hop test cutoff score of ≥ 12.88 s identified balance deficits associated with FAI. The positive and negative likelihood ratios were greater and less than 2 and 0.5, indicating that the posttest probability changed significantly from the prevalence, respectively.

Table 7. Means (SD) of Subject Demographics

	Age (yr)	**Height (cm)**	**Mass (kg)**	**Gender**	**Test Foot**	**Dominance**
FAI (N=17)	23.35 (3.62)	167.72 (9.11)	67.81 (12.29)	Female=13 Male=4	Right=14 Left=3	Right=17 Left=0
Healthy (N=17)	23.35 (3.26)	168.16 (8.32)	66.22 (12.35)	Female=13 Male=4	Right=14 Left=3	Right=17 Left=0

Table 8. Means (SD) of Dependent Measures

Dependent Measure	FAI	Healthy
Foot Lift Test (foot lifts)	5.57 (2.38)	3.20 (2.68)
Time-in-Balance Test (s)	28.99 (17.30)	46.01 (19.64)
Balance Error Scoring System (errors)	13.59 (4.00)	11.06 (3.01)
Center of Pressure Velocity (cm/s)	1.81 (0.38)	1.61 (0.40)
Center of Pressure Area (cm^2)	3.50 (0.68)	3.50 (1.41)
AP Time-to-Boundary Standard Deviation of the Minima (s)	3.78 (0.54)	3.95 (0.43)
Star Excursion Balance Test-anteromedial reach direction (normalized to leg length)	0.85 (0.08)	0.90 (0.09)
Star Excursion Balance Test-medial reach direction (normalized to leg length)	0.87 (0.08)	0.92 (0.09)
Star Excursion Balance Test-posteromedial reach direction (normalized to leg length)	0.88 (0.09)	0.95 (0.12)
Side Hop Test (s)	16.76 (8.30)	12.20 (5.39)
Figure-of-Eight Hop Test (s)	16.88 (4.52)	14.92 (3.48)

Table 9. Area Under the Curve Values for Dependent Measures

Dependent Measure	Significance	AUC
Foot Lift Test	P = 0.01	0.76
Time-in-Balance Test	P = 0.02	0.73
Balance Error Scoring System	P = 0.25	0.62
Center-of-Pressure Resultant Velocity	P = 0.03	0.72
Center-of-Pressure Area	P = 0.55	0.56
Anterior-posterior Time-to-Boundary Standard Deviation of the Minima	P = 0.05	0.69
Star Excursion Balance Test-anteromedial reach direction	P = 0.13	0.65
Star Excursion Balance Test- medial reach direction	P = 0.13	0.65
Star Excursion Balance Test-posteromedial reach direction	P = 0.04	0.71
Side Hop Test	P = 0.04	0.70
Figure-of-Eight Hop Test	P = 0.12	0.66

Table 10. Diagnostic Parameters for Center-of-Pressure Resultant Velocity (cm/s)

Cutoff Scores	Sensitivity	1-Specificity	Prevalence	+ Posttest Probability	- Posttest Probability	+ Likelihood Ratio	- Likelihood Ratio
1.36	0.94	0.71	0.50	0.57	0.17	1.33	0.20
1.56*	0.76	0.35	0.50	0.68	0.27	2.17	0.36
1.83	0.53	0.18	0.50	0.75	0.36	3.00	0.57
2.22	0.06	0.06	0.50	0.50	0.50	1.00	1.00

*Cutoff score with the greatest sensitivity and least false positive score

Table 11. Diagnostic Parameters for Anterior-posterior Time-to-Boundary Standard Deviation of Minima (s)

Cutoff Scores	Sensitivity	1-Specificity	Prevalence	+ Posttest Probability	- Posttest Probability	+ Likelihood Ratio	- Likelihood Ratio
3.45	0.82	0.65	0.50	0.63	0.33	1.71	0.50
3.72*	0.71	0.35	0.50	0.67	0.31	2.00	0.45
3.94	0.47	0.29	0.50	0.62	0.43	1.60	0.75
4.04	0.24	0.18	0.50	0.57	0.48	1.33	0.93

*Cutoff score with the greatest sensitivity and least false positive score.

Table 12. Diagnostic Parameters for Foot Lift Test (foot lifts)

Cutoff Scores	Sensitivity	1-Specificity	Prevalence	+ Posttest Probability	- Posttest Probability	+ Likelihood Ratio	- Likelihood Ratio
1.84	0.94	0.65	0.50	0.59	0.14	1.45	0.17
4.84*	0.71	0.18	0.50	0.80	0.26	4.00	0.36
7.34	0.24	0.12	0.50	0.67	0.46	2.00	0.87
8.50	0.12	0.06	0.50	0.67	0.48	2.00	0.94

*Cutoff score with the greatest sensitivity and least false positive score.

Table 13. Diagnostic Parameters for Time-in-Balance Test (s)

Cutoff Scores	Sensitivity	1-Specificity	Prevalence	+ Posttest Probability	- Posttest Probability	+ Likelihood Ratio	- Likelihood Ratio
25.89	0.82	0.35	0.50	0.70	0.21	2.33	0.27
38.77	0.71	0.24	0.50	0.75	0.28	3.00	0.38
41.23*	0.65	0.18	0.50	0.79	0.30	3.67	0.43
56.75	0.18	0.12	0.50	0.60	0.48	1.50	0.93

*Cutoff score with the greatest sensitivity and least false positive score.

Table 14. Diagnostic Parameters for Star Excursion Balance Test Posteromedial Reach Direction (normalized to leg length)

Cutoff Scores	Sensitivity	1-Specificity	Prevalence	+ Posttest Probability	- Posttest Probability	+ Likelihood Ratio	- Likelihood Ratio
0.87	0.88	0.59	0.50	0.60	0.22	1.50	0.29
0.91*	0.65	0.29	0.50	0.69	0.33	2.20	0.50
0.92	0.53	0.24	0.50	0.69	0.38	2.25	0.62
0.98	0.18	0.06	0.50	0.75	0.47	3.00	0.88

*Cutoff score with the greatest sensitivity and least false positive score.

Table 15. Diagnostic Parameters for Side Hop Test (s)

Cutoff Scores	Sensitivity	1-Specificity	Prevalence	+ Posttest Probability	- Posttest Probability	+ Likelihood Ratio	- Likelihood Ratio
8.33	0.88	0.76	0.50	0.54	0.33	1.15	0.50
10.01	0.76	0.47	0.50	0.62	0.31	1.63	0.44
12.88*	0.65	0.18	0.50	0.79	0.30	3.67	0.43
17.28	0.41	0.06	0.50	0.88	0.38	7.00	0.63

*Cutoff score with the greatest sensitivity and least false positive score.

Legend to Figures

Figure 1. Balance Error Scoring System Receiver Operating Characteristic (ROC) Curve. The P-value (0.25) and Area Under the Curve value (0.62) were not significant, it did not discriminate between ankle groups.

Figure 2. Foot Lift Test Receiver Operating Characteristic (ROC) Curve. The P-value (0.01) and Area Under the Curve value (0.76) were significant and discriminated between ankle groups. The cutoff score ≥ 4.84 foot lifts identified balance deficits.

Figure 3. Time-in-Balance Test Receiver Operating Characteristic (ROC) Curve. The P-value (0.02) and Area Under the Curve value (0.73) were significant and discriminated between ankle groups. The cutoff score ≥ 41.23 s identified balance deficits.

Figure 4. Center-of-Pressure Resultant Velocity Receiver Operating Characteristic (ROC) Curve. The P-value (0.03) and Area Under the Curve value (0.72) were significant and discriminated between ankle groups. The cutoff score ≥ 1.56 cm/s identified balance deficits.

Figure 5. Center-of-Pressure Area Receiver Operating Characteristic (ROC) Curve. The P-value (0.55) and Area Under the Curve value (0.56) were not significant, it did not discriminate between ankle groups.

Figure 6. Anterior-posterior Time-to-Boundary Standard Deviation of the Minima Reciever Operating Characteristic (ROC) Curve. The P-value (0.05) and Area Under the Curve value (0.69) were significant and discriminated between ankle groups. The cutoff score ≥ 3.72 s identified balance deficits.

Figure 7. Anteromedial Reach Direction of Star Excursion Balance Test Receiver Operating Characteristic (ROC) Curve. The P-value (0.13) and Area Under the Curve value (0.65) were not significant, it did not discriminate between ankle groups**.**

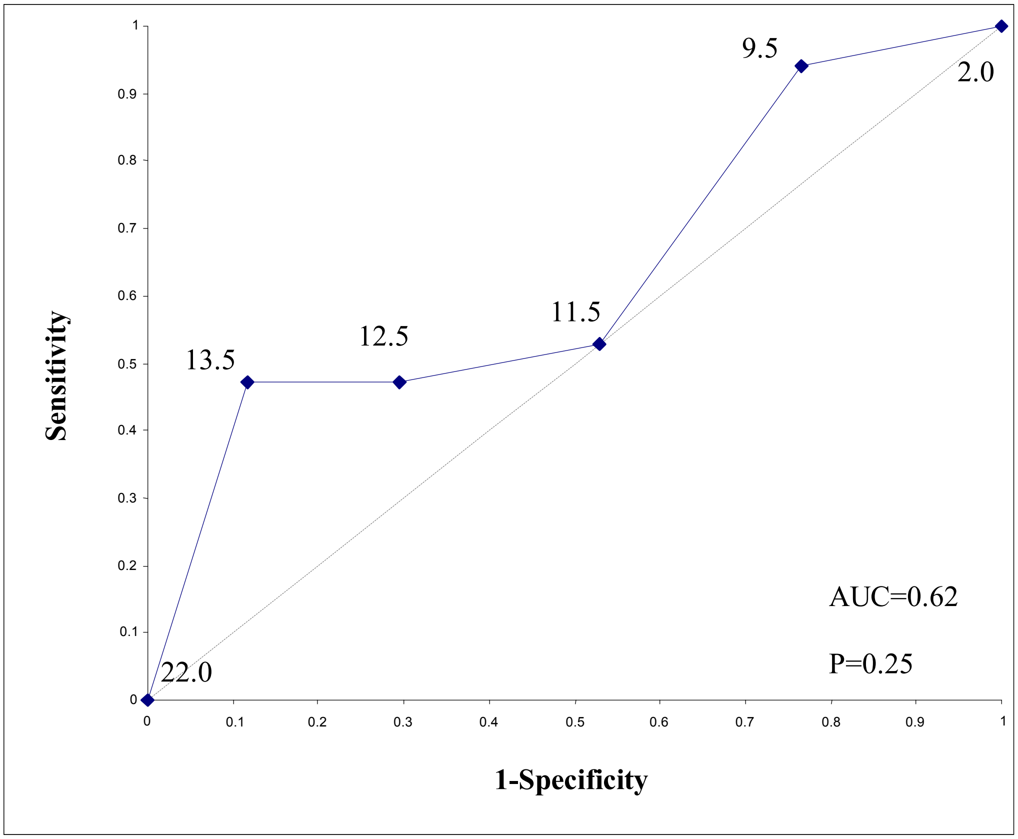
Figure 8. Medial Reach Direction of Star Excursion Balance Test Receiver Operating Characteristic (ROC) Curve. The P-value (0.13) and Area Under the Curve value (0.65) were not significant, it did not discriminate between ankle groups.

