COMPARING MEASURES OF ANKLE PROPRIOCEPTION, STRENGTH, AND POSTURAL STABILITY IN MALE SOCCER PLAYERS WITH AND WITHOUT CHRONIC ANKLE INSTABILITY AS A RESULT OF NON-CONTACT LATERAL ANKLE SPRAINS

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Ankle injuries are common in a wide variety of individuals, ranging from physically-active students to ballet dancers, and from college athletes to military personnel. It has been estimated that nearly 28,000 ankle injuries occur in the United States each day. If specific laboratory measurements can be shown to be sensitive enough to detect differences between healthy controls (CON) and individuals with chronic ankle instability as a result of lateral ankle sprains (CAI-LAS), those measures can be utilized in assessments of injury risk, assist in monitoring rehabilitation from injury, and be incorporated as measures of potential improvement in training interventions. The purpose of this study was to examine if differences in laboratory measures of ankle flexibility, proprioception, strength, and postural stability existed in soccer players, with and without chronic ankle instability. The laboratory measurements for this study included ankle range of motion (ROM), the Star Excursion Balance Test (SEBT), lower leg musculature size, threshold to detect passive motion (TTDPM), strength, time to peak torque (TTPT), static postural stability, and dynamic postural stability. ROM was significantly worse ($p \leq 0.039$) in CAI-LAS. Performance on the SEBT was significantly lower for the anterior reach ($p \leq 0.040$), posteromedial reach ($p \leq 0.016$), and composite score ($p = 0.018$). Inversion TTDPM was 56.5% worse in CAI-LAS compared to CON ($p = 0.016$). There was not a statistically significant

difference ($p = 0.181$) for eversion TTDPM, however CAI-LAS had 24.1% greater error. There were no significant differences reported between the groups for musculature size, strength, TTPT, or postural stability, however, trends did exist in the data that are indicative of diminished neuromuscular characteristics. Utilization of ankle ROM and proprioception assessments as part of a screening tool may highlight neuromuscular deficiencies that can be improved with more individualized training aimed at preventing injury occurrence.

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PREFACE

I would first like to thank Dr. Scott Lephart and Dr. Timothy Sell for providing the opportunity for me to pursue a PhD at the University of Pittsburgh. I will be a better educator, I will be a more efficient mentor, and I will certainly be a stronger researcher thanks to my years at Pitt.

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1.0 INTRODUCTION

Ankle injuries are common in a wide variety of individuals, ranging from physically-active students to ballet dancers, and from college athletes to military personnel.[10, 38, 65, 70, 135] It has been estimated that nearly 28,000 ankle injuries occur in the United States each day.[70] In athletics, some estimates have reported that nearly half of all injuries are ankle sprains.[37, 64] The most consistent risk factor for ankle sprains in athletes, when compared to a multitude of intrinsic (within the body) and extrinsic (external to the body) risk factors, is a previous ankle sprain, which is likely a result of diminished neuromuscular function as a result of the initial injury.[10] For those suffering an ankle sprain for the first time, there is a high recurrence rate, long-lasting symptoms, lowered quality of life, diminished activity levels, risk of chronic ankle instability (CAI), and a heightened risk for developing ankle osteoarthritis.[10, 57, 65] It is important to reduce injury occurrence, whether preventing the initial sprain or lowering the risk of a recurrent sprain. Finding a way to further the understanding of the neuromuscular deficits that result from a history of lateral ankle sprain (LAS) injuries will aide in achieving this goal.

While eliminating LAS entirely is not realistic, there are known risk factors for ankle sprains associated with neuromuscular deficits, which are modifiable. Examples of such neuromuscular deficits include inadequate strength, impaired sensorimotor function, and decreased range of motion (ROM).[6, 10, 11, 57, 69, 70, 87, 173] While a previously uninjured athlete can train preventively against suffering an initial ankle sprain, it is imperative for individuals who have suffered LAS to train these characteristics in an attempt to reduce their risk of suffering a recurrent LAS.[30, 52, 53]

Before a proper training program can be prescribed, it is important to establish which measures can discriminate between individuals with CAI, a repetitive-nature injury that often results from proprioceptive deficits to ligamentous structure,[40, 57] and healthy controls (CON). These discriminatory measures could then be included in a testing battery that encompasses assessments of multiple neuromuscular deficits to achieve a comprehensive understanding of the risk factors for ankle (re)injury. Differences in strength,[75] ROM,[78, 166] and postural stability have been reported in individuals with a history of ankle sprains versus those with healthy ankles.[40, 45, 79] Also, differences in tests of proprioception have been examined in studies comparing individuals with a history of ankle sprain injuries to CON.[42, 99] The majority of proprioception research has focused on joint position sense testing in individuals with a history of ankle injuries,[12, 28, 41, 42, 51] but little is known regarding threshold to detect passive motion (TTDPM) at the ankle.[83] It has been reported in previous studies on proprioception and kinesthesia of other regions of the body that TTDPM is a better indicator of the abilities of the sensorimotor system.[10, 11, 80, 81] Therefore, examining TTDPM data specific to the ankle may provide a better examination tool and indicator of ankle function/risk factor for injury; adding significantly to the scientific literature.[83, 153, 173]

While the empirical evidence has explored the individual risk factors for LAS; examining all of the tests within the same individuals and comparing across CAI and CON has not been explored.[30, 57, 59] Separate studies have established differences in strength and proprioception while others have demonstrated differences in ROM and stability.[6, 16, 79] To better assess the injury risk in an individual, it was proposed to use a wide test battery that includes assessments of the following neuromuscular characteristics: ROM, flexibility, musculature size, proprioception, strength, time to peak torque (TTPT), static postural stability, and dynamic postural stability. Comparing results of these neuromuscular characteristics in athletes with and without CAI as a result of non-contact lateral ankle sprains (CAI-LAS) was proposed to enable a comprehensive identification and improved understanding of the neuromuscular deficits occurring as a consequence of a previous LAS. Because non-contact LAS often results due to intrinsic risk factors, specifying this study to CAI-LAS was believed to allow for detectable differences between groups to be better associated with neuromuscular deficiencies associated with LAS. By testing a broader spectrum of neuromuscular characteristics as part of a comprehensive evaluation, it was believed that fewer neuromuscular deficiencies will be overlooked during training and rehabilitation.

Ankle sprains affect people of all activity levels at a higher rate than other musculoskeletal ailment.[24, 26, 38] In sports, LAS are the most common injury type.[37, 38] Fong et al.[38] conducted a systematic review of more than 30 years of ankle injury data and concluded that of all injuries in sports, the ankle is the most frequently injured area of the body. Ferran and Maffuli [37] reflected similar numbers by suggesting that nearly 45% of all athletic injuries can be attributed to LAS. There are many intrinsic and extrinsic variables that can contribute to the likelihood of suffering an ankle injury.[10] The only consistent intrinsic risk factor across the data is a previous ankle sprain, however the data is conflicted on others, such as strength, ROM, and postural stability.[10] Beynnon et al.[10] acknowledged a need for future research to help develop a consensus on all ankle sprain injury risk factors, allowing for future intervention studies to be designed to reduce the incidence and severity of ankle injuries. The study detailed herein aimed to provide additional insight into which laboratory measures could detect a difference between CAI_LAS and CON, allowing for the measurements to be included as part of a screening tool.

While signs and symptoms, accompanied by pain, can last for more than a year from a single LAS, it is estimated that 30% of people will experience a similar injury in the future.[30] The repetitive nature of this injury is known as CAI. It was hypothesized by Hertel[57] and Freeman[40] that the increased likelihood of a recurrent sprain is caused by proprioceptive deficits resulting from an initial injury to the lateral ligaments of the ankle. While the structure of the ankle is multi-faceted, it is believed the damage to articular mechanoreceptors in the lateral ankle ligaments are the cause of diminished abilities in the dynamic stabilizers of the ankle.[118] This diminished ability/function ultimately leaves the individual susceptible to re-spraining the ankle due to a complex paradigm (Figure 1) that propagates itself with each injury occurrence.[58, 80, 81]

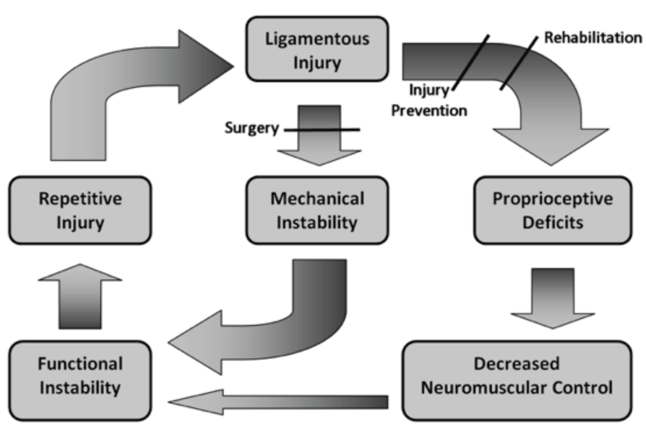


Figure 1. Joint Stability Paradigm

Following a ligamentous ankle sprain injury, one is generally categorized as having mechanical instability and/or functional instability. While a surgical procedure may help correct for deficiencies associated with mechanical instability, successfully overcoming the burden of functional instability rests with injury prevention strategies and rehabilitation.[30] Without adequate rehabilitation, recurrent injuries may occur as a result of proprioceptive deficits and decreased neuromuscular control, which are both consequences of a LAS. The cycle then continues itself following the repeat injury; and without proper diagnoses of specific neuromuscular deficits and individualized training, chronic issues may persist.[30, 57]

1.1 RISK FACTORS FOR ANKLE SPRAIN INJURIES

Ankle sprains account for the greatest loss of playing time compared to other injuries in sports.[122] Some anatomical and genetic injury risk factors are harder to correct for, such as increased pronation or higher BMI serving as risk factors for medial tibial stress syndrome. [9, 180] Below are risk factors commonly associated with LAS.[155]

1.1.1 Range of Motion & Flexibility

It is reported that limited ROM of the ankle results as a consequence of suffering a LAS.[57] Diminished ROM can result from lower extremity musculature becoming inflexible, creating an inability to reach full dorsiflexion and leaving the ankle in a more plantar flexed position. Given the talocrural joint is most stable in full dorsiflexion (closed packed position), the ankle is therefore left in a more vulnerable position, susceptible to inversions and internal rotations. Therefore, this diminished dorsiflexion could lead to a higher risk of a recurrent sprain.[57, 78, 99, 166]

Therefore, assessing ROM as a component of a testing battery could highlight a risk factor that may otherwise be overlooked in assessments focused on strength or balance.

1.1.2 Muscular & Neuromuscular Characteristics

Ankle sprain injury risk factors associated with muscular and neuromuscular characteristics include musculature size,[90] proprioception,[83, 174] strength,[5] and muscle reaction time.[10, 93] Musculature size (i.e. limb girth) has been reported as a risk factor for ankle sprains.[8, 137] While significant relationships between gastrocnemius circumference and the incidence of lateral ankle sprains has been reported,[90] some have concluded that radiographic techniques such as computed tomography scans are the only means of accurately measuring limb girth.[93] Utilization of magnetic resonance imaging of ankle musculature has been successful in associating increases in physiological cross-sectional area of the muscles with improvements in strength as a result of utilizing minimalist footwear during training.[14] By imaging the lower leg musculature of CAI-LAS and CON, it was believed a further understanding of the role of musculature size in ankle sprain injuries would be made possible.

Various methodologies for assessing proprioception of the ankle have been implemented in previous research, leading to mixed results.[41, 42, 99, 142] Findings indicate that there is a deficit in proprioception as a result of an initial LAS, which could contribute to recurrent LAS.[173] The majority of studies on ankle proprioception focus on tests of active and passive joint position sense,[39, 41, 42, 79] which measures the accuracy of position replication.[120] Although these measures are valid and widely used, other tests of proprioception have been shown to have higher reliability when testing other joints.[11, 80, 81, 94, 95] An example of one of these tests is TTDPM.[10, 55] Joint position sense testing at the ankle is commonly performed on an isokinetic dynamometer,[57,

[173] while only a single study has investigated TTDPM at the ankle in the same way.[83] Testing inversion and eversion with TTDPM, which assesses one's ability to detect a change in positional homeostasis, will test the sensitivity of the slow-adapting mechanoreceptors that would need to adequately signal musculature to contract correctively during perturbations.[80, 120]

Ankle strength, which is also commonly measured on an isokinetic dynamometer, has been investigated as a risk factor for LAS.[5, 176] By implementing strengthening regimens for the ankle musculature, individuals can reduce their risk of injury,[14, 30, 52, 53] and these gains are associated with improved postural stability.[141] This study aimed to determine if strength discrepancies could be detected between CAI-LAS and CON. Another measurable dependent variable captured during isometric strength testing is time to peak torque (TTPT). Time to peak torque is important to clinical practice because the timely generation of force by the dynamic restraints has the effect of reducing excessive ankle joint displacements and correcting ankle joint alignment in potential injury situations.[177] A delay in a muscle's ability to reach peak torque quickly may signal a neuromuscular deficit that could compromise the protective effect of the muscles on ankle joint stability. If detectable differences in TTPT could be seen in this study's subjects, it was believed a better understanding of the effect of CAI-LAS on muscle function would be made available.

1.1.3 Static & Dynamic Postural Stability

Individuals who have greater difficulty performing tasks related to postural stability have been shown to prospectively have a higher occurrence of injury. [87, 173] Tasks of dynamic postural stability have been implemented in assessing injury risk as well.[129, 130] Both are common assessment tools but are not strongly correlated with one another, [127] so assessing both static and dynamic postural stability assessments in CAI-LAS and CON was proposed as a means of providing more information to discriminate between populations. Nonlinear measurements, such as sample entropy (SampEn) can also be collected during static trials. While static balance has been widely used as an assessment of postural stability, there may be underlying significance in the collected data.[113] It was proposed that SampEn measurements, which are calculations of the variability within a trial,[147] would offer further information into the differences in postural stability between CAI-LAS and CON.