Figure 9. Posteromedial Reach Direction of Star Excursion Balance Test Receiver Operating Characteristic (ROC) Curve. The P-value (0.04) and Area Under the Curve value (0.71) were significant and discriminated between ankle groups. The cutoff score ≥ 0.91 reach distance normalized to leg length identified balance deficits.

Figure 10. Side Hop Test Receiver Operating Characteristic (ROC) Curve. The P-value (0.04) and Area Under the Curve value (0.70) were significant and discriminated between ankle groups. The cutoff score ≥ 12.88 s identified balance deficits.

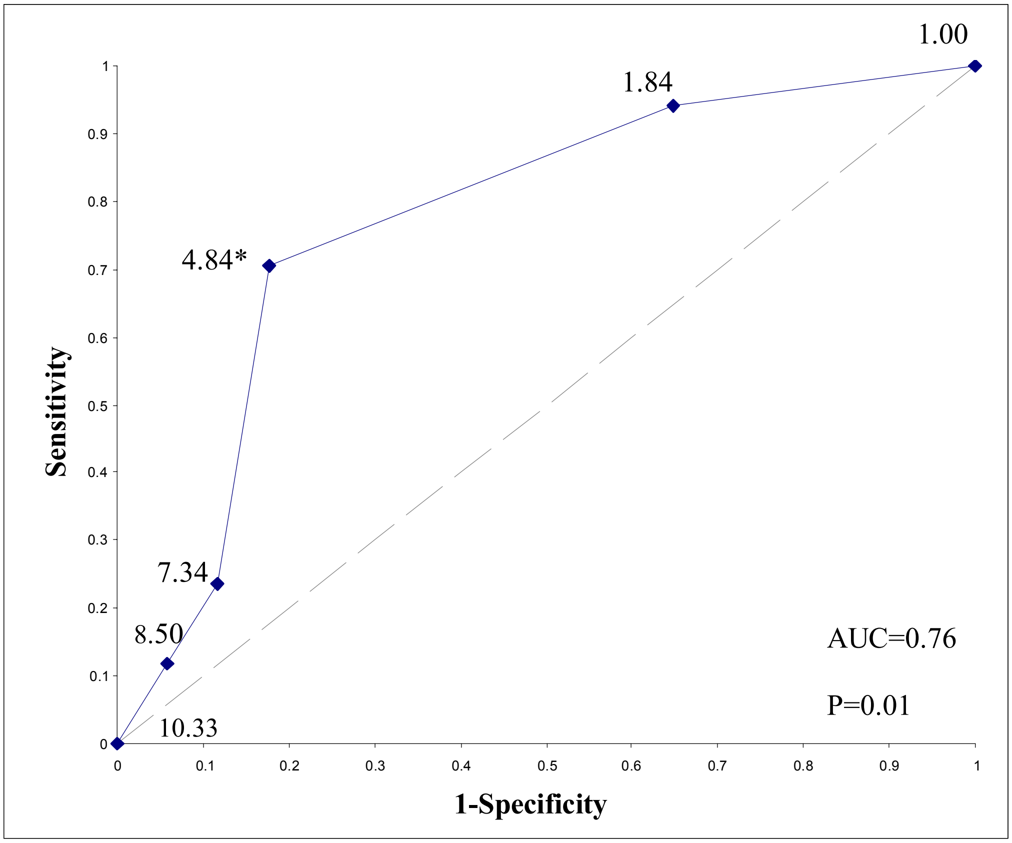
Figure 11. Figure-of-Eight Hop Test Receiver Operating Characteristic (ROC) Curve. The P-value (0.12) and Area Under the Curve value (0.66) were not significant, it did not discriminate between ankle groups.

Figure 1.



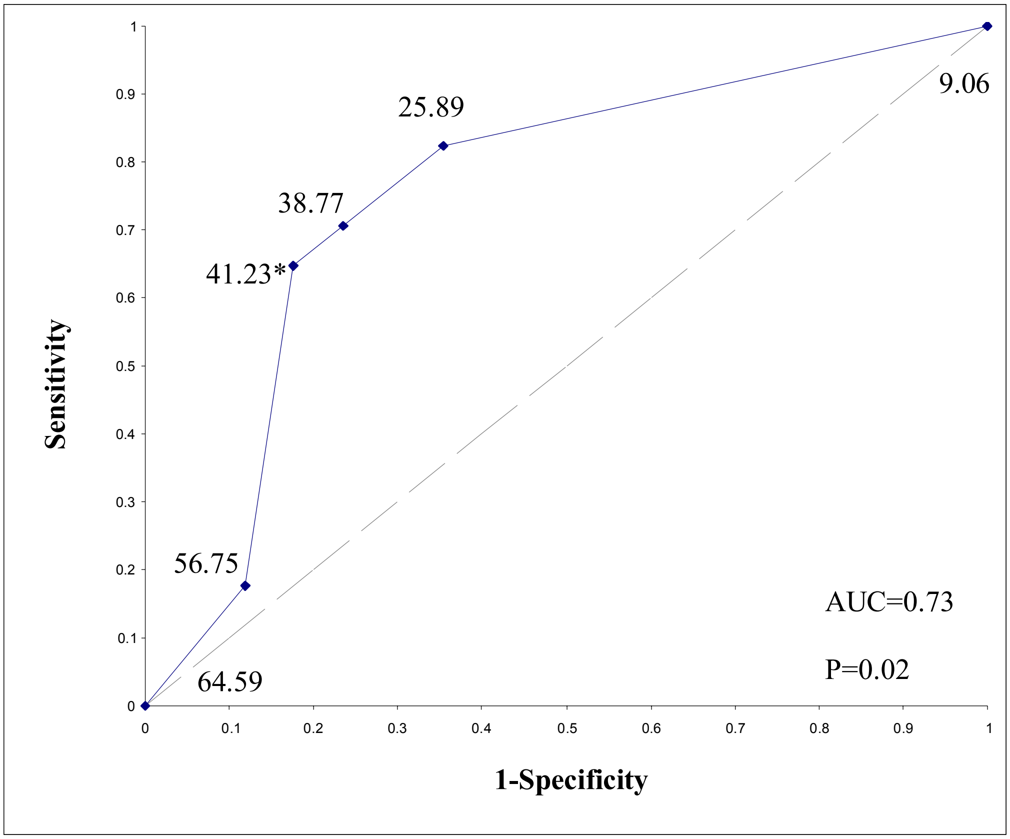
Balance Error Scoring System (total # of errors) Receiver Operating Characteristic Curve

Figure 2.



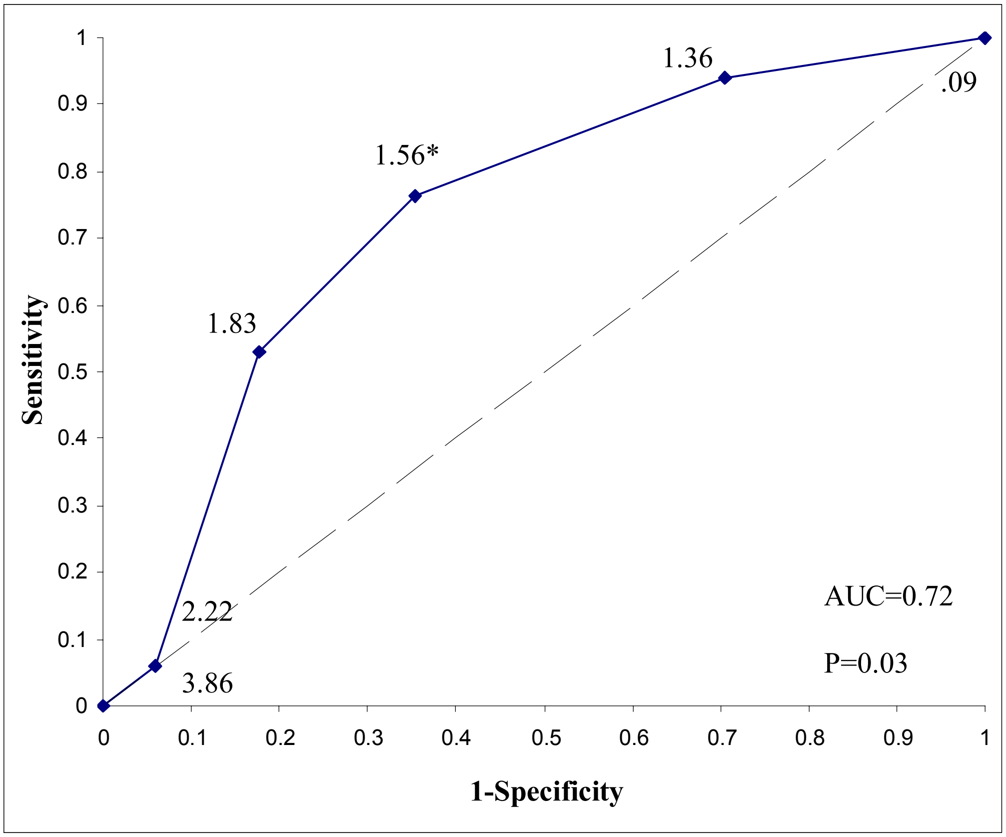
Foot Lift Test (foot lifts) Receiver Operating Characteristic Curve
* Cutoff score

Figure 3.