1.2 DEFINITION OF THE PROBLEM

Lateral ankle sprains are prevalent among athletes and individuals of all ages, skill levels, and occupations.[10, 38, 65, 69, 70, 135] If a wider test battery can be implemented to assess differences in neuromuscular characteristics between CAI-LAS and CON, a more complete understanding of the effect of previous LAS on future injury risk can be ascertained. Lateral ankle sprains can lead to recurrent LAS,[30, 34, 150] and the time lost from these injuries can have both performance and psychosocial ramifications.[65] This study proposed the investigation of a wide battery of tests to understand which laboratory measures were able to discriminate between CAI-LAS and CON. It was proposed for these measures to help highlight needs for improvements in ROM, flexibility, musculature size, proprioception, strength, TTPT, static postural stability, and/or dynamic postural stability in athletes who may be at risk for (re)injury. With a more comprehensive assessment tool, clinicians and researchers will overlook fewer neuromuscular deficiencies during training and rehabilitation, and more individualized training programs tailored to enhancing the specific deficiencies of an individual can be utilized.

1.3 PURPOSE

The purpose of this study was to examine if differences in laboratory measures of ankle flexibility, proprioception, strength, and postural stability existed in soccer players, with and without CAI-LAS. The proposed laboratory measurements for this study included ROM, the Star Excursion Balance Test (SEBT), lower leg musculature size, TTDPM, strength, TTPT, static postural stability, and dynamic postural stability. Previous studies have examined risk factors related to the laboratory measures in isolation, but it was the aim of this study to utilize a wide battery of tests to determine which laboratory measures could aid in discriminating differences in the CAI-LAS and CON groups. It was proposed that significant differences between the two groups would further the understanding of the effects of CAI-LAS injuries. Laboratory measures that showed significance can be utilized to help clinicians and team personnel improve function, enhance quality of life, and better the prognosis for non-contact LAS.

1.4 SPECIFIC AIMS AND HYPOTHESES

<u>Specific Aim 1</u>: To examine the differences in ROM and flexibility in athletes with or without CAI-LAS

> <u>*Hypothesis 1*</u>: Individuals with a CAI-LAS will exhibit less ROM at the ankle joint and perform more poorly on the SEBT compared to CON

<u>Specific Aim 2</u>: To examine differences in musculature size, function, and strength in athletes with or without CAI-LAS

Hypothesis 2: Individuals with CAI-LAS will have smaller lower leg musculature, have a greater (worse) TTDPM at the ankle, have less isometric strength, and have longer TTPT values during strength testing compared to CON

Specific Aim 3: To examine differences in postural stability in athletes with or without CAI-LAS

Hypothesis 3: Individuals with CAI-LAS will have worse static postural stability, exhibit a more deterministic center of pressure (CoP) SampEn, and display worse dynamic postural stability compared to CON

1.5 STUDY SIGNIFICANCE

Previous research has looked at various risk factors for ankle sprain injury in healthy and injured populations, however the scientific literature is replete with inconsistent findings. This is likely due to certain deficiencies being overlooked in subjects and improper comparisons being investigated within an individual, such as side-to-side comparisons among healthy and previously injured limbs. However, if a wider test battery incorporating measures of neuromuscular characteristics is implemented in comparing individuals with CAI-LAS to CON, it will be possible to further understand the neuromuscular deficiencies that result from suffering a LAS. Utilizing laboratory measures related to reported risk factors for LAS, it was proposed for this study to be equipped with the ability to recommend measurement tools that are sensitive enough to detect neuromuscular deficiencies that may result from LAS in an individual, which predisposes them to future similar injury. Corrections of modifiable factors may prevent re-injury. Findings in this study will highlight the need for the inclusion of a more comprehensive assessment tool to be utilized as part of injury prevention and rehabilitation programs.[19]

Further, it was proposed that results of this study may lend greater credence to the idea of individualized training programs focused on correcting neuromuscular deficiencies. A wider assessment tool will be able to indicate individuals at a greater risk for injury and provide a means for determining weaknesses to monitor during competition. Future studies can utilize the test battery as part of an injury prevention model similar to the five-phase University of Pittsburgh Injury Prevention and Performance Optimization Model (Appendix A). The laboratory measures could dictate individualized injury prevention strategies aimed at lowering injury risk. The individual could then be tested with the battery of laboratory measures proposed herein to determine the effectiveness of the training program.

2.0 REVIEW OF THE LITERATURE

2.1 EPIDEMIOLOGY OF ANKLE SPRAIN INJURIES

Estimates suggest nearly 28,000 LAS occur every day,[70] and over two million each year in the United States alone, making it an injury that requires further understanding to minimize the occurrence of injury.[6, 11] In a systematic review of research related to ankle injuries in sports over a 28-year period, Fong et al.[38] discovered 32,059 ankle sprains among 201,600 patients. Roughly half of the research articles reviewed provided information related to the type of ankle injury, resulting in 11,847 ankle sprains reported in the literature. The greatest number of injuries reported came from court games and team sports, and even though the data spanned multiple countries,[47, 48] LAS were the most common injury type across all 70 sports reported in the review.[38] Specific to the United States, ankle injuries (12.3%) were second to knee injuries (22.1%), but LAS were still the predominant injury type (68.3%) for ankle injuries.[38]

Ferran and Maffulli[37] reported LAS account for 85% of all ankle injuries, and they reiterated that the ankle is the most commonly injured body site during sporting activities. This epidemiological assessment of ankle injuries stressed the influence of LAS being underreported and the consequence it had on the athlete by means of chronic pain, muscular weakness, and instability.[37] Ferran and Maffulli[37] reported the significant effect of LAS on professional soccer clubs in the English Football Association, highlighting days lost in training, missed match play, and cost of rehabilitation as negative outcomes. With a third of LAS occurring during training and the other two-thirds occurring during match play, LAS accounted for 12,138 missed days and totaled 2,033 matches missed over just two competitive seasons.[179] Not only are professional soccer players at risk, as injury rates are high across skill levels,[178] and LAS are among the most often reported injury type and location. Tourny et al.[158] reported that more than a third of all soccer injuries are LAS, which is likely due to the demands of the sport that include high-velocity cutting maneuvers, single-leg landings, and contact with other players as extrinsic risk factors for injury.[161]

Beynnon et al.[10] examined multiple intrinsic and extrinsic risk factors and their role in lateral ankle sprains. The reviewers highlighted intrinsic risk factors such as: previous sprain, gender, height and weight, limb dominance, anatomic foot type and size, generalized joint laxity, anatomic alignment, ankle joint laxity, ROM of the ankle, muscular strength, muscle reaction time, and postural sway.[10, 31, 32, 88, 90] A majority of the literature reviewed did not indicate gender as a risk factor for ankle injuries.[66] In a season-long analysis of collegiate athletes, investigators indicated that even with a substantial difference in the performance of screenings for injury risk factors among the genders, there was no significant difference among the genders in terms of exposure.[11] Males suffered 1.6 injuries per 1000 person-days of exposure to their respective sport, and females sustained 2.2 injuries per 1000 person-days.[11] The findings from the literature were mixed, however, on potential risk factors such as height,[139, 164] weight,[11, 90] limb dominance,[31, 150] ankle-joint laxity,[4, 5] anatomical alignment,[10] muscle strength,[5, 11] muscle-reaction time,[9] and postural sway.[11, 87] Beynnon et al.[10] concluded that differing findings could be a result of various rehabilitation programs administered to certain individuals and compliance to those rehabilitation programs.

2.1.1 Previous Ankle Sprain

It is believed the most commonly investigated risk factor for LAS is a previous LAS,[10] and the mechanism related to the injury and subsequent disruptions are stated below. Despite the generous amount of attention paid to this risk factor, however, the literature does present differing arguments on the role of a previous LAS on whether a future injury will occur. Ekstrand and Gillquist,[31] in an early prospective analysis of injury history, did show an association between previous LAS and subsequent LAS. They examined 180 soccer athletes over the course of one year, and during that year 124 of the athletes suffered a total of 256 injuries to the lower extremity.[31] Among those injured, it was reported that athletes who had suffered a previous LAS were at an increased risk for injury during the study period.[10] Arnason et al.[2] reported previous injury to be a risk factor for LAS in soccer players at an odds ratio of 5.3. In addition to soccer players, previous injury has been shown to be a risk factor for injury in basketball players and military recruits.[88, 90] McKay et al.[88] reported that basketball players who had suffered LAS previously were nearly five times more likely to sustain LAS, reporting a statistically significant odds ratio of 4.94. Milgrom et al.[90] examined 390 Israeli infantry recruits, and they reported an incidence rate of 18% during basic training activities for these individuals; concluding that previous LAS resulted in a higher morbidity rate for LAS during basic training.

Baumhauer et al.[6] did not find previous LAS to be a risk factor for a subsequent injury when comparing collegiate athletes who sustained an injury during a competitive season to athletes who did not suffer LAS. The authors stated this departure from conventional thinking to be a result of their recruitment strategies. Athletes with a history of grade II or grade III LAS were excluded from the study to eliminate the confounding effects of including subjects with CAI. It was concluded that a history of a mild LAS was not enough to determine an increased risk of LAS being sustained during a competitive season.[6] Some of the discrepancies in findings could be attributable to the severity of the initial LAS.[10] To collect significant results, it is believed proper classification of individuals with a history of LAS that resulted in detectable neuromuscular deficiencies is needed, as this study aimed to do.

2.1.2 Burden of Ankle Sprains

Ankle sprain injuries are especially prevalent in athletic populations, and collegiate athletes seem to be particularly vulnerable to LAS.[65] In a surveillance study spanning over 16 years, Hootman et al.[65] identified LAS as the most common injury, accounting for 15% of all injuries in collegiate athletes during that time. The authors implemented a surveillance system for 17 different sports. Injuries were included in the analysis if they occurred as a result of participation in organized intercollegiate practice or contest, required medical attention by a team athletic trainer or physician, and resulted in restriction of the athlete's participation or performance for at least one day following the injury.[65] Between 1988 and 2004, the surveillance system recorded 182,000 injuries occurring in more than one million exposure records, which were defined as one practice or game. Over the course of the study, more than 27,000 LAS were reported, averaging approximately 1,700 LAS per year. This approximated to 15% of all college athletes, suggesting that collegiate athletes in these particular sports suffer more than 11,000 LAS per year.[65] These injuries were particularly high in men's and women's basketball, with nearly 25% of all injuries in each sport being LAS. The incidence rate of LAS was highest in spring football (1.34/1000) and men's basketball (1.30/1000).[65]

In a prospective study investigating risk factors for LAS, Baumhauer et al.[6] analyzed intercollegiate athletes who played soccer, lacrosse, or field hockey. All athletes were tested on measures of joint laxity, foot and ankle anatomical alignment, ankle ligament stability, and isokinetic strength. Over the course of the competitive season that followed testing, 10.3% of the participants suffered LAS, and the data indicated eversion-to-inversion strength imbalances as a risk factor for LAS. Interestingly, 35% of the athletes in the group that did not suffer LAS had a previous history of LAS. In the group that suffered LAS during the study, just 27% of the athletes had suffered a previous ankle sprain. Baumhauer et al.[5] concluded that training modifications can be implemented to help reduce the incidence of injury and aid in ankle injury prevention if strength imbalances are detected prior to competitive seasons.

Beynnon et al.[11] re-analyzed the same Division I college athletes from the study by Baumhauer et al.,[5] however, they excluded data from any athletes that had suffered a previous LAS, had undergone foot or ankle surgery, had sustained trauma to the lower extremity, or if they used ankle supports. Prior to their competitive seasons, each athlete with no previous LAS was screened with various measures of suspected ankle injury risk factors. In addition to the risk factors investigated by Baumhauer et al.,[5] the study by Beynnon et al.[11] included gender, height, weight, limb dominance, anterior-posterior center of gravity, and muscle reaction time.[11] During the competitive seasons, the athletes were continuously monitored, and a single investigator assessed any sustained ankle injury. While there were no significant differences on injury risk based on gender, it was found that women who played soccer were at a higher risk for suffering LAS than women who played field hockey or lacrosse, but men did not have varying risk of injury incidence based on sport. In addition, women with greater eversion ROM were at a greater risk for LAS.[11]

Ankle sprains are not solely limited to athletic populations, as many of the injuries incurred on the playing field are similar to those that occur on the military battlefield. Training strategies and interventions for fighting forces are similar to those of elite athletes, dubbing those in the military as tactical athletes. Citing unintentional musculoskeletal injuries as persistent health concerns for the United States military, Sell et al.[135] conducted an injury surveillance of Soldiers from the 101st Airborne Division (Air Assault) in Ft. Campbell, KY. As part of an analysis of the tasks and demands placed on these individuals (Appendix A), the authors tested 404 Soldiers from across 121 different Military Occupational Specialties and all Physical Demand Rating Categories. In a retrospective analysis of self-reported injury data, information was collected on 99 total injuries from the year prior to subject recruitment. Among these injuries, nearly two-thirds of all injuries occurred in the lower extremity, and 18.2% of all injuries were reported at the ankle, the most commonly injured body site.[135] Additionally, LAS were the most common specific injury type, accounting for 16.2% of all injury types. The injury epidemiology data indicated that injuries occurred primarily during physical and tactical training, and the injuries are potentially preventable through various training alterations and interventions.

In a separate investigation, Sell et al.[136] looked at the effects of the increased load of body armor on dynamic postural stability. Postural stability, which is the process of coordinating corrective movement strategies and movements at selected joints to remain in postural equilibrium,[118, 119] has been shown to be a risk factor for LAS in athletic populations.[87, 127, 130] Examining the base of support when it is recovering from movement or when an external perturbation has been applied to the body assesses dynamic postural stability, which can be an indicator of one's risk of suffering LAS.[168] The study by Sell et al.[136] implemented a jump landing task similar to the one that will be utilized in this study and conducted the investigation by having the Soldiers perform the jump landing task in casual wear and in their own body armor, which averaged an additional 15.6% of body weight. The results showed that the subjects had significantly different dynamic postural stability between the load and no-load conditions. Scores for dynamic postural stability in the loaded condition were significantly worse, indicating a potentially heightened risk for lower extremity injuries while wearing body armor.[136] With soldiers being exposed to a higher injury risk because of increased load, it is understandable why ankle injury rates are high. Utilizing preventive exercises tailored to an individual's neuromuscular deficiencies will ultimately result in safer performance during dynamic tasks and ideally lower the risk of injury.[136]

2.1.3 Time-loss Injury

Lateral ankle sprains are the most common injuries in sports, as indicated previously. The common burden of LAS is exacerbated by the fact that they also account for the greatest loss of playing time of any injury.[122] In an analysis of AS in professional soccer players in England, Woods et al.[179] documented the cause and effect of LAS sustained for 91 different teams over two consecutive seasons. The study collected information on 1,011 LAS, which accounted for 17% of all injuries sustained over the two-year period.[179] The total number of days missed from competition and training because of these injuries was 12,138, and the players inflicted with LAS missed 2,033 competitive matches over the two seasons. In the injury surveillance of professional soccer players, Woods et al.[179] reported that 83% of the 1,011 LAS sustained during the competitive seasons followed resulted in players missing one month or less. Although the reported re-injury rate in this study was low (9%), it was reported that initial LAS averaged 18 days of missed training and three missed matches. For those who suffered a re-injury, average number of missed days was 19, and four matches were missed.[179]

While an average knee reconstruction likely takes more time to recover from than the average LAS, the high volume of LAS takes a substantial toll on the affected population. In the surveillance of collegiate athletes by Hootman et al.,[65] only one out of five LAS sustained during the study resulted in a time loss of greater than ten days, but even a small proportion of LAS resulting in long-term morbidity or disability causes a large burden on athletes, teams, and institutions. In addition to missing time from action as a result of LAS, a significant financial burden can take place from a single injury and certainly from multiple injuries. It has been estimated that the financial toll on the US government to cover the medical costs for a military member in his or her twenties can exceed $250,000.[135] When accounting for treatments for pain, loss of duty time, rehabilitation training, and potential attrition from the military, the cost per individual can exceed $1,000,000.