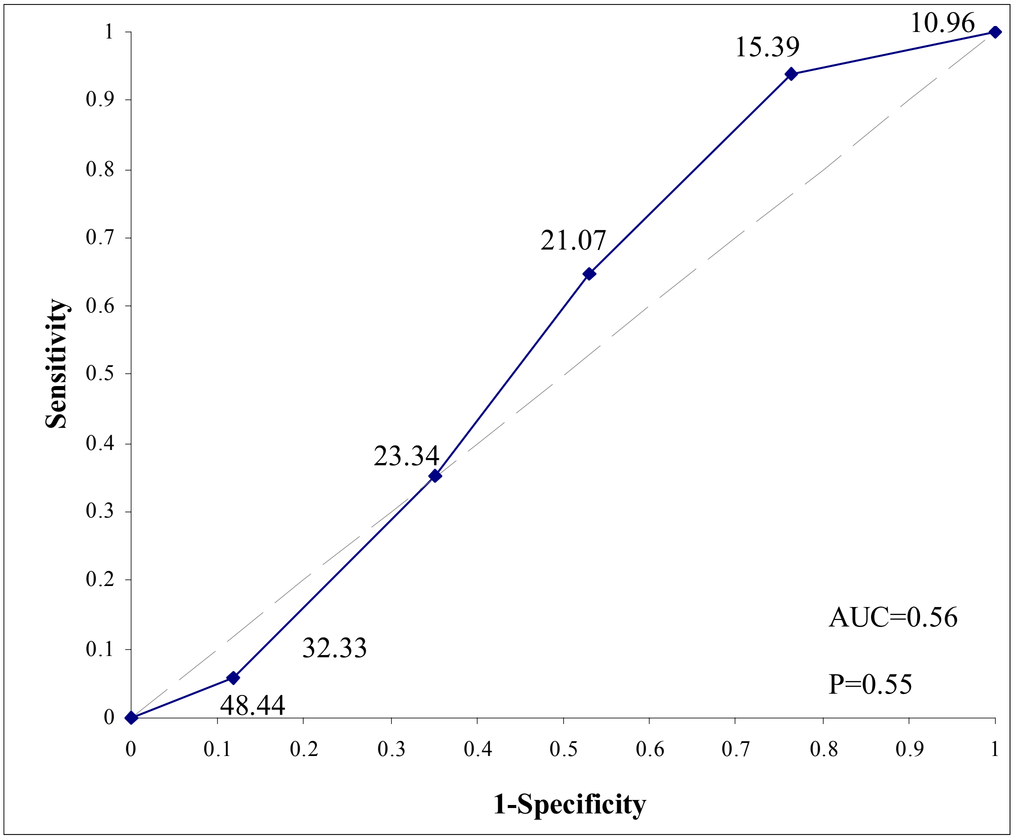
Time-in-Balance Test (s) Receiver Operating Characteristic Curve
* Cutoff score

Figure 4.



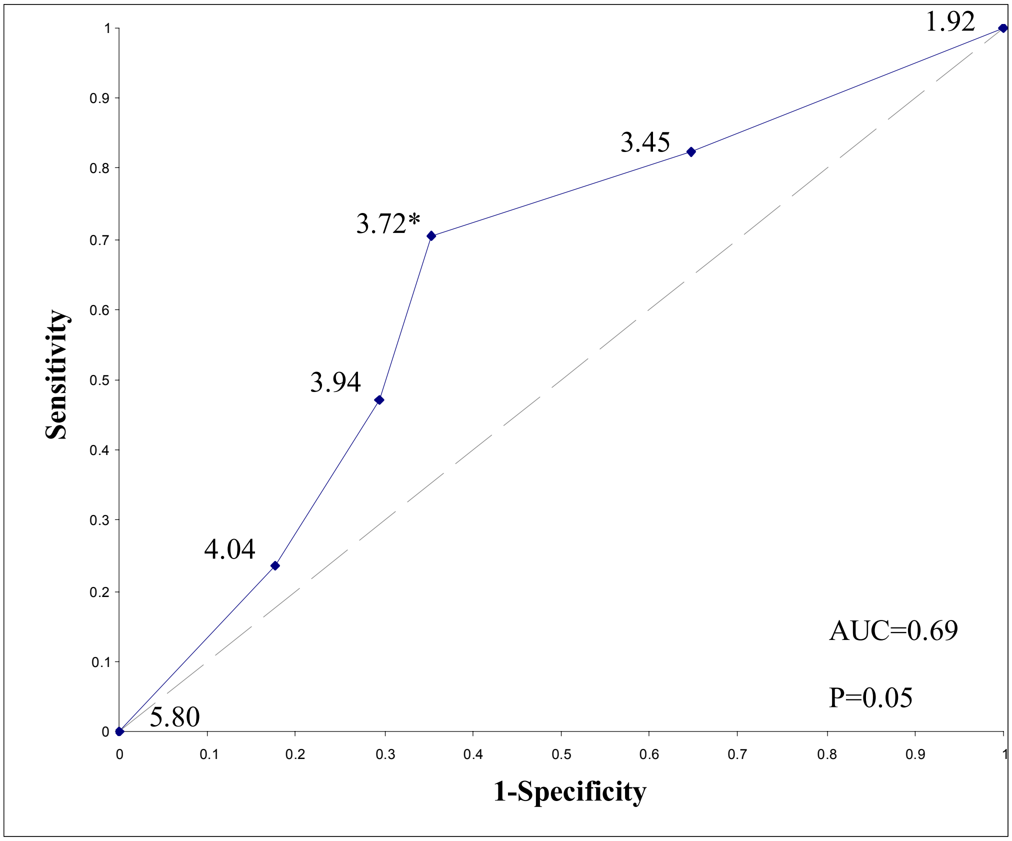
Center-of-Pressure Resultant Velocity (cm/s) Receiver Operating
Characteristic Curve
* Cutoff score

Figure 5.



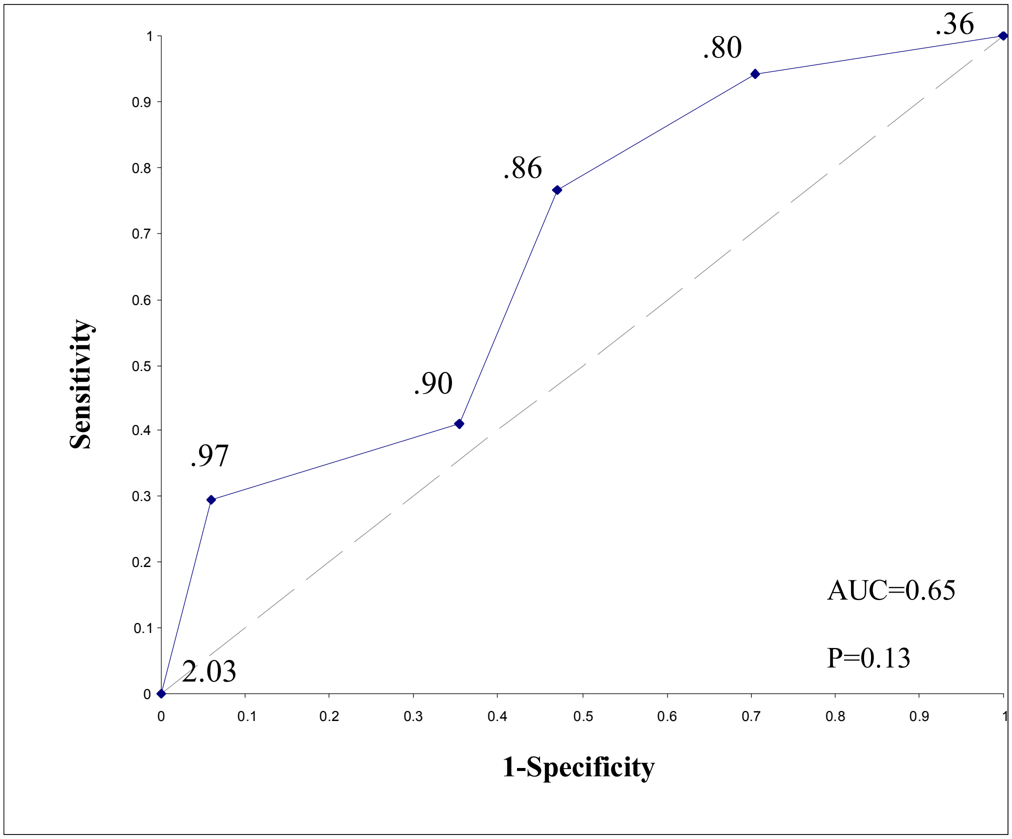
Center-of-Pressure Area (cm^2) Receiver Operating Characteristic Curve

Figure 6.



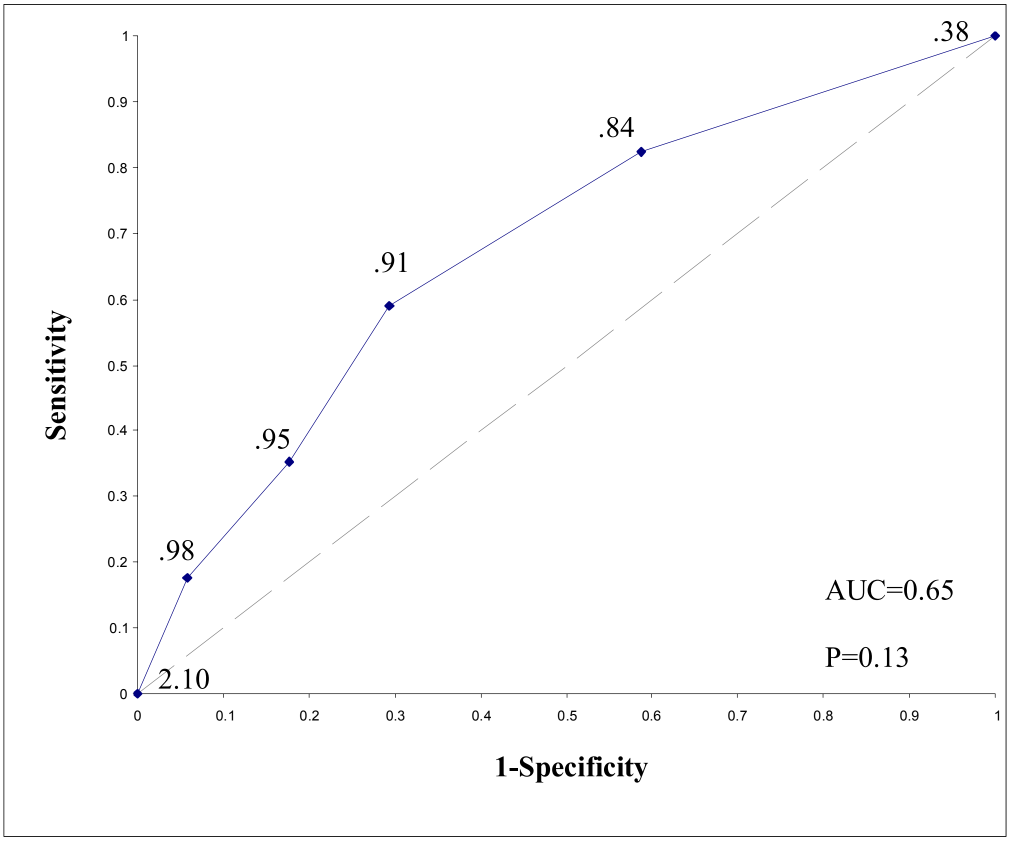
Anterior-posterior Time-to-Boundary Standard Deviation of the Minima (s)
Receiver Operating Characteristic Curve
* Cutoff score

Figure 7.