2.2 CHRONIC ANKLE INSTABILITY

Individuals who are prone to repetitive LAS and injuries are often categorized as CAI.[40] It is not uncommon for individuals with CAI to have deficits in ankle strength and balance, both of which are central areas of interest for this study. In particular, the strength and balance deficits can lead to recurrent feelings of instability, repeated episodes of the ankle giving way, and weakness during physical activity.[53] Focusing on the role of weakness and instability in individuals with CAI is of particular importance from a research perspective, as having a better understanding of these neuromuscular deficiencies can help further the knowledge related to improving strategies for injury prevention and rehabilitation. Donovan and Hertel[30] included strength and balance training as integral components of their CAI rehabilitation paradigm. Improving strength as a result of utilizing a regimented strength training program has been shown to be beneficial, and the benefits of balance-focused training on reducing the occurrence of and the risk for ankle injury has been shown in as little as four weeks of training.[52, 53] The CAI rehabilitation paradigm presented by Donovan and Hertel also included ROM testing and training, just as the study proposed herein aims to include.[30] While rehabilitation and injury prevention models can vary in nature and include a wide array of testing modalities, the end goal of injury prevention in clinical and research efforts is the same – minimize the occurrence of injury. By incorporating measures of ROM, flexibility, musculature size, proprioception, strength, TTPT, static postural stability, and dynamic postural stability into a single battery of testing in CAI-LAS compared to CON, it was believed further knowledge of various risk factors and their relationship to one another would be elucidated. While a full complement of training and rehabilitation that includes ROM improvement, strength enhancement, balance exercise, and more fine-tuned functional activities is ideal for the optimization of injury prevention and rehabilitation, strength and stability – two main tenets of this study's testing battery – appear to be the core to avoiding re-injury.[28, 57] Too often, an initial LAS falls into a cycle of repetitive injury as a result of proprioceptive deficits and instability.[80] It was also believed that furthering the understanding of the dynamic restraints of the ankle, as this study also aimed to do, would help delay or stop the cycle from occurring.

2.2.1 Functional Ankle Instability

Chronic ankle instability refers to individuals with a history of repetitive LAS. One way to further classify these individuals is to break down those with mechanical instability, a condition often diagnosable with clinical tests, and those with functional instability. Lateral ankle sprains cause structural damage to not only the ligamentous structures of the ankle but also to the neuromuscular tissues that surround the entire ankle complex. If an individual develops joint laxity because of the injury, clinical tests can often diagnose mechanical instability. However, after seemingly full recovery, underlying neuromuscular deficits likely linger, which diminishes the proprioception of the individual and can delay muscle-firing patterns. This is what is known as functional ankle instability (FAI), and it is a subset of CAI accentuated by neuromuscular deficits that result from an initial injury.[57]

Hypersupination of the ankle complex, the oft-cited cause of LAS, tends to sprain the ligaments that support the lateral aspect of the talocrural and subtalar joints, disrupting the sensory receptors within the ligamentous structures.[58] This damage ultimately leads to a decreased ability to detect changes in joint position because nervous tissue tends to heal much more slowly than other body tissues, if at all.[57] This could lead to future sensations of the ankle seeming to "give way" because the proper proprioceptive mechanisms do not correct for excessive motion of the ankle the same way a previously uninjured ankle would.[40] Properly functioning ankles would send afferent signals to the spinal cord once increased tension in the ligaments is sensed and receive efferent responses to the muscles to perform corrective actions.[57] With diminished proprioception, the ability of this process is limited, and another injury could occur.[81] This is the basis of FAI and the primary cause for repetitive LAS.

2.2.2 Anatomy of Ankle Sprain Injuries

The anatomy involved in a predominant amount of LAS is the talocrural, subtalar, and distal tibiofibular joints. These are the three articulations that constitute the ankle.[58] Each joint works together to perform the actions of the ankle: plantar flexion-dorsiflexion, inversion-eversion, and internal rotation-external rotation. The talocrural joint is comprised of the superior aspect of the talus, the distal segment of the tibia, and the medial and lateral malleoli. The axis of rotation of this joint passes through the malleoli and allows for the joint, when viewed on its own, to be considered a hinge joint, allowing for plantar flexion and dorsiflexion.[58] Several crucial ligaments support the talocrural joint, including the anterior talofibular ligament (ATFL), posterior talofibular ligament (PTFL), calcaneofibular ligament (CFL), and deltoid ligament. The ATFL, PTFL, and CFL are the major ligaments of the lateral aspect of the ankle, the portion that is often most susceptible to LAS.[15, 144]

The subtalar joint is made up of the talus and calcaneus to form an articulation similar to a ball-and-socket joint. This allows for an axis of rotation with triplanar motions of pronation and supination as well as internal and external rotation. The sinus tarsi divides the subtalar joint into anterior and posterior joints, each with separate ligamentous joint capsules.[58] The anterior joint is more medial than the posterior joint, while the ligamentous support is extensive yet not fully understood due to conflicting descriptions in the literature. The ligaments are summarized into three categories: deep, peripheral, and retinacula. Again, much of the ligamentous structures are concentrated on the lateral aspect of the ankle. Statically, these ligaments provide resistance to supination of the foot, and they are often injured because of hypersupination mechanisms that are associated with LAS.[63, 73, 149] The distal tibiofibular joint, as its name indicates, is the articulation between the tibia and fibula. There is limited motion in this syndesmosis joint, however some accessory gliding does occur to accommodate for normal mechanics throughout the entire ankle complex.[58] While the interosseous membrane is the primary stabilizer for this joint, added support comes from the posterior and inferior tibiofibular ligaments, the latter of which is often injured during eversion ankle injuries.[3, 163] Such damage is related to high ankle sprains as opposed to the more common LAS.[91]

The musculature of the ankle region is predominated by the peroneus longus and peroneus brevis. These muscles assist with supination of the foot and protect against LAS.[58] The musculature also consists of the tibialis anterior, extensor digitorum longus and brevis, and the peroneus tertius. During dynamic tasks, it is the stiffness generated by these muscles that protects the joints, specifically by slowing down the plantar flexion component of supination to prevent lateral ligament injury.[57] The motor movement is innervated by three mixed nerves and two sensory nerves that descend from the lumbar and sacral plexes. Mechanoreceptors are the main source of innervation for the lateral ligaments and joint capsules of the talocrural and subtalar joints. The mechanoreceptors are vital for proprioception, and damage to these areas is a major concern and likely cause for recurrent LAS.[89, 151]

2.2.3 Mechanisms of Injury and Neuromuscular Control

Lateral ankle sprains often result from a combination of excessive inversion and plantar flexion of the foot acting in accordance with external rotation of the leg.[30] While the nature of recurrent AS is likely similar to that of the initial injury, it is the damage to the intrinsic factors that heighten the propensity of the subsequent injury to occur. A healthy individual might step in the same pothole as an FAI individual, however, the latter person is more likely to suffer LAS due to diminished neuromuscular control. This theory traces back to 1965 when Freeman[40] hypothesized that the disruption of mechanoreceptors and afferent nerves accompanied the damage to ligament tissues during an ankle sprain because the neural components are less tensile than the ligaments. Diminished ROM, reductions in strength, and various impingements might also be problems associated with FAI,[57] but it is the altered neuromuscular mechanisms that deserve focus, particularly in relation to altered joint position sense and delayed reaction time.

Both of these fit with the theories associated with feedback and feedforward mechanisms.[118] If either one is not optimally functioning, it is more understandable to see why the recurrent sprain is likely to occur.

Joint stability in a healthy ankle is maintained with a properly functioning sensorimotor system. This system is an incorporation of afferent, efferent, and central integration and processing components that work to maintain functional joint stability.[119] Healthy mechanoreceptors in the muscular, joint, and ligamentous tissues send afferent signals to the spinal cord when they sense increased tension.[57] The brain processes the signal and sends a subsequent efferent signal to the intrafusal and extrafusal muscle fibers. The intrafusal muscle fibers – muscle spindles – act as a defense mechanism, sensing changes in muscle length. If change is detected, the extrafusal muscle fibers are innervated to contract. Because a contracted muscle is more difficult to stretch, the joint is subsequently stiffer, making for a more stable joint. It is this system that becomes compromised with the initial or recurrent LAS that can place one into the FAI category. If mechanoreceptors are not working properly, they cannot send the appropriate efferent signal, which results in an improper or delayed afferent signal. This could lead to an ankle that is not functionally stable or one that is not able to respond as quickly to sudden perturbations.[81, 118, 151]

During sudden changes to the foot-surface interaction, such as stepping onto uneven pavement during a run, the peroneal muscles are among the first to contract in response to the stress of a quick inversion of the ankle. Efferent signals would cause the peroneals to contract eccentrically to slow the inversion in this instance, and if the contraction were strong enough, ankle eversion might take place to counter the inversion.[57] Diminished capabilities of such a feedback mechanism are hypothesized as the cause of FAI. Previously injured ankles have been reported to have significantly slower reaction times to inversion perturbation in the peroneus longus, peroneus brevis, and tibialis anterior muscles.[76] Another neuromuscular concern for FAI is a deficit in joint position sense.[79] In a comparison between injured and uninjured ankles, individuals displayed greater error in trying to actively replicate various degrees of plantar flexion, with greater severity of initial injury leading to greater error in joint positioning.[42] . Similarly, deficits in ankle kinesthesia were shown in athletes who had suffered an ankle sprain, having a decreased ability to detect passive plantar flexion in the previously injured ankle compared to the non-injured ankle.[41] Both are signs of deficiencies in the neuromuscular system.

2.3 RISK FACTORS FOR ANKLE SPRAIN INJURIES

Multiple risk factors have been associated with LAS in the literature. This section will attempt to highlight the primary known neuromuscular deficiencies associated with LAS injury and relate them to the proposed study within. While a considerable amount of work has been done in this area, it is believed the novel component of this study is the combination of testing multiple neuromuscular characteristics in the subjects to assess which laboratory measures can discriminate differences in the groups. Comparing differences in these tests across athletes with and without CAI-LAS will provide a more thorough understanding of the effect of LAS history on laboratory measures related to ankle injury risk factors. Findings in this study will help provide rationale for the utilization of a wider battery of measures in screening athletes for deficiencies that are modifiable with training. The work in much of the literature tends to focus on one or two risk factors at a time, whereas this study aimed to assess a battery of testing that proposed at least seven potential laboratory assessments related to ankle sprain injury. Further, each test has multiple variables that may present significance worthy of further examination. This section will detail what is currently known in the literature and the common means of assessment, ultimately clarifying the rationale and importance of the methods proposed in this study. Of interest to this study are the mixed findings for the testing of risk factors related to: ROM and flexibility; muscular and neuromuscular characteristics; and static and dynamic postural stability.

2.3.1 Range of Motion

It is reported that LAS result in a decreased ROM at the ankle joint, and the decrease is a key contributor to functional instability for the individual moving forward.[57] The anatomical changes that result from the trauma are long lasting, and in some cases are an ongoing presence in individuals who are susceptible to LAS. Leanderson et al.[78] showed that basketball players with a history of LAS had significantly less ROM than healthy controls. While much of the study was focused on basketball players with a history of bilateral sprains, they did include athletes with unilateral LAS history. When comparing the injured and uninjured ankles in these individuals, the ROM was not significantly different, limiting their healthy ankle to a ROM still significantly lower than the healthy controls. This would lead to the suggestion that individuals susceptible to LAS, even healthy individuals who have never suffered LAS, might be at risk of suffering an injury if ROM is less than average.

Wiesler et al.[166] also noted a significant difference in ankle flexibility among individuals with a history of LAS versus those with no history of LAS. In comparing 148 dance students, Wiesler et al.[166] reported that dorsiflexion ROM was significantly less in those reporting previous injuries as compared to those who reported no previous ankle injury. Similar to the athletic and military populations mentioned above, Wiesler et al.[166] also reported ankles to be the most common injury site in their investigated group of subjects. Among the 177 total reported injuries by the dancers, 69 if them occurred at the ankle, accounting for 39 percent of all injuries sustained.[166]

2.3.2 Musculature Size & Strength

It is established that previous LAS injury history is a significant risk factor for subsequent LAS. However, what if the initial injury could be prevented? This would require an assessment of previously uninjured individuals and a prospective analysis of their injury history for an extended period. A robust analysis such as this is unfortunately not that common. Withcalls et al.[176] attempted to summarize studies that included both previously sprained ankles and ankles with no history of being sprained. The purpose of the review was to determine what functional deficits, if any, could be detected as predictors of injury risk, thus providing information to be used in modifications to training programs in an attempt to reduce LAS. Across thirteen published studies, Withcalls et al.[176] found that having higher concentric plantar flexion strength at faster speeds and lower eccentric eversion strength at slower speeds were associated with an increased risk of LAS. The authors concluded having measurable risk factors would enable clinicians and coaching staff to train specific deficits in athletes to prevent LAS.