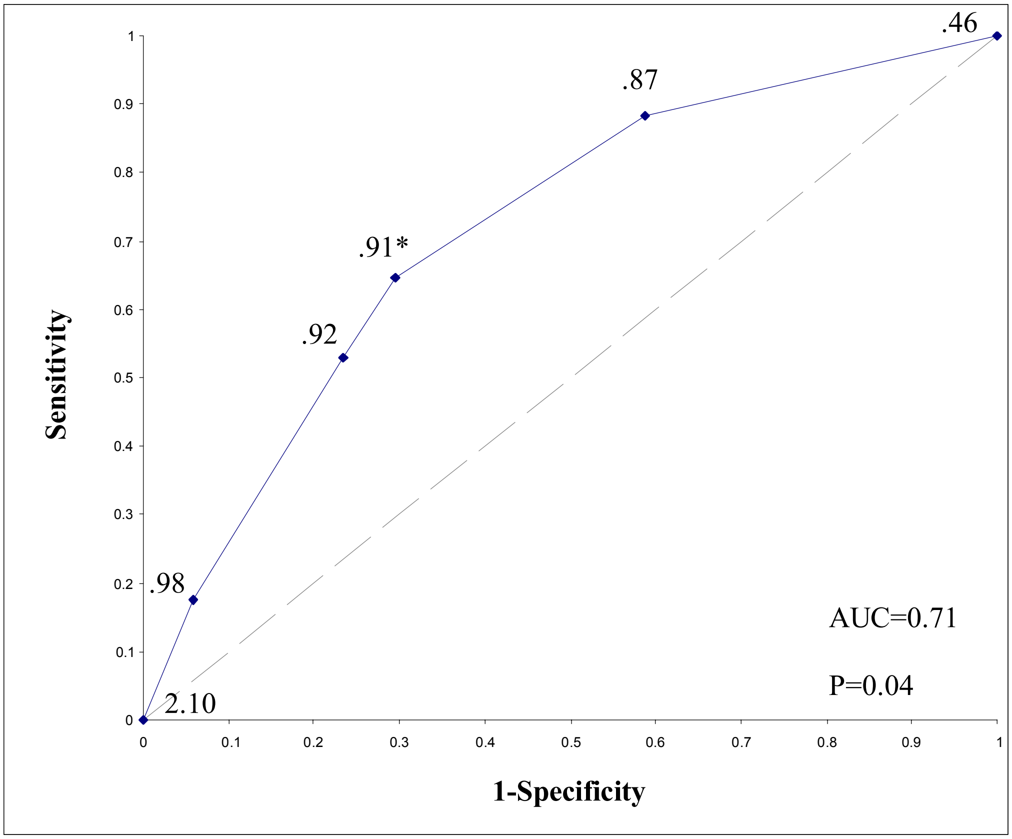
Anteromedial Reach Direction of Star Excursion Balance Test (normalized to leg length) Receiver Operating Characteristic Curve

Figure 8.



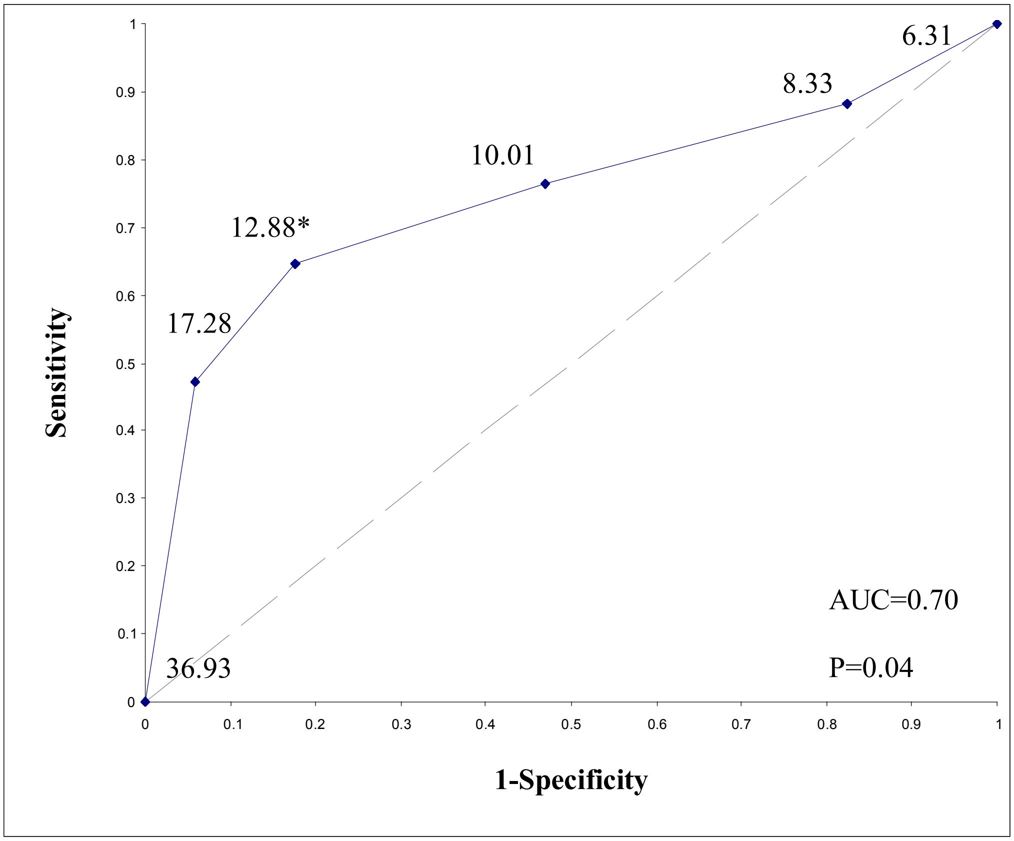
Medial Reach Direction of Star Excursion Balance Test (normalized to leg length) Receiver Operating Characteristic Curve

Figure 9.



Posteromedial Reach Direction of Star Excursion Balance Test (normalized to leg length) Receiver Operating Characteristic Curve
* Cutoff score

Figure 10.



Side Hop Test (s) Receiver Operating Characteristic Curve
* Cutoff score

Figure 11.

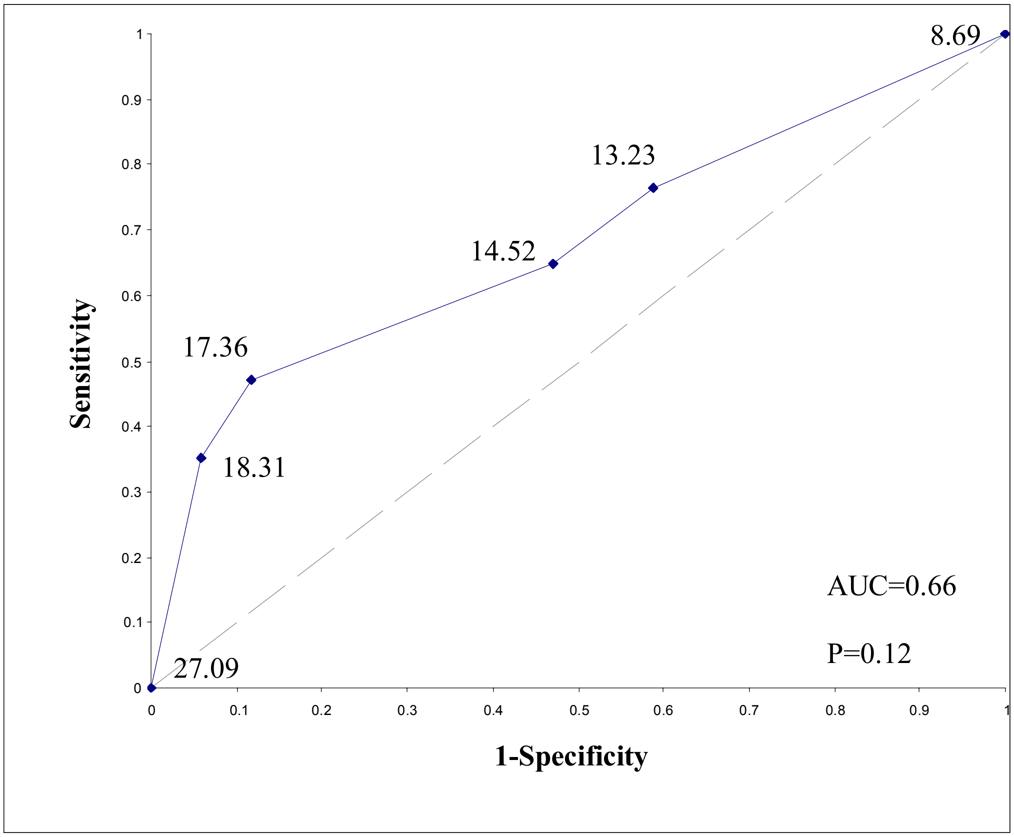


Figure-of-Eight Hop Test (s) Receiver Operating Characteristic Curve

DISCUSSION

Several static balance measures were found to be sensitive and accurate for detecting balance deficits associated with FAI. The foot lift test, time-in-balance test, center-of-pressure velocity, and anterior-posterior Time-to-Boundary standard deviation of the minima were all found to be sensitive and accurate measures. However, the foot lift test was the most sensitive and accurate static clinical balance test and also outperformed all other measures for detecting balance deficits associated with FAI. The cutoff score that should be applied clinically is 4.84 foot lifts; which means that subjects that lift their foot an average greater than or equal to 4.84 times during three trials will be categorized as having balance deficits associated with FAI. Furthermore, clinicians can include the time-in-balance test as part of their balance assessments. The cutoff score of 41.23 s was determined to be the best; however, scores on this test had to be converted for the ROC analysis. Therefore, a longer time indicated impaired balance when in fact shorter times indicate impaired balance. The cutoff score of 41.23 s actually converts to 28.83 s; which means that subjects that balance on a single leg with their eyes closed for less than or equal to 28.83 s will be categorized as having balance deficits associated with FAI.

The most sensitive and accurate static force plate measure for detecting balance deficits associated with FAI was center-of-pressure velocity. The cutoff score that should be applied clinically is 1.56 cm/s; which means that subjects that sway with a velocity greater than or equal to 1.56 cm/s on average between three twenty second trials will be categorized as having balance deficits associated with FAI. While not as accurate, anterior-posterior Time-to-Boundary standard deviation of the minima can also be included in balance assessments. The cutoff score of 3.72 s was determined to be the best; however, this measure also had to have its scores converted for the ROC analysis. Therefore, longer times indicated impaired balance when in fact shorter times indicate impaired balance. The cutoff score of 3.72 s actually converts to 3.83 s which means that subjects with a time less than or equal to 3.83 s on average between three twenty second trials will be categorized as having balance deficits associated with FAI.