As with other risk factors not having a clear consensus on the impact on injury occurrence, strength is no exception. In their prospective study of ankle injury risk factors, Baumhauer et al.[6] found that individuals with muscle strength imbalance as measured by an elevated eversion to inversion ratio, exhibited a higher incidence of LAS. In later work by the same authors, however, they failed to detect any significant differences in strength values between previously injured and uninjured individuals in assessments of peak torque for dorsiflexion, plantar flexion, inversion, and eversion.[11]

Previous LAS, while serving as a risk factor for future injury, also serves as an indicator for diminished strength of evertor and pronator musculature, which often results from the damage incurred in the ankle complex following LAS.[76, 159, 160, 172] Wilkerson et al.[172] reported that significant strength deficits existed in individuals with unilateral LAS injury history with a range of 5 to 18 percent less strength in the affected ankle when compared to the uninjured ankle. When comparing twenty-five individuals with a history of LAS to twenty-five matched healthy controls, Bush[16] found strength values were lower in the injured group. Interestingly, it was not only the previously injured ankles that were weaker, but the unaffected ankle in the injured group also showed significantly less evertor strength than the control group. Further, this study established a regression equation from their data that could correctly identify an injured subject 72 percent of the time.

In addition to musculature strength, TTPT was analyzed for this study. Beynnon et al.[11] reported that similar-performing athletes within the same sport did not have significantly different peak torque values for ankle strength between athletes who suffered LAS and those who did not. Beynnon et al.[11] claimed to be the only known investigators of lower extremity strength and prospective analysis of LAS, and in an earlier investigation they reported results that indicated higher ratios in inversion and eversion peak torques were associated with LAS in a similar athlete population.[6, 10] Being able to generate peak torque at a quicker rate may be in line with muscle reaction time, as both are related to neuromuscular function. Beynnon et al.[10] cited unclear interpretations of the results they found in the literature, however, as the methods of collection varied, but their own previous research indicated that the ability of muscles to react to perturbations may be compromised as a result of suffering LAS.[11] A slower reaction time of muscles that are expected to serve a protective effect by stiffening a joint could suggest that neuromuscular deficits exist in individuals with a history of LAS compared to a healthy group of individuals. If this can also be reflected in longer TTPT values, there may be an easier means of assessing this neuromuscular deficiency in individuals more at risk for LAS.

Musculature size is also of interest to this study, as physiological cross-sectional area of muscle has been shown to be proportional to the maximum force that it can produce.[93] This assessment has been relegated to limb girth in much of the literature, and the results are inconsistent. Bennell et al.[8] found that smaller gastrocnemius girth was associated with injury in women, but the authors did not find the same association in men. In contrast, Milgrom et al.[90] found that male military recruits with a larger gastrocnemius circumference had a higher incidence of LAS. A more accurate measurement technique for assessing musculature size is radiographic imaging.[93] Brüggemann et al.[14] used magnetic resonance imaging to assess ankle musculature cross-sectional area as part of pre- and post-intervention assessments in a footwear-related investigation. Half of the athletes in the footwear study utilized minimalist footwear during training activities during the intervention period while the other half utilized a more standard type of athletic footwear. Brüggemann et al.[14] found that musculature size increased as a result of minimalist footwear use, and the increase in cross-sectional area coincided with an increase in ankle musculature strength. Utilizing radiographic images by means of ultrasound technology will be implemented in the study proposed herein.

2.3.3 Proprioception

Proprioception is a component of the somatosensory sensations, which in turn are part of the sensorimotor system.[118] The sensorimotor system is a subcomponent of the motor control system. Lephart et al.[82] defined the sensorimotor system as one that encompasses the sensory, motor, and central integration and processing components involved in maintaining joint homeostasis during bodily movements. It is this maintained joint homeostasis that results in functional joint stability. The somatosensory system involves mechanoreceptors from cutaneous, articular, and muscular sources, which all work through feedforward and feedback mechanisms. Mechanoreceptors are the sensory receptors that transduce mechanical deformation of tissue. When a stretch or deformation is detected by the mechanoreceptors, afferent signals are sent to the spinal cord and brain, which returns efferent signals for corrective motion.[57] Hyper-supination of the ankle, for example, results in stretching of the skin and musculotendinous structures around the ankle as a combination of inversion, plantar flexion, and internal rotation occurs.[59] If mechanoreceptors are delayed in detecting a departure from homeostasis, corrective feedback contractions might not be signaled quickly enough to save the supination from resulting in LAS. However, when more closely examined, ankle joint stability is made up of more than just mechanoreceptors. It involves both mechanical and functional joint stability.

Joint stability as a whole is defined as the ability of a joint to remain in or promptly return to proper alignment and functional position through an equalization of forces.[119] Joint stability is achieved and maintained through a complementary relationship of static and dynamic components. Static components include ligaments, joint capsule, cartilage, bony geometry, and friction. Dynamic components are related to the feedback, as well as feedforward, mechanisms mentioned above that control skeletal muscles that cross the joint.[119] Mechanical joint stability refers to joint stability that results from the mere presence of the non-contractile tissues that give the joint its shape and structure, such as the bones, capsules, and ligaments.[118] Functional joint stability refers to joint stability during movements where there is no apprehension or pain, and it is made up of skeletal muscles that act as dynamic restraints. Functional joint stability is determined by the effectiveness of the skeletal muscles to perform the proper feedforward and feedback signaling they are intended for. Damage to the static and/or dynamic components because of injury can hamper the full capabilities of joint stability. In particular, ankle joint stability can be compromised by LAS, which often results in damage or impairments to the ATFL, PTFL, and CFL.[58]

To compensate for a deficit in static stabilizers, dynamic restraints are relied upon even more to maintain functional joint stability. Feedforward mechanisms in the dynamic restraints can serve as preventive measures of injury by balancing the reduction in output from the static stabilizers. Feedforward control is preparatory activation of the dynamic restraints prior to the onset of afferent signals that would result from joint loading.[80] This protective pre-activation of the dynamic restraints is a result of learned movements and would result from training. This puts particular emphasis on rehabilitation, training, and adequate strengthening following injury.

The likely cause of the reduced proprioceptive abilities following LAS is damage to the mechanoreceptors of the lateral ligaments of the ankle.[75] The initial injury causes the ligaments to be stretched, and as the ligaments heal, they remain in an elongated state. This subsequently results in reduced tension of the ligament at any given angle, creating for a misinterpretation of inversion angles moving forward, ultimately putting an individual in a more vulnerable state than prior to the injury. It is established that proprioceptive differences do exist as a result of injury,[59] but proprioception has also been shown to be a predictor of injury in prospective analyses as well.[25] One study in particular showed that among measures of strength, flexibility, and proprioception, the latter was the only measure that proved to be significant in college basketball players.[99] For all subjects, proprioception values were predictors of left ankle injury, but strength and flexibility measures were not significant predictors.

Kinesthesia, or movement threshold, is a means of testing proprioception.[75] Although it has not been extensively investigated at the ankle, it is a valuable testing tool that can provide insight into the neuromuscular function of the joint as a result of injury. Kinesthesia is often assessed by measuring TTDPM in an individual by positioning the investigated joint in a neutral position prior to slowly moving the limb about the joint,[81] and absolute angle error is collected and used in analysis of performance.[42, 83, 110, 112]

Results related to TTDPM are conflicting throughout the literature, however. This is likely a result of varying methods,[75] but the disparity in the findings and the studies that do indicate a significance highlight the importance of investigating and further understanding TTDPM in ankles, as it is paramount to the interests of ankle injury prevention. Glencross and Thornton[42] established that functionally unstable ankles had significant impairment in the ability to detect passive motion. Refshauge et al.,[110] however, found that individuals with a history of ankle sprains had no significant difference in TTDPM measurements between their injured and uninjured limbs. In contrast, a later study by Refshauge et al.[112] reported significant differences in the detection of movement in the directions of inversion and eversion when comparing CAI and control groups.[59] Additional studies have looked at the role of ankle taping, a common prophylactic measure for ankle injuries, on proprioception.[56] Measures of TTDPM appear to have greater error when compared to an unbraced or untaped condition.[67] To further the discrepancy among the literature however, a study by Hubbard and Kaminski[69] reported no significant differences in TTDPM between ankles with a history of instability and uninjured ankles within the same individual. Lim and Tan[83] also did not find side-to-side differences within individuals, but they report strong reliability of a kinesthetic measurement tool, which suggests the usefulness in comparing groups of individuals rather than within-subject differences. This study aims to do that while utilizing similar methodology presented by Lim and Tan.[83] If proprioception is compromised, the ability to detect motion of the foot will be diminished, leading to a heightened risk of injury. Obtaining further understanding of the role ankle sprain history has on TTDPM is important for furthering the prevention of LAS.[174]

2.3.4 Postural Stability

Stacoff et al.[143] reported that ankle sprains account for 15 to 30 percent of all injuries in sports that involve a high volume of cutting movements in a lateral direction, such as soccer, basketball, and tennis. Although the authors were examining the role of footwear design and the lateral stability components of various footwear, they established an important relationship between ankle injury risk and postural stability.

Postural stability is the ability of an individual to maintain their body within the limits of their base of support, utilizing the interaction of their somatosensory, visual, and vestibular orientation inputs.[120, 134, 138] Whether assessed statically or dynamically, tests of postural stability are often used as a gauge to determine ability or likelihood of injury.[59, 126, 168, 171, 173] Diminished postural stability has been shown to be a risk factor for ankle injuries. Male subjects with worse postural stability suffered a higher number of LAS,[87, 173] and females with decreased movement coordination are more likely to sustain LAS.[175]

McGuine et al.[87] prospectively analyzed whether ankle sprain injuries were predictable. Utilizing a rationale that motor control and balance deficits were present after an ankle injury, they assessed if detectable deficits in these traits were present before an injury as well.[87] They measured balance and postural sway in a prospective cohort of male and female basketball players during the preseason to see if the measures could be a predictor of LAS. The 210 subjects in the study were only included if they were at least 12 months removed from their most recent lower extremity injury, and none of the subjects used bracing or taping during the season. In a single season, the cohort suffered 23 LAS. Among those injured, individuals had higher composite scores for balance testing and higher postural sway scores, both of which were reported to represent worse performance of the tasks.[87] It was calculated that the subjects who had higher composite scores for balance testing and/or higher postural sway scores had nearly seven times more LAS than those with lower values.[87] The authors concluded that preseason balance measurements in basketball players, served as a predictor of LAS susceptibility.

In a similar nature, Willems et al.[173] wanted to prospectively see if any measurable risk factors could serve as predictors of injury. Utilizing 241 male physical education students from a university setting, the authors assessed various intrinsic risk factors, including ankle joint position sense, isokinetic muscle strength, and postural control. Postural control was assessed with a Neurocom Balance Master and included several balance measures such as percentage weight baring, postural sway, and center of gravity. In addition, they had a "general balance" measurement tested with the flamingo balance test, and they found that there was a significant association of this test with ankle sprains in that higher scores were present in subjects with a higher risk for the development of ankle sprains.[173] Roughly 18 percent of the male subjects suffered one or more LAS, and four of the subjects suffered bilateral LAS. In another publication from the same study by Willems et al.,[175] 159 female physical education students were prospectively analyzed for ankle injuries. The female subjects were tested for the same intrinsic risk factors for LAS, and 20 percent of the subjects suffered LAS during the 3-year observation period. It was seen that females with less coordination of their postural control were at a greater risk for suffering LAS.[175]

In both Willems papers,[173, 175] subjects were excluded from the analysis if they were injured or had a previous history of significant LAS. Pederson[100] reported that static and dynamic postural stability deficits were seen in individuals with a history of LAS compared to healthy controls. While other papers have further established the deficits in postural stability because of ankle injury, it is significant to see that detectable deficiencies can be seen prior to injury in vulnerable populations. This indicates the need for balance and stability training to be used as a means of reducing the risk of LAS, especially in those more prone to them.

While static postural stability has long been used as an assessment of postural stability, there is a chance important information can be overlooked with standard analysis. Typically, static balance is measured in terms of postural sway, as it relates to the linear excursions from the CoP in the anterior-posterior (AP) and medial-lateral (ML) directions.[113] However, even in controlled settings, impulsive-like muscle movements can alter one's ability to maintain a completely rigid stance,[96] having a negative effect on static postural stability scores.[36] While an individual with CAI might have more sway due to laxities in dynamic stabilizers, there is a chance a poor postural stability score could be misleading, as it has been argued that variability does not necessarily indicate instability.[147] Stergiou and Decker[147] stated that CoP behaviors can evolve over time, and using a nonlinear analysis of dynamic systems to monitor human behavior, such as SampEn, can provide a better understanding of the variability in postural stability and how it relates with pathology.

Single-leg stability trials require simultaneous corrections in the AP and ML directions to avoid loss of balance.[113] A combination of the two directions can be analyzed together, providing a better interpretation of the postural control process, and this is commonly how stability is assessed. A resultant vector related to the magnitude of CoP is commonly used, but direction is overlooked.[123] While the magnitude component provides valuable information quantifying how far the CoP moves from moment to moment, it is possible the magnitude vector could reflect spuriously low readings if incremental movements are going in different directions.[113] For instance, if abrupt directional changes occur during a stability trial, conclusions on postural instability might go unobserved if only the magnitude component is being analyzed. Including a quantification of the change in direction of the CoP from moment to moment will allow for better analysis of variability in postural stability.[113] The SampEn metric, which is a measure of regularity,[116] has also been employed in quantifying the variability. It has been suggested that too much regularity in postural control is reflective of maladaptive behavior, which can contribute to an increased risk of falling.[123]

2.3.5 Neuromuscular Characteristics of Lateral Ankle Sprains

As highlighted above, there appear to be many testable options in relation to one’s risk of suffering an ankle injury. While this proposed study aims to further the understanding of these testable neuromuscular characteristics as a means of comparing groups of CAI-LAS with CON, the study aimed at providing ground work for prospective cohort and epidemiological studies that can utilize the testing modalities proposed herein.[173]

2.4 METHODOLOGICAL CONSIDERATIONS

In this section, the rationale for each laboratory measure used in this study is described. The specific protocols and procedures for each testing method are further detailed in Chapter 3.