Two dynamic measures were also found to be sensitive and accurate for detecting balance deficits associated with FAI. The posteromedial reach direction of the Star Excursion Balance test and the side hop test were both sensitive and accurate for detecting balance deficits. However, the posteromedial reach direction of the Star Excursion Balance test slightly outperformed the side hop test; and therefore, is the most sensitive and accurate dynamic balance measure for detecting balance deficits associated with FAI. The cutoff score that should be applied clinically is 0.91 (normalized to leg length); however, this measure also had to have its scores converted for the ROC analysis. Therefore, longer reach distances normalized to leg length indicated impaired balance when in fact short reach distances normalized to leg length indicate impaired balance. The cutoff score of 0.91 actually converts to 0.89 which means that subjects with a reach distance normalized to leg length less than or equal to 0.89 will be categorized as having balance deficits associated with FAI. Lastly, the side hop test can be included as part of dynamic balance assessments. The cutoff score of

12.88 s; which means that subjects that take a longer or equal amount of time of 12.88 s to complete the ten lateral hops will be categorized as having balance deficits associated with FAI.

Hypotheses

Our results supported our first hypothesis that the foot lift test would be the most sensitive and accurate static clinical balance measure for detecting balance deficits associated with FAI compared to the Balance Error Scoring System and time-in-balance test. However, our results did not support our second hypothesis that the Time-to-Boundary standard deviation of minima in the anterior-posterior direction would be the most sensitive and accurate static force plate balance measure for detecting balance deficits associated with FAI compared to center-of-pressure velocity and center-of-pressure area. We found that the center-of-pressure velocity was the most sensitive and accurate force plate balance measure for detecting balance deficits associated with FAI. Our results supported our third hypothesis that the Star Excursion Balance Test, specifically in the posteromedial direction, would be the most sensitive and accurate dynamic balance measure for detecting balance deficits associated with FAI compared to the anteromedial and medial reach directions of the Star Excursion Balance Test, figure-of-eight hop test, and side hop test. Lastly, our results did not support our fourth hypothesis that the Time-to-Boundary standard deviation of the minima in the anterior-posterior direction would be the most sensitive and accurate static or dynamic balance measure for detecting balance deficits associated with FAI.

Determining Clinical Meaningfulness

The posttest probability scores provide helpful information on how well a test identifies those with a history of ankle instability with a positive test result while minimizing negative results when an individual actually has FAI. Positive and negative posttest probabilities describe the probability of having FAI after a given test result. Whether or not these probabilities have clinical meaningfulness was dependent on the likelihood ratios associated with the posttest probabilities. Positive likelihood ratios ≥ 2 indicated that test results were sensitive and minimized the occurrence of identifying those without FAI as having FAI. Negative likelihood ratios ≤ 0.5 indicated that test results were specific and reduced the number of those with FAI being identified as healthy.[149, 150] Thus, an accurate test result distinguished a high proportion of individuals with ankle instability with a positive test (positive posttest probability) and a low proportion of individuals with ankle instability with a negative test (negative posttest probability). Lastly, meaningful likelihood ratios indicate that following the administration of a balance test there were significant changes in positive and negative posttest probability from pretest probability (i.e., prevalence).[149, 150] Therefore, a meaningful test indicates that clinicians may gain pertinent clinical information from employing a particular balance test.

Static Balance Measures

Foot Lift Test

Since the foot lift test was found to be significant, diagnostic parameters were calculated for this measure. First, the accuracy of this measure was "fair" with a score of 0.76 which may be due to the simplicity of this test; it evaluates only the foot. A score ≥ 4.84 foot lifts was identified as the "best" cutoff score for the foot lift test determined by the corresponding positive likelihood ratio (≥ 2) and negative likelihood ratio (≤ 0.5). Likelihood ratios indicate the change from the pretest probability to the positive and negative posttest probabilities. Our pretest probability was 50%. The positive posttest probability associated with a cutoff score ≥ 4.84 foot lifts was 0.80, indicating that the probability of having FAI was 80% in our subjects with positive test results. The negative posttest probability associated with a cutoff score of ≥ 4.84 foot lifts was 0.26, indicating that the probability of having FAI was 26% in our subjects who had a negative test result. As a result, the changes in positive and negative posttest probabilities from the pretest probability were small but significant. This change between pretest and posttest probabilities indicates that information gained by administering this single leg clinical balance test with foot lifts as the outcome measure was clinically relevant. This balance test was clinically significant because of its ability to identify a high proportion of individuals with a positive test who have FAI and a low proportion of individuals with a negative test who have FAI. We suggest the foot lift test with a cutoff score ≥ 4.84 foot lifts be included in an assessment protocol for FAI.

Our results agree with those reported by Hiller et al.,[16] in which is was found that healthy subjects with no history of ankle sprain injury lift the foot fewer times than those with a history of ankle sprain injury. Furthermore, our results support those of a recent meta-analysis in which it was found that the foot lift test had the largest standard difference of the mean than all other measures.[151] One reason the foot lift test may be more sensitive and accurate is due to its focus only on the foot. This makes sense when considering that the maintenance of upright posture involves three strategies in adults: the ankle, knee, and hip strategies. These joints are moved in a coordinated manner to maintain upright posture with the ankle being the primary joint used to control balance on a firm flat surface. People with FAI have been shown to change their postural control strategy from a predominantly ankle strategy to predominantly hip strategy.[152, 153] This could result in the ankle being held relatively still in the mediolateral direction to limit movements associated with an ankle sprain injury. The result of utilizing the hip strategy may mean that during single leg balance, the foot is lifted from the ground to counterbalance the shifts at the hip while people without injury can keep the foot flat and counterbalance the lateral shifts by control of subtalar ankle movement.[16] Therefore, one would expect those with FAI to lift the foot more often than those who have never sprained and have neuromuscular control of their ankle joint complex.

Time-in Balance Test

The time-in-balance test was found to be significant and therefore diagnostic parameters were also calculated for this measure. First, the accuracy of this measure was determined to be "fair" with a score of 0.73, which may be due to this test focusing on how long a subject can maintain their foot-to-ground contact before having to correct for an excessive sway. A score of $\geq$ 41.23 s was identified as the "best" cutoff score for the time-in-balance test determined by the corresponding positive likelihood ratio ($\geq$ 2) and negative likelihood ratio ($\leq$ 0.5). Likelihood ratios indicate the change from the pretest probability to the positive and negative posttest probabilities. Our pretest probability was 50%. The positive posttest probability associated with a cutoff score ≥ 41.23 s was 0.79, indicating that the probability of having FAI was 79% in our subjects with positive test results. The negative posttest probability associated with a cut off score ≥ 41.23 s was 0.30, indicating that the probability of having FAI was 30% in our subjects who had a negative test result. As a result, the changes in positive and negative posttest probabilities from the pretest probability were small but significant. This change between pretest and posttest probabilities indicates that information gained by administering this single leg clinical balance test with time as the outcome measure was clinically relevant. This balance test was clinically significant because of its ability to identify a high proportion of individuals with a positive test who have FAI and a low proportion of individuals with a negative test who have FAI. We suggest the time-in-balance test with a cutoff score ≥ 41.23 s be included in an assessment protocol for FAI.

Our results agree with those reported by Chrintz et al.,[13] in which it was reported that those without a history of ankle injury were able to stand on a single leg with their eyes closed significantly longer than those with FAI. Our results also support those found by Arnold et al.,[151] in which it was found that within the static measures analysis, the time-in-balance test out performed all static and dynamic balance measures with the exception of the foot lift test. We believe that this test may be sensitive and accurate because, as mentioned before, those with FAI are more likely to use a hip strategy in order to maintain their balance.[152] The result of using this strategy may mean that during single leg balance, the foot is lifted from the ground to counterbalance the shift at the hip leading to a loss of balance; while people without injury can keep the foot flat and maintain their upright posture.[16]

Time-in-balance scores had to be converted in our analysis for longer times to be indicative of impaired balance. However, in the literature, shorter times are indicative of impaired balance. Our cutoff score of 41.23 s converts to a shorter time of 28.83 s meaning that individuals who score less than 28.83 s have impaired balance.

Center-of-Pressure Velocity

Center-of-pressure velocity was found to be significant; therefore, diagnostic parameters were also calculated for this measure. First, the accuracy of this measure was "fair" with a score of 0.72 which may be due to the spatiotemporal characteristic of this test. A score ≥ 1.56 cm/s was identified as the "best" cutoff score for center-of-pressure velocity determined by the corresponding positive likelihood ratio (≥ 2) and negative likelihood ratio (≤ 0.5). Likelihood ratios indicate the change from the pretest probability to the positive and negative posttest probabilities. Our pretest probability was 50%. The positive posttest probability associated with a cutoff score ≥ 1.56 cm/s was 0.68, indicating that the probability of having FAI was 68% in our subjects with a positive test result. The negative posttest probability associated with a cutoff score ≥ 1.56 cm/s was 0.27, indicating that the probability of having FAI was 27% in our subjects who had negative test results. As a result, the changes in positive and negative posttest probabilities from the pretest probability were small but significant. This change between pretest and posttest probabilities indicates that information gained by administering this single leg force plate balance test with center-of-pressure velocity as the outcome measure was clinically relevant. This force plate measure was clinically significant because of its ability to identify a high proportion of individuals with a positive test who have FAI and a low proportion of individuals with a negative test who have FAI. We suggest the center-of-pressure velocity measure with a cutoff score ≥ 1.56 cm/s be included in an assessment protocol for FAI if a force plate is available.

Our results support the study conducted by Hertel et al.[26] that found injured subjects have significantly higher center-of-pressure velocity values than a control group. Furthermore, it has been reported that higher center-of-pressure velocity values correspond with increased risk for ankle sprains.[20] Ross et al[154] also found anterior-posterior and medial-lateral center-of-pressure velocity means to discriminate between ankles with FAI and those that were stable. In another study, Ross et al[155] found center-of-pressure velocity to discriminate between those with a history of FAI and those with stable ankles better than center-of-pressure area and the Balance Error Scoring System. We found that the center-of-pressure velocity measure was a sensitive and accurate measure for detecting balance deficits associated with FAI. However, we expected the anterior-posterior Time-to-Boundary to be more sensitive and accurate due to the promising results reported by Hertel et al.[15] Yet our velocity results are advantageous because most software programs used with force plates calculate center-of-pressure resultant velocity for clinicians; while any Time-to-Boundary measure requires a custom software program.

Anterior-Posterior Time-to-Boundary Standard Deviation of the Minima

The anterior-posterior Time-to-Boundary standard deviation of the minima was found to be significant; therefore, diagnostic parameters were also calculated for this measure. First, the accuracy of this measure was "poor" with a score of 0.69 which may be due to the way in which this measure is calculated only using minima data points. A score ≥ 3.72 s was identified as the "best" cutoff score for anterior-posterior Time-to-Boundary standard deviation of the minima determined by the corresponding positive likelihood ratio (≥ 2) and negative likelihood ratio (≤ 0.5). Likelihood ratios indicate the change from the pretest probability to the positive and negative posttest probabilities. Our pretest probability was 50%. The positive posttest probability associated with a cutoff score ≥ 3.72 s was 0.67, indicating that the probability of having FAI was 67% in our subjects with positive test results. The negative posttest probability associated with a cutoff score ≥ 3.72 s was 0.31, indicating that the probability of having FAI was 31% in our subjects who had negative test results. As a result, the changes in positive and negative posttest probabilities from the pretest probability were small but significant. This change between pretest and posttest probabilities indicates that information gained by administering this single leg force plate balance test with time as the outcome measure was clinically relevant. This force plate measure was significant because of its ability to identify a high proportion of individuals with a positive test who have FAI and a low proportion of individuals with a negative test who have FAI. We suggest the anterior-posterior Time-to-Boundary standard deviation of the minima measure with a cutoff score ≥ 3.72 s be included in an assessment protocol for FAI if a force plate and custom software are available.