2.4.1 Sonomyography

Ultrasound technology was available for this investigation, and it has been shown that sonomyography is an acceptable alternative to imaging and measuring musculature.[85, 86] If less strength is a known risk factor for ankle sprain injuries,[93] there is potential for musculature size to be an indicator of injury risk. By measuring the longitudinal and transverse musculature widths, as well as cross-sectional area, of the tibialis muscle group during this study, the ability to compare group averages was provided for muscles related to dorsiflexion, inversion, eversion, and toe extension.[86] All images were optimized for depth, gain, and foci to allow for the best visualization of the musculature. Currently there is no known literature assessing musculature size via sonomyography in individuals with CAI versus healthy individuals, but if a significant difference was determined in this study, it would provide new knowledge for clinical and research communities. Scans of the peroneus muscle group were also used.[7, 68] In addition, comparing musculature size with other variables tested provided more information on the relationship of musculature size to other neuromuscular deficiencies detectable in CAI-LAS. The ultrasound measurements that were proposed for this study have been shown to have excellent reliability (ICC > 0.92), and the measurement techniques have allowed for significant differences to be detected within and across athletes.[85, 86] Because of this, it was believed this study would be able to measure a detectable difference between the affected limbs of CAI-LAS and the dominant limb of CON with no history of LAS.

2.4.2 Range of Motion

Flexibility of the ankle joint is often compromised because of LAS.[57, 78] Dorsiflexion ROM values are lower in individuals with a history of LAS, leaving the ankle in a vulnerable position for re-injury. Values for plantar flexion ROM have not been reported to be as significantly different as dorsiflexion when comparing individuals with a history of ankle sprains to healthy controls. This study utilized ankle joint dorsiflexion and plantar flexion testing with a goniometer while subject rested on a treatment table, and the protocol for this testing has been reported to have good reliability (ICC = 0.76).[98] Utilization of this measure for ROM will further the knowledge of flexibility differences between the two groups. Including this assessment as part of a battery of testing between CAI-LAS and CON allowed for correlations to be made between ROM values and the outcomes of other laboratory measures related to LAS.

2.4.3 Threshold to Detect Passive Motion

Proprioception deficits have been shown to be a negative outcome after LAS. This deficit in proprioception is believed to be a contributing factor to recurrent LAS.[174] Previous research has utilized tests of proprioception of the ankle, focusing more on passive joint position sense, and the results have been mixed. It is believed testing TTDPM can elicit significant findings related to ankle proprioception. Testing TTDPM, a common measurement of kinesthesia, has not been reported to a great extent in the literature despite TTDPM being argued to be a more effective measurement of proprioception.[94, 95] One study that has assessed kinesthesia of the ankle has shown it to be a highly reliable (ICC = 0.893) means of testing.[83] The addition of headphones playing white noise to eliminate auditory cues, the use of a blindfold to block visual cues, and the utilization of an inflatable pad to minimize tactile cues are common practice during proprioception assessments.[82, 120]

If significant differences were found in proprioception values between CAI-LAS and CON, it was believed a broader understanding of the effects of a CAI-LAS on proprioception could be gleaned. This would allow for future implementation in clinical and research settings. Clinicians will be able to test for proprioceptive deficits as a criterion for return to play while researchers can utilize the positioning and attachment utilized in this study to further the understanding of neuromuscular function as it relates to ankle inversion and eversion. In addition, testing TTDPM as part of a full battery of laboratory measures associated with LAS would allow for further understanding of the relationship between ankle proprioception and other neuromuscular deficiencies related to LAS.

2.4.4 Isometric Strength Testing

Strength is also a known risk factor for LAS, as those with significantly weaker ankle strength have been shown to have a higher risk of suffering LAS.[176] Isometric testing is utilized in sports medicine research due to the ease of quantifying torque, work, and power. For this proposed study, the testing position and attachment used for TTDPM testing was implemented for strength testing as well. With proper instruction, testing an individual against a fixed resistance from a quiet position will allow for more accurate analysis of TTPT, a variable that was believed to serve as an indicator of one’s ability to quickly contract muscles in a corrective manner. By implementing a protocol that can better analyze TTPT in individuals with CAI, a broader knowledge base of the role of strength as a risk factor for LAS was provided. Isometric strength testing could provide further understanding of the role of ankle strength and its relationship to other known neuromuscular deficiencies detectable in individuals with CAI.

2.4.5 Ankle Testing with an Isokinetic Dynamometer

In addition to investigating the potential merit of an expanded test battery for LAS injury prevention, a key component of this study was assessing the validity of utilizing an isokinetic dynamometer for ankle testing. There is a clear need for clinicians to evaluate kinesthetic deficits and to design exercise programs to improve kinesthetic awareness to decrease the risk of re-injury associated with CAI in individuals with multiple LAS.[41] The consistency of measurement methods, however, is lacking, and a majority of studies involve joint position sense testing.[42, 99] It has been argued that TTDPM is a better means of testing proprioception,[94] and a call for further ankle proprioception investigations involving movement detection and its relationship to injury history has been made.[25]

The lack of consistency in measurement tools and methods led to the investigation of ankle TTDPM testing on an isokinetic dynamometer, a common device used in human performance testing. Only one study was found to utilize a dynamometer for kinesthetic testing,[83] and even within these methods, a potential confounder was determined.

The recommended testing position with a Biodex dynamometer (Figure 2) puts the subject into a position that creates an axis of rotation that intersects the ankle at a 45° angle, which results in accessory rotation of the test leg (Figure 3) that may serve a confounding factor in assessing ankle function. For this reason, an alteration to the attachment used for ankle testing on the Biodex has been recommended.

Figure 2. Testing position for the ankle with the Biodex as suggested by the manufacturer, which creates an axis of rotation (red line) through the ankle at a roughly 45-degree angle

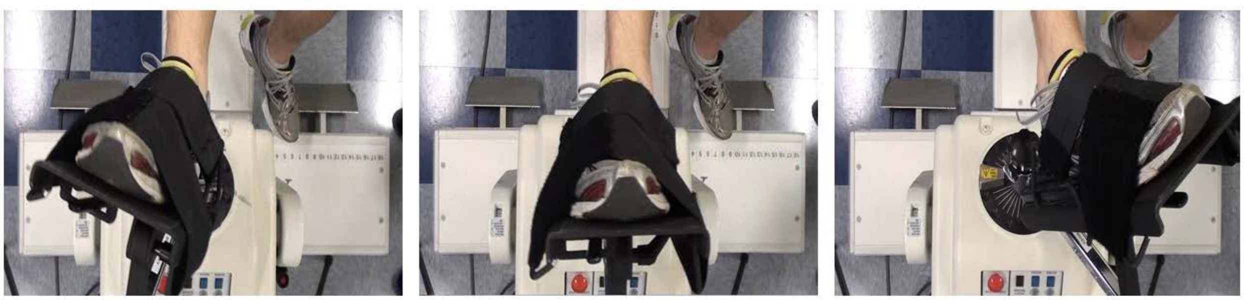


Figure 3. Ankle inversion/eversion testing with the recommended Biodex attachment (BA), which results in more of a foot "swing" and lateral displacement of the lower leg

2.4.5.1 *Modified Attachment for Biodex Ankle Testing*

Because of the concerns with the recommended Biodex attachment (BA), various means of repositioning the footplate attachment were attempted. Eventually, Dr. Nicholas Heebner found that by attaching an additional arm from the hip attachment to the footplate attachment, it allowed for subjects to be positioned for ankle testing with an axis of rotation that is directly in line with the calcaneus (Figure 4). This modification resulted in what will be referred to as the

Heebner Attachment (HA). Testing in this position limits the accessory leg rotation present with the original attachment, and creates movement limited to inversion/eversion about the calcaneus with minimal accessory motion (Figure 5).

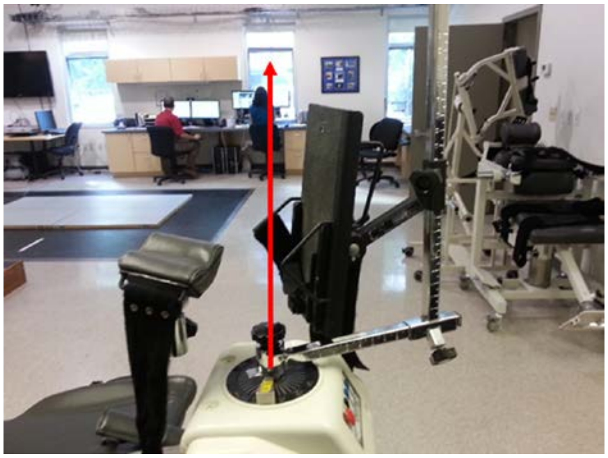


Figure 4. The modified ankle attachment added an additional long arm (vertical silver bar), allowing the footplate to be attached so the axis of rotation (red line) is in line with the foot

Figure 5. Ankle inversion/eversion testing with the modified Heebner attachment (HA), which provides an axis of rotation about the calcaneus and minimal lateral displacement of the lower leg

In a pilot study comparing BA and HA during tests of isokinetic and isometric ankle strength, it was found that HA had less variability in results. The coefficient of variation during isokinetic strength testing for HA was 7.5 compared to 10.4 for BA. During isometric strength trials the coefficient of variation between repeated trials was lower for HA (HA =5.8, BA = 8.8), indicating isometric testing to be a more appropriate assessment of ankle strength with HA.

Additional pilot testing showed that HA had excellent reliability during isometric strength testing ($ICC \geq 0.799$) as well as during TTDPM testing ($ICC \geq 0.805$).

It is agreed upon in the literature that ankle proprioception is a difficult thing to assess, whether it is being investigated with kinesthesia or joint position sense testing.[76] Need for set up time, equipment, and laboratories equipped for the testing, have resulted in a lack of consistency in the methods used. Refshauge et al.[112] utilized what appeared to be a custom-made device for their testing.[111] This is fine except it limited the inversion and eversion motion to 5°, which was exceeded by subjects in both CAI-LAS and CON groups in the current study. The need for a consistent measurement tool in measuring ankle proprioception is further argued by de Jong et al.,[23] who stated performance in different proprioceptive tests is not well correlated, leading to the conclusion that general proprioceptive status cannot be inferred from the assessment of a single proprioceptive test. If the literature is populated with various methodologies and their subsequent various results, it is hard to discern what is accurate information. If a consistent measurement tool can be implemented with an isokinetic dynamometer, a device that is very common in exercise science laboratories and sports medicine clinics, a better understanding of the role of proprioception can be ascertained.

2.4.6 Star Excursion Balance Test

This assessment, as part of a battery of testing, served as an additional measurement of ROM, flexibility, and dynamic postural stability. The SEBT is a unique testing modality, in that it assesses stability while having the subject strive to maximally disturb their base of support.[49, 60] Originally, the SEBT utilized eight directions for maximal reach distance, but the procedures for this study only involved three – anterior, posteromedial, and posterolateral. Research has shown this modification to still be an accurate and valid protocol, while serving to be far more efficient than the original test, as each of the eight directions are highly correlated with one another.[46, 104] Plisky et al.[105] created a composite score calculation from the three directions and used it to measure injury risk. The utilization of the composite score in this study will be to have the ability to compare SEBT outcome to the other collected variables to analyze if a relationship exists between SEBT and the other laboratory measures for ankle injury. Of particular interest will be the relationship to the values collected during ROM testing, as the SEBT can be argued to be a functional measurement of ROM. Another interesting comparison is believed to be the values of SEBT and dynamic postural stability. It was believed seeing the relationship between manually controlled perturbations in balance versus recovery from a standardized dynamic perturbation could provide more knowledge on the testing modalities and provide insight on future direction of assessing dynamic postural stability in clinical and research settings.

2.4.7 Static Postural Stability

Tests of postural stability have been utilized previously as an indicator of one's likelihood of suffering lower extremity injuries.[87] It has been shown that those with poorer scores in postural stability assessment are at a heightened risk of suffering LAS,[168, 170, 173]. The testing protocol typically used is a force plate assessment,[43, 44] which has been shown to have excellent reliability (ICC = 0.94).[133] The specific procedures of this testing are further detailed in Chapter 3, but inclusion of this assessment was believed to provide more information on the differences between CAI-LAS and CON while also allowing for analysis of the relationship between static postural stability and other neuromuscular deficiencies related to LAS.

Simultaneously incorporating a nonlinear measure of postural stability was believed to provide further insight into the differences that exist between CAI-LAS and CON. If large deviations in both magnitude and direction of the CoP were to be seen in calculations incorporating SampEn,[123] observations of greater instability would be quantified, providing a more holistic analysis of postural control.[113]

2.4.8 Dynamic Postural Stability

Static and dynamic postural stability have both been shown to be valid tests,[126, 127] yet they are not strongly correlated. As a result, testing dynamic postural stability can be argued to be more appropriate for an athletic populations.[133] Jump landing tasks have been utilized to assess dynamic postural stability in athletic populations, as it assesses how quickly an individual is able to stabilize after a dynamic task. With the implementation of force plates, performance markers for this task utilize ground reaction force data that is sensitive to changes in forces in the AP, ML, and vertical directions. The protocol prosed for this study has been utilized in previous studies and has been shown to be valid and have excellent reliability (ICC = 0.96).[171] The implementation of a test of dynamic postural stability in this study was believed to allow for further understanding of the postural stability differences that exist between CAI-LAS and CON while also furthering the understanding of dynamic postural stability and its relationship to other measurable neuromuscular deficiencies detectable in individuals with CAI.

2.5 SUMMARY

The burden of LAS is evident. It is an injury that affects all individuals, and those that have a more dynamic and more demanding lifestyle, such as athletes and military personnel, are at an exceptionally high risk. The pain, time lost, and financial burden created by this common injurious event are all reasons better screening tools need to be discovered. While many researchers have focused their attention on LAS, there is still little dissipation in its occurrence and effects. If this study could show performance differences in tests of certain known neuromuscular deficiencies related to LAS between CAI-LAS and CON, it would prove beneficial to include a comprehensive battery of tests to assess at-risk individuals. Testing methods that can discriminate differences in CAI-LAS and CON can help highlight deficiencies with this battery, which can be used in the implementation of rehabilitation and training strategies to help lower the occurrence of LAS.