Our results support some of the findings in the Hertel et al.[15] study in which it was found that the anterior-poster Time-to-Boundary standard deviation of the minima was able to detect balance differences between injured and healthy subjects. Furthermore, our results also support the findings in the McKeon et al.[27] study that Time-to-Boundary measures can detect balance differences between those with a history of ankle injury and those without a history of ankle injury. However, we did not find the Time-to-Boundary measure to be better than other center-of-pressure measures. The Time-to-Boundary measure is a theoretical calculation that estimates the time it would take for the center-of-pressure to reach the boundary of the base of support if the center-of-pressure was to continue on its trajectory at its instantaneous velocity.[15] The calculation of this measure is inherently linked to center-of-pressure velocity measures because center-of-pressure velocity is included in the equation to calculate time-to-boundary. Researchers have indicated that Time-to-Boundary impairments associated with FAI indicates that while FAI subjects were controlling their balance they were doing so in a manner that placed the center-of-pressure closer to the limits of stability, in the time domain, compared to the uninjured group.[15, 27] In other words, their postural control system operated in a manner that placed them nearer in time to episodes of potential loss of balance than controls. Researchers have suggested that anterior-posterior Time-to-Boundary standard deviation of the minima provides more insight into the spatiotemporal aspects of postural control than do traditional center-of-pressure based measures such as center-of-pressure resultant velocity because it takes into account the rate of displacement of the center-of-pressure and the direction of center-of-pressure excursions in relation to the boundaries of the foot.[15] However, these differences did not result in a more sensitive or accurate measure for detecting balance deficits associated with FAI compared to center-of-pressure resultant velocity in our study. According to Hertel and Olmsted-Kramer,[15] the most important difference between Time-to-Boundary measures and center-of-pressure velocity is that center-of-pressure velocity represents the mean of all center-of-pressure excursions from an entire trial, while Time-to-Boundary measures are based only on those select data points that yield minima during each trial. Conversely, our results suggest that removing all data points other than the minima points may be causing this measure to lose sensitivity and accuracy for detecting balance deficits associated with FAI.

Time-to-Boundary scores had to be converted in our analysis for longer times to be indicative of impaired balance. However, in the literature, shorter times are indicative of impaired balance. To align our cutoff score of 3.72 s with the literature, we converted back to 3.83 s to indicate that individuals who score less than 3.83 s have impaired balance.

Center-of-Pressure Area

Center-of-pressure area was not subjected to additional diagnostic parameter calculations because the area under the curve was not statistically significant. We speculate that center-of-pressure area was an inaccurate test because of the lack of the time components in its calculation. This variation from center-of-pressure velocity and Time-to-Boundary measures may have desensitized this measure in detecting differences between FAI and stable ankles. We suggest using other force plate measures such as center-of-pressure velocity and Time-to-Boundary standard deviation of the minima would be more useful in an evaluation protocol for FAI when a force plate is available.

Center-of-pressure area was the only static force plate measure that was not sensitive or accurate for detecting balance impairments associated with FAI. Our results support those presented by Tropp et al.[142] in which significantly greater center-of-pressure area values for soccer players with FAI were not found. Our results also support those presented by Arnold et al.[151] in which area values were the only static balance measure not to produce significant standard difference of the mean results. In addition, Ross et al.[155] did not find the center-of-pressure area measure to discriminate between ankle groups. The center-of-pressure area (95% confidence ellipse) can be simplified and thought of as the area that the center-of-pressure traverses during a balance trial; however, it eliminates extreme center-of-pressure points in the data set. The center-of-pressure area measure is not a time dependent measure while the other two force plate measures are time dependent; meaning to calculate this measure a distance is not divided by a particular time period. This component may explain its lack of significant results. The important factor may not be the actual area that FAI subjects travel, but the time in which a postural correction is made compared to those with stable ankles.

Balance Error Scoring System

The Balance Error Scoring System was not subjected to additional diagnostic parameter calculations because the area under the curve was not statistically significant. We speculate that the Balance Error Scoring System was an inaccurate test because of the difficulty of the single limb foam and tandem foam conditions for all subjects. This difficulty may have desensitized this measure in detecting differences between FAI and stable ankles. We suggest testing whether the removal of those trials improves sensitivity and accuracy of this measure.

Our results contradict those from Docherty et al.,[14] in which it was concluded that the Balance Error Scoring System may be useful in screening athletes for balance deficits following lower extremity injury. We have found that other clinical tests may be easier to use and assess. Furthermore, our results did not find a significant difference in total Balance Error Scoring System scores between our groups. Yet, Docherty et al.,[14] did find a significant difference in total Balance Error Scoring System scores between groups; 15.7 ± 6.0 errors in the injured group versus 10.7 ± 3.2 errors committed by the healthy group. We believe that our insignificant finding for sensitivity and accuracy is related to the difficulty of completing the single-limb foam and tandem foam trials. Those with and without ankle instability had great difficulty with these tasks. In performing further analysis on our data with a one-way ANOVA, no statistical difference was found for either of the single-limb foam ($F_{(1,32)}$=1.045, P=0.314) or tandem foam trials ($F_{(1,32)}$=1.451, P=0.237) between our groups. This means that subjects with and without ankle instability committed a similar amount of errors during these two trials. Many subjects experienced difficulty when simply positioning themselves in the testing positions on top of the foam surface during these two trials. Future research may want to remove these two trials from the Balance Error Scoring System when determining FAI status.

Dynamic Balance Measures

Star Excursion Balance Test

The Star Excursion Balance Test in the posteromedial reach direction was found to be significant; therefore, diagnostic parameters were also calculated for this measure. First, the accuracy of this measure was "fair" with a score of 0.71 which may be due to the lack of apprehension felt by participants while performing this reach direction compared to other reach directions. A score ≥ 0.91 reach distance/leg length was identified as the "best" cutoff score for posteromedial reach direction of the Star Excursion Balance Test determined by the corresponding positive likelihood ratio (≥ 2) and negative likelihood ratio (≤ 0.5). Likelihood ratios indicate the change from the pretest probability to the positive and negative posttest probabilities. Our pretest probability was 50%. The positive posttest probability associated with a cutoff score $\geq$ 0.91 reach distance/leg length was 0.69, indicating that the probability of having FAI was 69% in our subjects with positive test results. The negative posttest probability associated with a cutoff score ≥ 0.91 reach distance/leg length was 0.33, indicating that the probability of having FAI was 33% in our subjects who had negative test results. As a result, the changes in positive and negative posttest probabilities from the pretest probability were small but significant. This change between pretest and posttest probabilities indicates that information gained by administering this single leg dynamic balance test with reach distance normalized to leg length as the outcome measure was clinically relevant. The posteromedial reach direction of the Star Excursion Balance Test was clinically significant because of its ability to identify a high proportion of individuals with a positive test who have FAI and minimize the proportion of individuals with a negative test who have FAI. We suggest the posteromedial reach direction of the Star Excursion Balance Test with a cutoff score ≥ 0.91 reach distance/leg length be included in an assessment protocol for FAI.

Our results support those reported by Hertel et al. [29] in which it was found that the posteromedial reach direction of the Star Excursion Balance Test could detect balance differences between those with a history of ankle injury and those who do not. It was found in several studies that those without a history of ankle injury reached further than those with a history of ankle injury.[29, 132, 133] It was not surprising to us that the posteromedial reach direction of the Star Excursion Balance Test was a sensitive and accurate measure for detecting balance deficits associated with FAI. It had been reported that the posteromedial reach direction was the most representative of the overall performance of the Star Excursion Balance Test in limbs with and without ankle instability.[29] Furthermore, maintaining single-leg stance while performing maximum reach with the opposite leg requires the stance leg to have sufficient ankle, knee, and hip motion.[133] Following a lateral ankle sprain, joint injury resulting in decreased motion in the talocrural or subtalar joint may affect performance on the Star Excursion Balance Test.[133] Olmstead et al.[133] also mentioned that subject apprehension may be the most critical performance-inhibiting factor. Many of their subjects with ankle instability reported feelings of apprehension when performing reaches while balancing on the injured limbs.[133] Several of our subjects with FAI reported similar feelings.

However, we did not find the anteromedial or medial reach directions of the Star

Excursion Balance Test to be able to detect balance deficits associated with FAI. Yet, at least one of these studies did not normalize to height or leg length and they pooled the scores from both legs on all reach directions to derive a composite score.[133] As mentioned above, feelings of apprehension were mentioned while completing the anteromedial and medial reach directions. Subjects with both stable and unstable ankles reported awkwardness, difficulty, and or uneasiness while reaching in the anteromedial and medial directions. Due to these reported feelings, we believe subjects with stable ankles appeared more unstable because of a lack of effort due to apprehension. Yet, subjects with both stable and unstable ankles reported ease and comfort while reaching in the posteromedial direction; therefore, true differences could be detected between groups based on ankle status without feelings of apprehension.

The anteromedial and medial reach directions of the Star Excursion Balance Test were not subjected to additional diagnostic parameter calculations because the areas under the curves were not statistically significant. We speculate that the anteromedial and medial reach directions of the Star Excursion Balance Test were inaccurate tests primarily because of the apprehension reported by subjects when reaching in these two directions. These feelings of apprehension may have desensitized this measure in detecting differences between FAI and stable ankles. We suggest including the posteromedial reach direction rather than the anteromedial and medial reach directions when evaluating for FAI.

Star Excursion Balance Test scores for each reach direction had to be converted for our analysis for longer reach distances to be indicative of impaired balance.

However, in the literature, shorter reach distances are indicative of impaired balance. Our posteromedial reach direction cutoff score of 0.91 converts to a shorter reach score (normalized to leg length) of 0.89, meaning that individuals who score less than 0.89 (normalized to leg length) have impaired balance.