This proposed study is believed to add to the literature a further understanding of the effects of LAS on individuals, and specifically how the effects of CAI-LAS discriminate between the groups in tests of ROM, proprioception, strength, and postural stability. As indicated in the sections above, while comparing CAI-LAS to CON is common for understanding LAS, it was the aim of this paper to consolidate multiple laboratory measures related to LAS risk factors into a single study. There have been separate studies on previous ankle injury,[6, 10, 88] ROM,[78, 166] proprioception,[42, 83, 110, 112] strength,[16, 172, 176] and postural stability.[87, 143, 173] However, there are very few studies that have incorporated all facets into a single study. If significant differences were detected in this study, there would be potential for clinicians and researchers to utilize a distinct battery of testing to determine one's likelihood of suffering an LAS while also honing in on specific deficiencies of an individual. This is believed to aide in providing specific training programs and highlight targeted weaknesses to monitor during competitions and better forecast appropriate return to play timelines for those at a higher likelihood of injury. It was hypothesized comparing groups will enable the further discrimination between CAI-LAS and CON and provide more significant findings to the literature while simultaneously providing insight into future research initiatives and enhancing clinical rehabilitation efforts for those who suffer LAS.

3.0 METHODS

3.1 STUDY DESIGN

This study utilized a cross-sectional study design.[74, 121] Equal subject numbers were recruited for two investigated groups in this study. The first group consisted of male club-level soccer players with CAI that resulted from LAS sustained during the past two years. The CON group consisted of healthy male club-level soccer athletes with no history of LAS.

3.2 SUBJECT RECRUITMENT

Ethical approval was obtained from the Human Research Protection Office (HRPO) of the University of Pittsburgh prior to implementation of all research procedures. Following approval from the University of Pittsburgh's HRPO, male soccer players with CAI-LAS as well as an equal number of CON were recruited to participate in this study. Potential subjects contacted the Principal Investigator, who administered a brief telephone screen relative to inclusion and exclusion criteria to gauge the eligibility of the individual. Questions on the phone screen included queries related to ankle sprain injury history to ensure CAI resulted from a non-contact lateral ankle sprain and information regarding current pain levels associated with CAI. Questions were also asked to ensure no injury history for CON, no vestibular or balance issues for subjects, and no history of lower extremity surgeries. Prior to participation, subjects provided written informed consent in accordance with HRPO standards.

3.3 SUBJECT CHARACTERISTICS

Club-level male soccer players ages 18-35 were recruited. Equal numbers of subjects with CAI-LAS and CON were targeted. Potential subjects claiming to have CAI-LAS were asked about the frequency, severity, and professional diagnosis of their previous injury or injuries and to which limb the injury occurred. Potential subjects for the CAI-LAS group needed to have suffered a LAS no less than three months and no more than 24 months prior to data collection. Potential CAI-LAS subjects were also assessed with the Cumberland Ankle Instability Tool (CAIT) questionnaire (Appendix B) to determine level of ankle sprain injury severity and to properly classify one as a sufferer of CAI.[61] Subjects with a cumulative CAIT score of 24 or less were considered for inclusion in the study, as it has been used as a more conservative measure to ensure group allocation meets CAI criteria.[62, 131] Individuals were not included in the study if they met or developed any of the items listed as exclusion criteria.

3.3.1 Exclusion Criteria

Subjects were excluded from the study if they sustained any lower extremity injury within the previous three months that limited their participation in normal fitness activities and exercises. Potential CAI-LAS subjects were excluded from participation if they had not sustained LAS within the previous 24 months. Subjects were also excluded from consideration in the CAI-LAS group if they had a cumulative CAIT score of 25 or greater.[107] Even though 27.5 has been suggested as a threshold for determination, a score less than 25 would serve as a more conservative indication of one's allocation to the CAI-LAS group in the investigation.[62, 131] Any history of surgery or reconstruction to the injured or dominant limb also excluded individuals from participation in the study. Subjects were excluded if they had any lingering pain at or around the ankle as a result of CAI-LAS. Subjects were also excluded if they had a history of vestibular or balance disorders that affect their ability to perform SEBT or stability measures.

3.4 SAMPLE SIZE JUSTIFICATION

An *a priori* power analysis was performed using G*Power 3 statistical software.[35] Previous data from a study that utilized a Biodex System 3 Dynamometer to collect measures of proprioception and strength at the ankle was used in calculating a sample size for this study. Utilizing previously reported data from Willems et al.,[174] a large effect size of d = 0.8 was assumed for a two-tailed t-test that compares the difference between two independent means.[108] Accounting for two groups – CAI-LAS and CON – along with an alpha level of $p = 0.05$ and a desired power of 80%, a total sample size of 52 was necessary for this study, with 26 individuals in each group.[174] To account for 10% attrition or data loss, three additional subjects were recruited for each group, bringing the desired total sample size to 58 subjects.

3.5 INSTRUMENTATION

All items listed below were utilized during the data collection portion of the study. Subjects reported to the Neuromuscular Research Laboratory (NMRL) for a single test session.

3.5.1 Demographic Data

Data collected for subject demographics included gender, age, height, weight, and body fat percentage. A wall-mounted stadiometer (Seca, Hanover, MD) was used to collect height, and an electronic scale (Life Measurement Instruments, Concord, CA) was used to collect weight. Body fat percentage was collected as part of body composition analysis.

3.5.2 Body Composition

Body composition analysis was conducted with the Bod Pod Body Composition System (Life Measurement Instruments, Concord, CA). The testing device was a fiberglass structure that houses two chambers; a reference chamber and the test chamber. The subject sat in the test chamber while air moved between the two chambers to measure air displacement plethysmography. Displacement provided a reading of body volume, which was then calculated with body mass to estimate density. Density was used in gender- and ethnic-specific calculations to provide an estimation of body fat percentage. Variations in room conditions, such as temperature, were accounted for with daily calibrations and an additional two-point calibration process that was used for normalization prior to each test.

3.5.3 Ultrasound Muscle Imaging

Ultrasound measurements were collected on the test limb of each subject using the X-Porte Ultrasound (FUJIFILM SonoSite, Inc., Bothell, WA) (Figure 6) while the subject was supine on a treatment table with their legs extended. Measurements were collected from captured images of the tibial musculature and peroneal muscle group.[7, 68, 86] Ultrasound images were collected using the SonoSite HFL50 probe, which had a measurement range of 15-6 MHz. Images were saved to an external memory device and transferred to a personal computer, where the images were analyzed using ImageJ software (National Institutes of Health, Bethesda, MD).

Figure 6. SonoSite Ultrasound

3.5.4 Range of Motion Testing

A 12-inch universal goniometer (Aircast, Summit, NJ) was used to assess static ROM of the ankle. For all measures, maximum ROM was measured to the nearest one degree. Subjects were long-sitting on a treatment table with their feet hanging over the edge for testing ROM. Later in the data collection session, the Star Excursion Balance Test (SEBT) was used as a functional measure of ROM and flexibility. For this test, three strips of athletic tape roughly 120 cm in length were placed on the laboratory floor. Each strip began from the same origin and the lines were spaced out 120 degrees from one another, creating a y-shape. Maximum reach distance was the collected measure during this test, and a measuring tape was used to measure this distance. Leg length was measured prior to the SEBT with a Gulick Tape Measure (Creative Health Products, Ann Arbor, MI).

3.5.5 Biodex Testing

The Biodex System III isokinetic dynamometer (Biodex Medical Systems, Inc., Shirley, NY) was used to measure both TTDPM and isometric strength of the ankle. Strength values collected and analyzed were peak torque, TTPT, and normalized peak torque during maximal isometric inversion and eversion contractions. Isokinetic dynamometers are a popular tool for both research and clinical measurements of TTDPM as well as TTPT.[95] Additional instruments used during TTDPM testing were a blindfold and headphones playing white noise that was used to eliminate visual and auditory cues, respectively. Small inflatable padding (Figure 7) was placed around the foot, without covering the talocrural joint, to mask cutaneous cues and tactile feedback during testing.

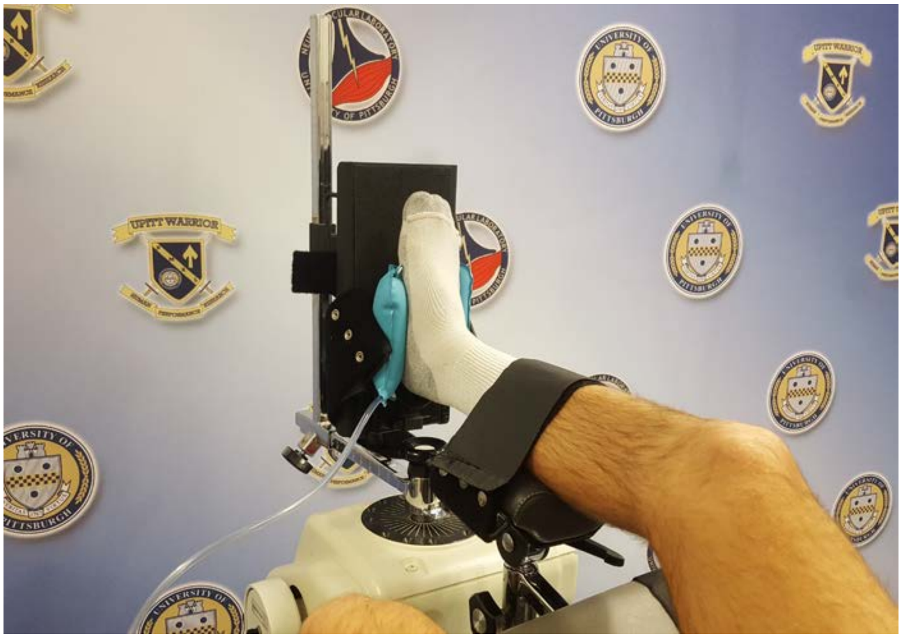


Figure 7. Footplate padding for TTDPM testing

3.5.6 Force Plate System

A piezoelectric force plate (Kistler 9286A, Amherst, NY) was used to calculate ground reaction force data, which was used in the assessment of static and dynamic postural stability. The force plate was embedded in a custom-made platform, which allowed the subject to take off from a surface level to the force plate during jump landing tasks. A sampling frequency of 1200 Hz was used during static trials to allow for additional calculations of SampEn related to the CoP.[113] A sampling frequency of 1200 Hz was also used for force plate measures during the dynamic task. Data were amplified and passed through an analog to digital board (Vicon Motion Systems Inc., Centennial, CO) before being stored on a personal computer.

3.6 TESTING PROCEDURES

Subjects reported to the NRML for a single two-hour session. The visit began with familiarization of the testing protocol, a confirmation of the individual's desire to participate, and the obtainment of written informed consent. Before any data collection, subjects were provided a copy of an Informed Consent Document approved by the University of Pittsburgh's HRPO. The principal investigator explained the testing procedures and discussed the consent document, allowing the potential subject to interject questions or comments. The subject's signature served as the providing of informed consent, after which the inclusion and exclusion criteria was reconfirmed. Subjects reporting for the CAI-LAS group were also assessed a brief questionnaire (Appendix B) to assess their injury history. The data served as additional demographic information. As long as the individual was between three and twenty-four months removed from a lower extremity injury and was clear for all activities, testing procedures commenced.

Subjects were given ample opportunity to familiarize themselves with any protocol that they were unfamiliar with in order to "prime" the nervous system and mitigate any acute learning effects that might serve as confounders in any of the collected data.[106] Specific test order was also utilized for each subject in an attempt to have any one measure create diminished performance on another task.[54] The passive tests were conducted first to reduce any potential effect of fatigue on subsequent tests, the higher skill task of proprioception assessments followed, with isometric strength assessments being conducted prior to finishing with the functional tasks.[18] Test order was: Injury Questionnaire, Informed Consent, Demographic Data Collection, Ultrasound Assessment, Static ROM Testing, TTDPM, Isometric Strength Testing, SEBT, Single-leg Balance Test, and Dynamic Postural Stability.

3.6.1 Demographic Data

Subjects were barefoot for collection of height and in minimal clothing for the collection of weight. Minimal clothing was spandex shorts and a swim cap for all subjects. This was the attire needed for the body composition analysis as well. Leg length, for normalization of SEBT distances, was also measured at this time by measuring the distance from the anterior superior iliac spine to the medial malleolus. For CAI-LAS subjects, the affected side was the tested limb for this and all other tests. For CON, the dominant limb was investigated. Limb dominance was determined by asking the subject which limb they would use to kick a ball for distance and accuracy. The specific demographic variables analyzed were age, height, and weight.

3.6.2 Body Composition

Body composition, along with height and weight, was collected at the beginning of the test session as demographic data. The data was used to assess if there were any significant differences between the CAI-LAS and CON groups. Body composition was assessed with the Bod Pod. In addition to the minimal clothing, subjects also wore a swim cap covering hair to reduce air impedance. Once the Bod Pod had been run through a two-point calibration, subjects were asked to sit in the test chamber with hands in their lap. They could breathe normally but were instructed to keep movement to a minimum. At least two volume measurements of 45 seconds each were performed, with the investigator checking on the subject in between. If, for some reason, the two tests had inconsistent readings, a third measurement was conducted to correct for a standard deviation that exceeded the acceptable range set by the manufacturer. The specific variable analyzed for inclusion with demographic data was body fat percentage.

3.6.3 Ultrasound Muscle Imaging

Subjects were supine on a treatment table with socks and shoes removed. Subjects were asked to slightly bend their test limb knee for palpation of the fibular head. A mark was placed at this location, and a measuring tape was used to measure from the fibular head to the lateral malleolus of the test limb. The proximal 20% of this distance was marked (Figure 8) and utilized as the imaging location for all subjects.[86]

Figure 8. Probe placement scan locations (*) at proximal 20% for the tibialis muscle group and distal 40% for the peroneal muscle group

Ultrasound gel was placed on the SonoSite HFL50 imaging probe, and three ultrasound readings were collected for the peroneal muscle group by placing the transducer over the lateral surface of the fibula.[68] The probe was placed in the transverse plane to view the peroneus brevis and peroneus longus in their short axis.[7] Three longitudinal images (Figure 9) were collected by placing the probe in line with the long axis of the lower leg.[85] Three transverse images were also collected by aligning the probe perpendicular to the long axis of the lower leg (Figure 10).

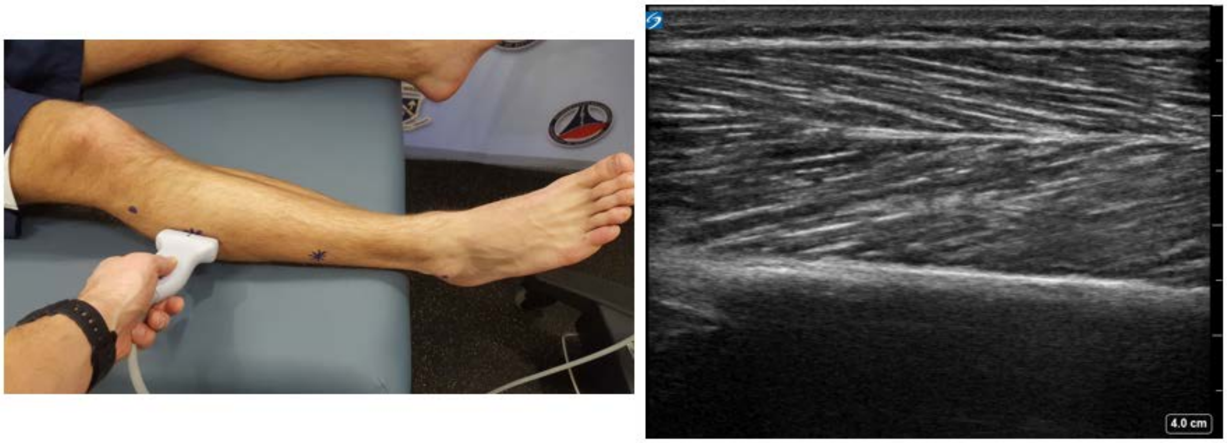


Figure 9. Longitudinal scan

Figure 10. Transverse scan

Ultrasound readings were also be collected for the lateral ankle by placing the transducer over lateral surface of fibula along the line between the fibular head and lateral malleolus.[68] A mark was placed at the distal 40% of this line, and the probe was placed above the lateral malleolus in the transverse plane to view the peroneal muscles in their short axis (Figure 11).[7]

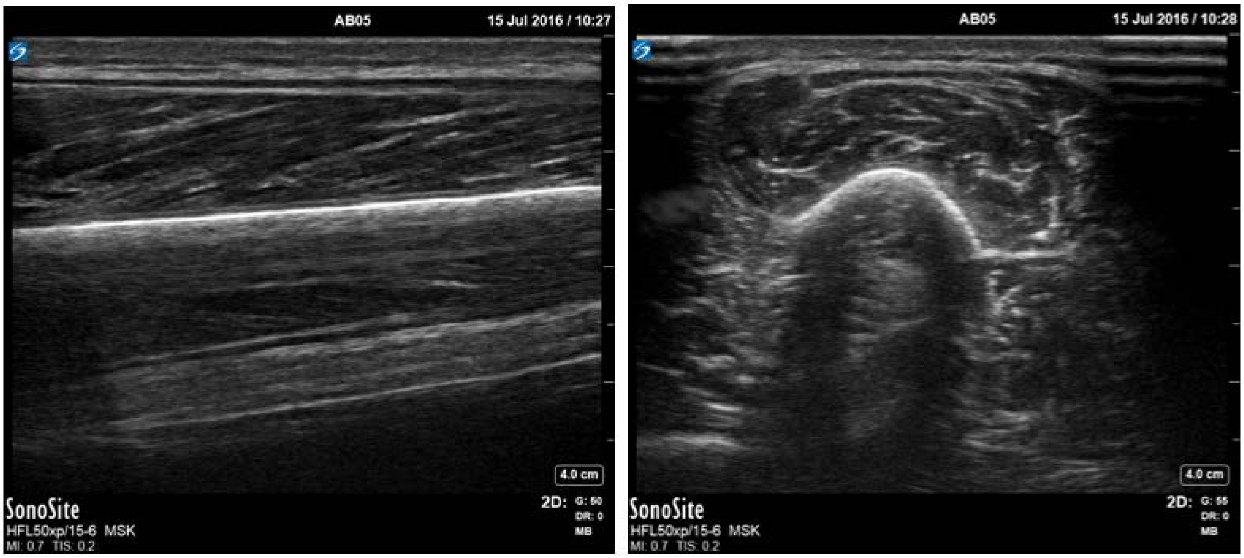


Figure 11. Longitudinal (left) and transverse scans at the lateral ankle (distal 40%)

All images were collected at a scale and depth of 4.0 cm to clearly capture lateral musculature. Images were saved onto the SonoSite hardware and exported to a personal computer with a portable memory device. Images on the personal computer were then analyzed and measured with ImageJ software. ImageJ software allowed for measurement of cross-sectional area of the musculature using the transverse image. The specific variables analyzed with ultrasound muscle imaging were musculature width in both planes and musculature cross-sectional area in the transverse plane.

3.6.4 Static Range of Motion Testing

Subjects remained on the treatment table and barefoot for ROM testing of the ankle. They were supine and long-sitting with their foot hanging off the end of the treatment table. The subjects were asked to plantar flex their foot as far as possible while an examiner maintained the subject's subtalar joint in a neutral position throughout the test. A standard goniometer was used to record the angle formed by the lateral midline of the leg, on a line from the head of the fibula to the tip of the lateral malleolus, and the lateral midline of the foot, in line with the border of the rearfoot (calcaneus). A total of three measurements was taken, and the average was used for data analysis. While in the same position and with similar measurement techniques, the subject then dorsiflexed their foot as far as possible for a total of three measurements that were averaged for analysis. The protocol for this testing has been reported to have good reliability (ICC = 0.76).[98] The specific variables analyzed with ROM testing were maximal plantar flexion and maximal dorsiflexion.

3.6.5 Threshold to Detect Passive Motion

The subject, while still barefoot, then moved to the Biodex testing chair. The subject was seated upright in the chair and mechanical adjustments to the chair were made to standardize patient positioning. The fore-aft position of the seat back was adjusted so the test foot was aligned with the foot plate attachment (Figure 12), and the height of the chair was adjusted so the lower leg was horizontal with the ground and the knee was at roughly 45 degrees of flexion. Two shoulder straps and a waist belt were tightened to keep the subject in the same position throughout testing trials but still be comfortable.

Figure 12. Foot positioning for testing with the Biodex attachment

The subject was fitted with a blindfold, foam earplugs, and over-the-ear headphones. The subject's foot was positioned in the padding prior to straps being fixed. Safety limits of the device were set at maximal inversion and maximal eversion ROM for each subject. During testing, the subject's foot was positioned to a neutral position of roughly seven degrees of inversion (Figure 13) in the Biodex software, as this has been deemed to be an ideal test position when looking at both inversion and eversion.[153] The subject was instructed to, "press the remote button once you are able to sense motion at your ankle and you can distinguish the direction of rotation. Within a minute of the white noise beginning the device will begin to move." To initiate the testing, white noise was turned on and the researcher engaged the dynamometer to begin moving at a speed of 0.25°/sec in either an inversion or eversion direction. Once the subject pressed the remote button, the dynamometer stopped moving, and the subject was asked which direction their foot was moving. The end position was recorded and used for analysis as the primary variable was absolute error as measured in the number of degrees toward inversion and the number of degrees toward eversion from the beginning position. The test limb was then returned to the starting position. Each subject was allowed one practice trial in each direction prior to the measured trials. Each direction had six successful trials collected in randomized order. The reliability of TTDPM at this speed has yielded good to excellent reliability (ICC [3,k] = 0.879 – 0.917, SEM = 0.194° – 0.216°).[94] The reliability of similar positioning set up for the foot and ankle for tests of kinesthesia has also been shown to be very good (ICC = 0.825 – 0.89).[83] The specific variable analyzed with TTDPM testing was average degrees of rotation into correctly identified eversion or eversion.

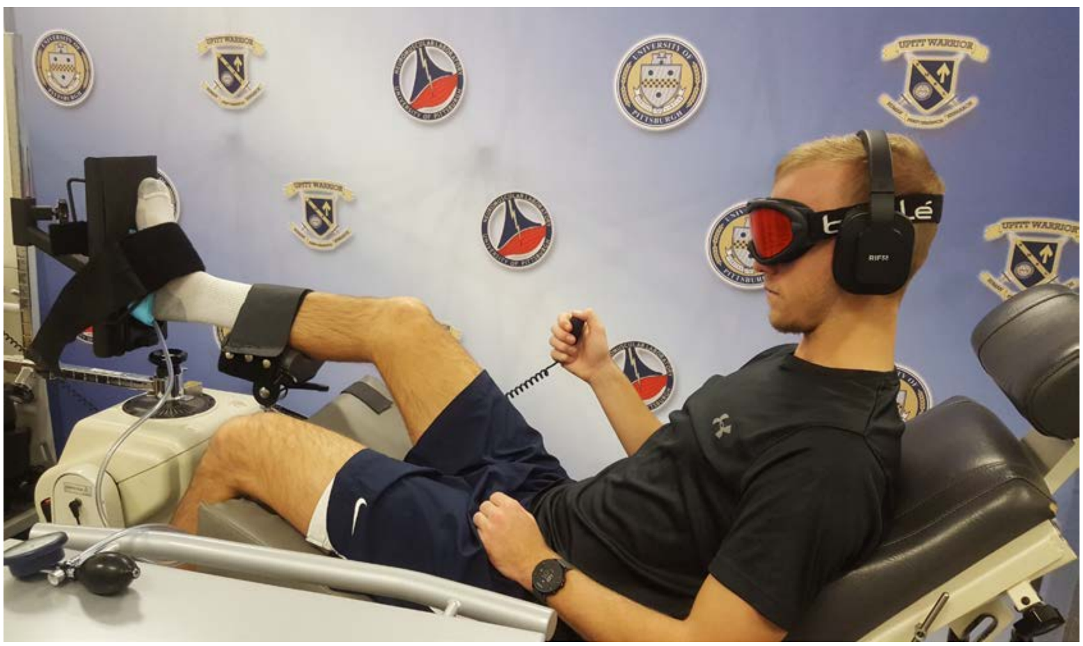


Figure 13. Subject setup and positioning for TTDPM testing

3.6.6 Isometric Strength Testing

Ankle inversion and eversion strength and TTPT of the dominant ankle was measured simultaneously on the Biodex system III isokinetic dynamometer. Subjects were seated in the

Biodex chair in the same position as TTDPM trials, but the padding was removed from the footplate attachment. Isometric strength testing was completed with the subject's foot placed into roughly seven degrees of inversion for optimal results.[153] The ROM limits on the Biodex dynamometer were then set per maximal inversion and eversion ranges for the subjects. The tester then placed the subject's foot into a slightly inverted position prior to initiating testing.[153] After verification of the subject's body position and dynamometer settings, the subject was given two sets of practice/warm-up trials, one at 50% effort and one at 100% effort. The tester instructed the subject to begin with their foot relaxed and neutral prior to engaging the first contraction towards eversion after a countdown of "3 – 2 – 1 – GO." The subject maintained this first contraction for five seconds prior to resting for five seconds. The instructions were repeated and the subject then contracted towards inversion and held that contraction for five seconds. This pattern was repeated during the collected trials until three measurements were collected for each direction. Subjects were not able to see the computer instructions in order to avoid premature contraction, allowing for appropriate collection of TTPT measurements in each subject. Subjects were given a one-minute rest period after the last warm-up trial prior to initiating maximal contractions for the collected trials where they were instructed to "push as hard and as fast as you can." The specific variables analyzed during strength testing were absolute strength, normalized strength, and TTPT in each direction.

3.6.7 Functional Range of Motion and Stability Testing

In addition to the static ROM assessments, subjects performed a measure of functional ROM, utilizing a modification of the SEBT.[104, 105] The SEBT originally utilized eight directions, but only three – anterior, posteromedial, and posterolateral – were used for this study to reduce redundancy of the test and minimize the potential for fatigue.[49, 67, 105] Utilizing only these three directions have been shown to have very good reliability (ICC = 0.84 – 0.92).[92] Subjects were asked to stand on their test limb, with their foot positioned on the center of the three-line grid so the medial and lateral malleoli were in line with the center intersection of all three lines. While maintaining a single-leg stance, the subjects were instructed to reach with their non-stance leg as far as possible in each direction along the tape line and tapping the ground with the great toe of their non-stance leg and avoiding touching completely down with their reach leg. While reaching, the subject was instructed to maintain a flat stance of their test limb foot and maintain its original position. Testing direction order was standardized for all subjects to control for consistency of administration of the test with subjects first reaching maximally in the anterior direction, then maximally in the posteromedial direction before reaching maximally in the posterolateral direction.[50, 104] Trials were considered complete once the subject had reached out to all three directions and returned the non-stance leg to the starting position. Trials were discarded if the subject failed to maintain unilateral stance, lifted or moved the stance foot from the center of the grid, touched down with more than the great toe of the reach leg, or failed to return the reach foot to the starting position.[104] Subjects were given at least four practice trials prior to the collected trials,[60] and they were provided as much rest as necessary between the three collected trials.[72] Maximal reach distance in each direction during each trial was recorded for data analysis. Subjects remained barefoot for functional ROM and stability testing. The specific variables analyzed with SEBT testing were maximal reach distance, normalized reach distance, and composite SEBT score.

3.6.8 Static Postural Stability Assessment

Static postural stability was assessed with a single-leg balance test on a force plate.[43]. This test has been shown to have excellent intersession reliability (ICC = 0.90 – 0.94).[134] While still barefoot, subjects were asked to stand on their test limb in the middle of the force plate with their non-dominant leg slightly flexed at the hip and knee to maintain the non-stance foot slightly off the ground. Subjects were further instructed to keep their hands on hips and to focus straight forward. During collection, subjects held this position for 30 seconds and remained as motionless as possible prior to relaxing. Three trials were performed with eyes open, and three trials were performed with eyes closed.

Trials were discarded if the subjects placed their non-stance leg on the ground outside of the force plate or if the non-stance limb touched any portion of the dominant leg during the trial. Trials were also discarded if the subject hopped or shifted the stance leg, and trials were recollected if the hands came off the hips for greater than five seconds. Trials were not discarded if the non-stance limb touched down on the force plate during the trial, granted the non-stance leg was quickly returned to the starting position. Subjects were instructed to correct their position as quickly as possible if a disturbance in the starting position occurred. Subjects were given practice trials prior to data collection and were given a one-minute rest between trials. The average output of the three eyes open and three eyes closed trials was used for analysis. The specific variables analyzed were linear and nonlinear measures of postural stability averaged over the three trials in each condition.