Side Hop Test

The side hop test was found to be significant; therefore, diagnostic parameters were also calculated for this measure. First of all, the accuracy of this measure was "fair" with a score of 0.70 which may be a result of the lateral movements which correspond to the typical mechanism of a lateral ankle sprain. A score ≥ 12.88 s was identified as the "best" cutoff score for the side hop test determined by the corresponding positive likelihood ratio (≥ 2) and negative likelihood ratio (≤ 0.5). Likelihood ratios indicate the change from the pretest probability to the positive and negative posttest probabilities. Our pretest probability was 50%. The positive posttest probability associated with a cutoff score ≥ 12.88 s was 0.79, indicating that the probability of having FAI was 70% in our subjects with positive test results. The negative posttest probability associated with a cutoff score ≥ 12.88 s was 0.30, indicating that the probability of having FAI was 30% in our subjects who had negative test results. As a result, the changes in positive and negative posttest probabilities from the pretest probability were small but significant. This change between pretest and posttest probabilities indicates that information gained by administering this single leg dynamic balance test with time as the outcome measure was clinically relevant. The side hop test was clinically significant because of its ability to identify a high proportion of individuals with a positive test who have FAI and a low proportion of individuals with a negative test who have FAI. We suggest the side hop test with a cutoff score ≥ 12.88 s be included in an assessment protocol for FAI.

Our results support those reported by Docherty et al.[31] in which a positive relationship was found to exist between FAI and performance deficits on the side hop test. We found the side hop test to be a sensitive and accurate measure for detecting balance deficits associated with FAI. It has been suggested that the side hop test identifies differences between groups because it forces the participants to move laterally, placing stress on the structures on the lateral aspect of the leg, including the lateral ligaments and peroneus muscle complex.[31] This is important because a typical mechanism of injury for an ankle sprain is lateral movement causing hypersupination of the ankle. Thus, our findings along with Docherty et al.'s[31] suggest that dynamic tests that place lateral stress on the ankle reveal balance deficits in participants with FAI.

Figure-of-Eight Hop Test

The figure-of-eight hop test was not subjected to additional diagnostic parameter calculations because the area under the curve was not statistically significant. We speculate that the figure-of-eight hop test was inaccurate because of the variable sizes of hops taken by subjects and the discomfort felt while completing the task. These feelings of discomfort and variable sizes of hops may have desensitized this measure in detecting differences between FAI and stable ankles. We suggest testing whether or not specifying how far in which a subject should hop and possibly testing on a more comfortable surface or wearing shoes could improve the sensitivity and accuracy of this dynamic balance measure.

Our results contradict those reported by Docherty et al.[31] in which a positive relationship was found to exist between FAI and performance deficits on the figure-of-eight hop test. The results of this study indicate that the figure-of-eight hop test was not able to detect balance deficits associated with FAI. A possible explanation for our results was the distances used by subjects to hop. Some subjects took larger hops in order to speed up their testing times. Another explanation could be the way in which subjects landed while performing the test. Some subjects were able to hop and then land lightly on their feet, while others landed quite hard on their feet. Some subjects reported discomfort while completing this test. In future studies, I would suggest instructing subjects to take a normal hop, not the largest hop possible. I would also suggest completing this measure wearing shoes, to prevent any discomfort.

Accuracy Classification

Our results do not have any accuracy classifications above "fair". This may be a result of balance only being one component of FAI. There are other categories of tests specific to such measures as strength and proprioception. Having a "fair" accuracy test is still acceptable. Most diagnostic tests do not have "excellent" accuracy. In order to combat this issue it is common for multiple tests to be employed. A clinician would commonly employ parallel testing, which means multiple tests that assess a certain outcome variable (e.g., balance) are given at once.[149] A positive test result of any test is considered evidence for the presence of FAI. Parallel testing generally increases the sensitivity and, therefore, the negative predictive value for a given condition prevalence, above those of each individual test.[149] But, specificity and positive predictive values are lower than for each individual test.[149] Meaning we are more likely to identify those without FAI as having FAI. However, due to the nature of our condition of interest, FAI, not being a life or death situation, treatment for FAI without having the condition should not harm the patient. Therefore, we suggest clinicians employ a parallel testing method with the use of our significant balance measures to identify those with balance deficits associated with FAI.

Clinical Balance Measures vs. Force Plate Measures

A prime component of any clinical setting is the budget. Therefore, clinical directors want to cut costs wherever possible without compromising the healthcare of their patients. Clinical measures have the advantage of requiring little equipment and therefore keep costs down. However, the question arises whether force plate measures are in fact better than clinical measures and therefore warrant the cost of the equipment. The cost of the equipment includes the force plate, computer, and software. According to our results the foot lift test and time-in-balance test, which are static clinical balance measures, are more sensitive and accurate at detecting balance deficits associated with FAI than all three of the force plate measures. The posteromedial reach direction of the Star Excursion Balance Test and the side hop test, which are dynamic clinical balance measures, were also found to be more sensitive and accurate at detecting balance deficits associated with FAI than the Time-to-Boundary standard deviation of the minima and center-of-pressure area force plate measures. These two dynamic clinical balance measures, however, were not more sensitive and accurate than the center-of-pressure velocity force plate measure for detecting balance deficits associated with FAI. A secondary component to a clinic's budget is the cost in time for clinicians to administer testing, including calculating results. Clinical measures again have the advantage of being quick and easy to administer and calculate results. Force plate measures are also typically easy to administer yet can be difficult and time consuming to calculate results. Therefore, we recommend using the foot lift test, time-in-balance test, posteromedial reach direction of the Star Excursion Balance Test, and the side hop test due to the ease of use, ease of calculating results, and our significant findings. Yet, if a larger budget is available, then we recommend using center-of-pressure velocity and anterior-posterior Time-to-Boundary measures in addition to the aforementioned clinical measures.

Static vs. Dynamic Measures

Balance testing began with a stationary measure of postural control. Static postural control is the ability to remain as still as possible while maintaining one's balance over a stable base of support.[133] Through the years researchers have added different stances, surfaces, and eye conditions in which to make the testing more challenging. Some authors have suggested that static single leg balance tests may not be sensitive enough to detect motor-control deficits related to balance performance, and that dynamic tests may provide better means of identifying functional deficits related to balance performance in subjects with FAI.[28, 29, 30] Dynamic postural stability has been defined as the extent to which a person can lean or reach without moving the feet and still maintain balance.[156] Maintenance of balance during dynamic movements involves the ability to keep the center-of-gravity over the stable base of support without losing one's balance.[157] Traditionally, dynamic tests were often used during the latter stages of rehabilitation and as criteria to determine return-to-play decisions. These tests are helpful because they combine multiple components, such as muscular strength, neuromuscular coordination, and joint stability, which could be affected after joint injury. More recently, ability of dynamic tests to detect functional performance deficits in participants with knee or ankle joint injuries has been investigated.[31] These researchers concluded that a positive relationship existed between FAI and performance deficits on two dynamic balance measures, the side hop and figure-of-eight hop tests.[31] Ross et al.[154] found the medial-lateral ground reaction force standard deviation, a static balance measure, to be more accurate than dynamic measures of balance at discriminating between ankle groups. In a recent meta-analysis researching whether ankle instability is associated with balance impairments, it was found that there was no difference between static and dynamic measures of balance, yet with a rather low p value of $p=0.063$.[151] The authors suggest that due to the conservative statistical analysis completed that there may truly be a difference between the two types of tests, with static measures actually outperforming dynamic measures.[151] Therefore, their suggestion was to focus on easy to administer static balance tests such as the foot lift test and time-in-balance test.[151] Our results also indicate that static balance measures are more accurate at detecting balance deficits associated with FAI. We suggest focusing on using static balance measures such as the foot lift test, time-in-balance test, and center-of-pressure velocity measure, which have shown to be slightly more accurate than the posteromedial reach direction of the Star Excursion Balance Test and side hop test.

Contribution of Causal Factors of FAI to Balance Impairments

Neuromuscular control is one of the causal factors of FAI. One way in which to detect neuromuscular control deficits is through autogenic muscle inhibition, which is defined as altered afferent output from joint mechanoreceptors following injury or effusion.[122] Autogenic muscle inhibition is measured by the H-reflex/M response ratio. A diminished H-reflex/M response ratio has been found in the peroneus longus muscle of individuals who have FAI.[122, 158] Incomplete activation of the peroneus longus could prevent adequate control of the ankle.[122, 158] Decreased muscle activity of the peroneus longus could lead to more episodes of giving way or sprains because of its role in counteracting the inversion movement typical of a lateral ankle sprain. Furthermore, what may be more interesting is that autogenic muscle inhibition of the hamstrings and increased alpha motoneuron pool excitability of the quadriceps muscles have also been reported among those who have FAI.[124] The lack of typical coordination between the hamstrings and quadriceps muscles could lead to the large shifts at the hips, because it has been shown that those with FAI use a hip strategy to balance rather than an ankle strategy. These large shifts at the hips often lead to a loss of balance in those with FAI. But what is interesting about the presence of autogenic muscle inhibition of the hamstrings and altered alpha motoneuron excitability of the quadriceps muscles is that these muscles are proximal to the injured joint, which supports the theory of a central mediated impairment.

Research has also shown the presence of bilateral postural control deficits with FAI, which again provides obvious evidence of central changes in neuromuscular control.[104] For example, increased center of pressure excursion velocity measures, on not only the limb with an acutely sprained ankle, but also on the contralateral uninjured limb has been discovered.[125] Furthermore, significant decreases in vibration perception and significant delays in gluteus maximus muscle recruitment during hip extension has also been found in those who suffered a severe unilateral ankle sprain.[126] These examples suggest that unilateral ankle sprains result in not only local sensorimotor deficits, but also centrally mediated impairments.[125, 126] This information combined with evidence of altered alpha motoneuron pool excitability of the hamstring and quadriceps muscles in individuals who have FAI indicates that spinal level motor control mechanisms are clearly altered[104] and could lead to balance deficits associated with FAI.

While performing the side hop test, if autogenic muscle inhibition of the peroneus longus is present then the difficulty of the task leading to longer time trials is understandable. Also, while performing the Star Excursion Balance Test, specifically the posteromedial reach direction, if a significant delay in guteus maximus muscle recruitment and autogenic muscle inhabitation of the hamstrings are in fact present, this could lead to the reach deficits demonstrated by those with FAI in this direction.

Proprioception is a component of neuromuscular control. Proprioception is the cumulative neural input to the central nervous system, from mechanoreceptors in the joint capsules, ligaments, muscles, tendons and skin.[28] The proprioceptive information conveyed to the spinal cord eventually results in excitation or inhibition of motor neurons.[28] Simplified, proprioception allows for the sensation of body movement and position in space.[28] The assessment of joint proprioception can primarily be divided into three components, kinesthesia, joint position sense, and force sense. Research has shown deficits in the detection of passive plantar flexion[111, 112] and inversion[90] within an injured ankle joint when compared to the non-injured ankle joint. Research has also reported deficits in active replication of joint position in the inversion range of motion[117] and deficits in passive replication of joint position in the plantar flexion range of motion[118] in subjects that have experienced recurrent lateral ankle sprains. These deficits in joint position sense could lead to further inversion ankle sprains because the normal stride depends on a very accurate sense of joint proprioception. In the late swing phase where the center of gravity has passed the supporting foot, the swing phase foot passes just 5 mm above the ground.[159] Inappropriately judging the amount of ankle inversion in this phase may cause the lateral part of the foot to hit the ground, creating an ankle inversion torque.[159] In addition, subjects who had unilateral FAI, demonstrated diminished eversion force sense between their involved and uninvolved ankles.[119, 120] The proprioceptive deficits identified in kinesthesia, joint position sense and force sense, indicate that it is likely that there are afferent proprioceptive deficits associated with ankle instability.[104]

We believe decreases in proprioception are what are leading to the increased trial times when employing our Time-to-Boundary measure and center-of-pressure velocity measure. Researchers have indicated that Time-to-Boundary and center-of-pressure velocity impairments associated with FAI indicates that while FAI subjects were controlling their balance they were doing so in a manner that placed the center-of-pressure closer to the limits of stability, in the time and velocity domains, compared to the uninjured group.[15, 27] In other words, their postural control system operated in a manner that placed them nearer in time and velocity to episodes of potential loss of balance than controls. If those with FAI could better sense their body position in space they would be less apt to be nearer a potential loss of balance. Furthermore, we believe that decreases in proprioception are what are leading people with FAI to change their postural control strategy from a predominantly ankle strategy to predominantly hip strategy. This could result in the ankle being held relatively still in the mediolateral direction to limit movements associated with an ankle sprain injury due to a lack of neural input. The result of utilizing the hip strategy may mean that during single leg balance, the foot is lifted from the ground to counterbalance the shifts at the hip while people without injury can keep the foot flat and counterbalance the lateral shifts by control of subtalar ankle movement.[16] Therefore, one would expect those with FAI to lift the foot more often than those who have never sprained and have neuromuscular control of their ankle joint complex. Those with FAI are also more likely to counterbalance these shifts at the hip which leads to lifting of the foot which will then lead to a loss of balance. These three examples explain our results from our foot lift test, time-in-balance test, Time-to-Boundary measure, and center-of-pressure velocity measure.

Two distinct theories regarding the relationship between muscle weakness and FAI have been proposed. The first theory suggested that the evertors must be strong enough to counter the inversion mechanism associated with a lateral ankle sprain.[87] This theory can be explained by when the foot and ankle are suddenly forced into inversion a strong concentric response on the part of the evertors must resist the inversion lever and prevent the sprain.[87] This theory has been supported by several studies in which eversion strength deficits were found in those with a history of ankle instability.[45, 52, 94, 97] The second theory involves eccentric control of the ankle invertors in an attempt to counter the lateral displacement of the lower leg during closed chain activities.[44, 93] Several studies in which inversion strength deficits were found in those with FAI compared to a control group support this theory. [52, 96, 98] More specifically, by the invertors acting eccentrically this may assist in controlling lateral postural sway by limiting closed chain eversion.[44] Closed chain eversion involves lateral displacement of the lower leg over the weight-bearing foot, whereas closed chain inversion involves medial displacement of the lower leg over the fixed foot.[160] When the center of mass is displaced laterally over a fixed foot with both its medial and lateral borders affixed to the ground, the lower leg moves laterally resulting in closed chain eversion.[161] Once the center of mass is moved beyond the lateral border of the foot and the limit of closed chain eversion is reached, the medial border of the foot begins to lift from the ground resulting in the foot being forced into rapid inversion.[44] If excessive lateral displacement of the lower leg outside the weight-bearing foot can be limited by the ankle invertors acting eccentrically to control closed chain eversion, this could prevent the medial border of the foot lifting from the ground and thus prevent the foot being forced in rapid inversion.[44] If invertor muscles are weak eccentrically, their role in dynamic stabilization may be impaired.[161] Thus, in a closed kinetic chain, invertor weakness may contribute to the symptoms of giving way associated with FAI.[161] Or if the rapid inversion moment can be counteracted by concentric contraction of the peroneals, this could prevent excessive inversion. If evertor muscles are weak concentrically, their role in dynamic stabilization may be impaired. Thus, in a closed kinetic chain, evertor weakness may contribute to the symptoms of giving way associated with FAI. Therefore, no matter the theory, strength appears to be a contributing factor to balance deficits associated with FAI.

It has been suggested that the side hop test identifies differences between groups because it forces the participants to move laterally, placing stress on the peroneal muscles.[31] If evertor muscle weakness is present then the inversion moment cannot be overcome, therefore placing the ankle in a vulnerable position. Thus, it is no wonder those with FAI have difficulty hopping side to side which therefore leads to longer trial times.

Limitations

Several limitations exist with this current study. One limitation that could have affected our results was that tradition study designs match subjects with FAI to subjects with stable ankles; therefore, creating a prevalence of fifty percent. This can increase the pre to post test probability difference potentially creating an artificial significant probability change. However, we do not expect this change to be great because of the small number of subjects included in our study.

Another potential limitation could have been that subjects with stable ankles may have poor balance. Furthermore, subjects with a history of ankle sprains may have learned to compensate for their proneness to injury and produced balance results more closely related to those of healthy subjects.

Timed tests could be controlled with an automated timing device rather than a stopwatch controlled by an examiner. There is a reaction time delay between when the examiner evaluates the subject to have completed a task and when he or she can stop the timer. An automated timing device would provide exact finishing times for the time-in-balance test, side hop test, and figure-of-eight hop test, controlled by the subject. However, the use of an automated timing device may reduce the ease of administration in the clinical setting.

Clinical Significance

The focus of this study was to determine the balance measure most sensitive and accurate in detecting balance deficits associated with FAI. Discovering that the foot lift test was the most sensitive and accurate measure has implications for improving balance testing related to ankle instability research and improving screening tools for ankle instability in the clinical setting. The employment of a common method of balance testing during research will allow future studies to be compared between populations. Our study included subjects that were between the ages of 18 and 40 and were physically active. It would be beneficial to know if the same results are found in children, elderly, and/or obese populations. While the foot lift test was the most sensitive and accurate measure for detecting balance deficits associated with FAI, other tests were found to be significant. The time-in-balance test is another static clinical balance measure found to discriminate between ankle groups. Two static force plate measures found to detect balance deficits associated with FAI were center-of-pressure velocity and anterior-posterior Time-to-Boundary standard deviation of the minima. Two dynamic balance measures found to discriminate between ankle groups were the posteromedial reach direction of the Star Excursion Balance Test and the side hop test. Clinically, therapists can now utilize the quick and easy foot lift test, time-in-balance test, posteromedial reach direction of the Star Excursion Balance Test, and the side hop test, which are all sensitive and accurate for detecting balance deficits. Static force plate measures can also be used in balance assessments if clinicians have easy access to a force plate. Clinicians can also utilize the cutoff scores corresponding to each of the measures in order to categorize subjects as having balance deficits associated with FAI; therefore, providing a more comprehensive evaluation in the hopes of correcting these impairments to prevent future ankle injury.

Conclusion

In conclusion, clear evidence exists that ankle sprains are one of the most common injuries acquired by physically active individuals. Furthermore, ankle sprains frequently result in a condition known as FAI. FAI is characterized with frequent giving-way of the ankle, which at best is an annoyance and is often an occupational handicap. FAI is also associated with balance deficits. However, several types of testing that assess balance exist, such as static and dynamic measures. We have found that the foot lift test, a static clinical balance measure, is the most sensitive and accurate measure to detect balance deficits associated with FAI. More specifically, we have found that the foot lift test is the most sensitive and accurate static clinical balance measure to detect balance deficits associated with FAI. We have found the center-of-pressure velocity measure to be the most sensitive and accurate static force plate measure to detect balance deficits associated with FAI. We have found the posteromedial reach direction of the Star Excursion Balance Test to be the most sensitive and accurate dynamic balance measure to detect balance deficits associated with FAI. If we combine the foot lift test, center-of-pressure velocity test, and posteromedial reach direction of the Star Excursion Balance Test into one screening tool we can improve the sensitivity and accuracy in detecting balance deficits associated with FAI. By combining these tests we increase the sensitivity and therefore the negative predictive value for FAI above those of each individual balance test. Meaning, FAI is less likely to be missed by an evaluation.

In the future, I would like to conduct a prospective study employing the foot lift test which we found to be the most sensitive and accurate balance measure for detecting balance deficits associated with FAI and its cutoff score of 4.84 foot lifts to determine injury risk ratios. In addition, I would like to determine the cost effectiveness of utilizing the foot lift test and its cutoff score for delivery of preventative treatments. Preventative treatment is a primary focus of an athletic trainer and any improvement in this area can have long lasting benefits.

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APPENDIX A

Diagrams of Dynamic Balance Measures

Star Excursion Balance Test Reach Direction Diagram

Left Limb Stance **Right Limb Stance**

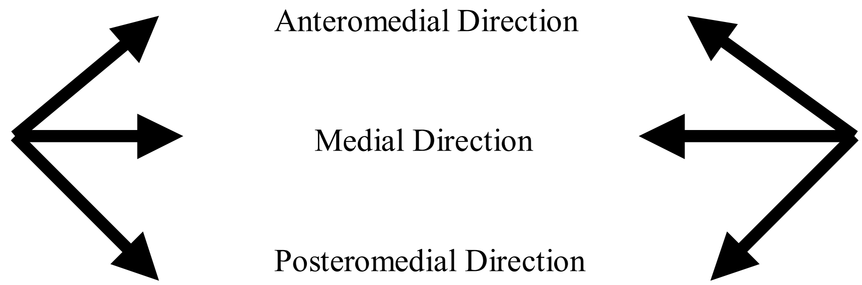
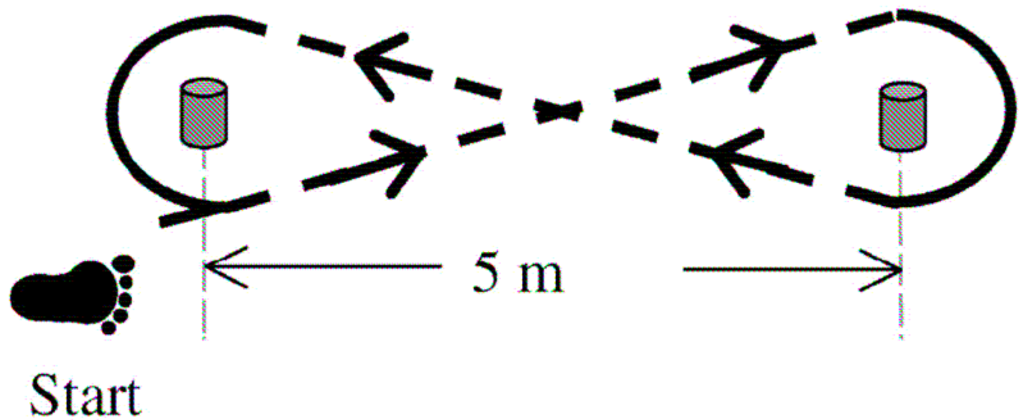


Figure-of-Eight Hop Test Diagram (Adapted from Docherty et al. 2005)



Side-Hop Test Diagram (Adapted from Docherty et al. 2005)

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