3.6.9 Dynamic Postural Stability Index

Dynamic postural stability was assessed with an AP direction jump, as well as an ML direction jump, and performance was measured with force plate data processed into the formula for the dynamic postural stability index (DPSI). This test has been shown to have excellent reliability (ICC = 0.86 – 0.92). For the AP DPSI jumps, subjects stood on two legs at a distance of 40% of their body height from the force plate, jumped toward the force plate, initiating enough height to clear a 30-centimeter hurdle, which was placed at the midpoint of the 40% distance.[134] This allowed for a normalization of jump distance across all subjects. This protocol is a modification of the protocol used by Ross and Wikstrom,[127, 130, 171] which normalized jump height rather than distance by utilizing a measure of maximal jump height prior to the assessment. For this study, subjects were instructed to land on their test limb, aiming for the center of the force plate. Upon landing, subjects were asked to stabilize as quickly as possible, place hands on hips, and balance for a period of roughly five seconds while focusing straight forward. For ML DPSI, subjects began at a starting line that was placed at 33% of their body height away from the force plate while aligned perpendicular to the force plate. They took off in the direction of their test limb side with two legs, and utilized enough height to clear a 15-centimeter hurdle.[134] Subjects landed with their test limb on the center of the force plate, stabilized, and balanced for five seconds with hands on hips.

For both AP and ML DPSI, upper extremity movement was not restricted, but subjects were encouraged to balance as soon as possible and place hands on hips once balance was attained.[134] Jump trials were discarded and re-assessed if the subject failed to clear or contacted the jump hurdle. Trials were also discarded if the non-stance leg touched the test limb or the ground. If the subject's test limb heel shifted upon landing or if a bounce occurred after initial contact with the force plate, the trials were recollected. The subjects were asked to continue until three successful trials were collected for each jump task, and the successful jumps were averaged and used for data analysis. The specific variables analyzed were the average DPSI score across the three trials in each direction.

3.7 DATA REDUCTION

Demographic and strength data was manually entered into a database on a personal computer by the principal investigator. Strength values normalized to body weight allowed for comparison of strength values between subjects. For the DPSI variables, data were reduced within Vicon Nexus Software (Vicon Motion Systems Inc., Centennial, CO) and processed with a custom script in Matlab R2012a (The Mathworks, Natick, MA).

3.7.1 Ultrasound Images

Saved ultrasound images were analyzed and measured on a personal computer using ImageJ software (Figure 14). The 4.0 cm scale from SonoSite corresponded to a scale of 152 pixels = 1 cm in ImageJ, and the scale was set for each image. For the longitudinal images, a straight-line distance from the posterior fascia to the anterior fascia was measured. This measurement technique has been shown to have excellent reliability (ICC = 0.920). For the transverse images, a straight-line distance from an anatomical landmark near the tibial fascia to the proximal fascia was measured. This measurement has been shown to have excellent reliability as well (ICC = 0.937). Additionally, the transverse images were used to assess cross-sectional area of the anterior tibialis musculature group.[85] Images were traced along the fascial line with the polygon tracing tool in ImageJ, and test-retest reliability of this measurement technique also has shown excellent reliability (ICC = 0.981). Images for the lateral leg evaluation of the peroneals utilized the same procedures as the transverse images. The average of the three measurements for each of the four separate scans was used for final analysis, and group differences in musculature size was used to compare the two groups.

Figure 14. ImageJ processing

3.7.2 Range of Motion

The average values for plantar flexion and dorsiflexion was recorded for each subject. These values were used to compare group averages to assess if any significant group differences in ROM of the ankle are detectable in the two groups.

3.7.3 Threshold to Detect Passive Motion

Proprioception data was analyzed using the Biodex Research Toolkit (Biodex Medical Systems, Inc.). Threshold to detect passive motion was calculated as the difference in degrees for each direction, measured as the number of degrees from the initial position to the final position.[94] Six successful trials were collected for each direction, and the deviation from the starting position was analyzed. The average error of the six trials was entered for each subject, and group averages were calculated for CAI-LAS and CON. The degrees of error in the two groups was analyzed to determine if there were any significant group differences in proprioception of the ankle.

3.7.4 Strength Variables

Isometric strength testing values were analyzed with the Biodex Advantage Software. The average peak torque from the three isometric trials was calculated and expressed as a percentage of the subject's body weight, allowing for comparisons of normalized strength to be made across individuals and across groups. Raw data from the Biodex system were exported to a personal computer for analysis in Microsoft Excel in order to calculate TTPT. Onset was determined by the subject initiating their contraction and exceeding five percent of their maximal contraction. The time it took the subject to achieve 95 percent of maximal torque was analyzed as TTPT for that trial. The average of the three trials in each direction was recorded as part of a group mean to see if any significant group differences existed between the two groups.

3.7.5 Star Excursion Balance Test

Maximal reach distance during the SEBT was recorded with a measuring tape from the center of the grid to the point reached. Raw scores were normalized to leg length by dividing the maximal reach distance by recorded leg length and multiplying by 10.[46] Normalized reach distance was calculated for each direction of the SEBT, and an average score for each direction was calculated from the distances of each trial.[148] A composite score was calculated as the sum of each normalized average, divided by three. This value contributed to a group mean that was used to compare group differences to see if any significant differences existed in functional ROM and balance in the two groups.

3.7.6 Static Postural Stability

Force plate data was passed through a zero-lag 4th order low pass Butterworth filter with a 10 Hz cutoff frequency and processed using a custom MATLAB (v7.0.4, Natick, MA) script file.[114] Single-leg balance test variables were calculated as the standard deviation of ground reaction forces (GRF) data in the AP, ML, and vertical directions using the equation where x was equal to each force measurement, X was equal to the mean of all force measurements in each direction, and n was equal to the number of measurements in the data set:[1]

$$\mathrm{SD} = \sqrt{\frac{\sum\ (x - X)^{2}}{n - 1}}$$

The average standard deviation was calculated in each direction from each of the 30-second trials. Simultaneously, nonlinear measurements were analyzed from the 30-second trial using a measure of sample entropy (SampEn).[77, 123] The criterion for SampEn was originally proposed by Lake et al.,[77] who derived it from approximate entropy. Lake et al.[77] stated, "SampEn(*m*,*r*,*N*) in the negative natural logarithm of the conditional probability that a dataset of length *N*, having repeated itself within a tolerance r for m points, will also repeat itself for $m + 1$ points, without allowing self-matches."

$$\mathrm{SampEn}(m, r, N) = -\log\left(\frac{A(r)}{B(r)}\right)$$

Ramdani et al.[109] details the equations that result in $A(r)$ and $B(r)$, which represent the total number of template matches in an m-dimensional phase space within a tolerance r. Additional calculation methods for directional displacement of CoP provided by Rhea et al.[113] were utilized, resulting in a total of eight variables were calculated from the CoP data; four in the AP and ML dimensions (Root Mean Square (RMS) x and y, Peak-to-peak Min-max Excursion (P2P) x and y, Normalized Path Length (NPL), and SampEn). The other four were calculated from the resultant vector created from the combined AP and ML time series (Normalized Path Length (NPL), and SampEn resultant magnitude and SampEn resultant direction). Path length was calculated with the following equation where N was the number of data points in the CoP displacement and i was each successive data point:

$$\text{Path Length} = \sum_{i=1}^{N=1} \sqrt{(\mathrm{AP}_{i+1} - \mathrm{AP}_i)^2 + (\mathrm{ML}_{i+1} - \mathrm{ML}_i)^2}$$

The direction of displacement between two successive CoP positions was calculated as Φ. The following formula was used to calculate Φ where y was the difference in successive AP positions, and x was the difference in successive ML positions:

$$\phi_i = \tan^{-1}(y, x)$$

An angular variable called heading change (ΔΦ) was analyzed as the quantification of the magnitude of displacement of Φ from moment to moment during the single-leg balance test. Further differences in postural stability were detectable in CAI-LAS and CON with the utilization of this analysis of CoP.[113]

In analyzing SampEn several considerations needed to be made in a custom Matlab code. First, each of the 30-second trials was down-sampled to 120 Hz to avoid redundancy in the data.[109] An *m* of 2, was used to compare two consecutive data points to another set of consecutive data points, which lowered the number of self-matches in the experimental data.[181] An *r* equal to 0.07xSD was used in the current analysis, as suggested by Rhea et al.[113] A higher *r* would prevent more noticeable features in the data to be distinguished,[77] and the suggested *r* allowed for the independent analysis of both the AP and ML time series.

3.7.7 Dynamic Postural Stability

The dynamic postural stability index (DPSI) was calculated using GRF data in the x, y, and z directions collected by the force plate during a jump landing task. The DPSI is a composite score of the medial-lateral stability index (MLSI), anterior-posterior stability index (APSI), and vertical stability index (VSI).[134, 169, 171] The following formula was used to calculate DPSI:[22]

$$\text{DPSI} = \frac{\sum\left(\frac{0-x}{body\ weight}\right)^2 + \sum\left(\frac{0-y}{body\ weight}\right)^2 + \sum\left(\frac{body\ weight - z}{body\ weight}\right)^2}{number\ of\ data\ points}$$

The MLSI and APSI were calculated by the mean square deviations of fluctuations around a zero point in the frontal (x) and sagittal (y) axes of the force plate, respectively. The VSI was calculated by assessing the fluctuations from the subject's bodyweight in the vertical (z) direction of the force plate.[22] All stability indices were calculated using the first three seconds of GRF data following initial contact with the force plate. The average of three successful trials was used to calculate DPSI scores. Analog data collected from the force plate during the jump trials were exported by Vicon Nexus Software and processed through a Matlab script.

3.8 STATISTICAL ANALYSIS

All variables were analyzed using SPSS (v23, SPSS Inc., Chicago, IL), including those generated with custom Matlab scripts. Descriptive statistics were calculated for all variables (means, standard deviations, medians, interquartile ranges). All data were examined for normality using the Shapiro-Wilk test, and normally distributed data were analyzed using independent samples t-tests to compare mean differences between the CAI-LAS group and CON. Groups were compared in ultrasound measurements, ROM values, TTDPM, isometric ankle inversion and eversion strength values, TTPT, SEBT, static balance assessment, and DPSI scores to determine if there was a significant difference between the groups. The Mann-Whitney U test was used for analysis for any variables that were not normally distributed. An alpha level of 0.05, 2-sided was set *a priori* as a significance level for statistical analyses. In addition to reporting group averages, post hoc effect sizes were calculated using Cohen's *d* for normally distributed data an effect size correlation *r* for non-normally distributed results.[20, 21, 124]

4.0 RESULTS

The purpose of this study was to examine if differences in laboratory measures of ankle flexibility, proprioception, strength, and postural stability existed in soccer players with and without a history of LAS. The following sections present the analyzed results of data collected during the study. Statistically significant differences, effect sizes, and percent differences among group averages are presented as well. Further interpretation of the results and the conclusions they provide are detailed in the following chapter.

4.1 SUBJECTS

A total of 58 (CON: n = 29; CAI-LAS: n = 29) club-level male soccer players volunteered for this study. Subjects were primarily recruited from the men’s club and varsity soccer teams at the University of Pittsburgh as well as the men’s club team at Carnegie Mellon University. Each participant had a minimum of five years of experience at the competitive level and were currently active with an organized team. Demographic information for both groups is displayed in Table 1. Each of the 58 volunteers successfully completed all modalities in the testing session. The groups were not statistically significantly different ($p \geq 0.250$) for any of the demographic measures, indicating the groups were homogenous samples.

Table 1. Demographic Data

	CON (n = 29)			CAI-LAS (n = 29)			Group Comparison
	Mean ± SD	Median	IQR	Mean ± SD	Median	IQR	
Age (yrs)	21.52 ± 3.08	21.00	18.50, 24.00	22.76 ± 4.46	21.00	19.00, 26.50	p = 0.452 [a]
Height (cm)	180.60 ± 6.73	180.50	176.00, 186.00	180.00 ± 8.74	178.50	173.00, 185.25	p = 0.769
Weight (kg)	78.22 ± 11.58	75.51	71.59, 82.65	78.12 ± 11.14	74.95	70.14, 85.75	p = 1.000 [a]
Body Fat %	15.18 ± 6.96	12.90	10.55, 19.35	13.62 ± 7.43	12.90	8.75, 18.15	p = 0.250 [a]
Limb length (cm)	95.50 ± 4.58	96.00	92.50, 98.00	95.07 ± 7.25	94.00	88.25, 98.25	p = 0.788

[a] *p-value calculated using Mann-Whitney U*

4.1.1 Cumberland Ankle Instability Tool

Prior to testing, each participant responded to the CAIT. No participant in the CON group reported a CAIT score lower than 27, and all the CAI-LAS participants had a 24 or less on the CAIT. The two groups were statistically significantly different based on the CAIT ($p < 0.001$) and average amount of time since last LAS is shown in Table 2.

Table 2. Cumberland Ankle Instability Tool (CAIT) Scores and Injury History

	CON (n = 29)			CAI-LAS (n = 29)			Group Comparison
	Mean ± SD	Median	IQR	Mean ± SD	Median	IQR	
CAIT	30.97 ± 1.27	31.00	31.00, 32.00	22.83 ± 2.54	24.00	23.00, 24.00	p < 0.001 [a]
Time since last sprain (months)	---	--	--	11.97 ± 8.18	10.00	4.00, 20.00	---

[a] *p-value calculated using Mann-Whitney U*

4.2 COLLECTED VARIABLES

The proposed laboratory measurements for this study included lower leg musculature size, ROM, TTDPM, strength, TTPT, SEBT, static postural stability, and dynamic postural stability.

4.2.1 Musculature Size

There were no significant differences between groups in any of the ultrasound measurements of the lower leg musculature ($p \geq 0.489$) (Table 3).

Table 3. Musculature Size (cm) as measured with ultrasound at 20% proximal and 40% distal (Lower Leg) points on the lateral leg between the fibular head and lateral malleolus

	CON (n = 29)			CAI-LAS (n = 29)			Group
	Mean ± SD	Median	IQR	Mean ± SD	Median	IQR	Comparison
Longitudinal (LON)	2.43 ± 0.26	2.43	2.25, 2.60	2.44 ± 0.26	2.43	2.31, 2.61	p = 0.932
Transverse (TRANS)	2.32 ± 0.24	2.32	2.11, 2.50	2.32 ± 0.25	2.34	2.24, 2.50	p = 0.950
Cross-sectional area (CSA)	6.22 ± 1.41	5.90	5.15, 7.19	6.34 ± 1.17	6.53	5.18, 7.05	p = 0.712
Lower Leg LON	1.37 ± 0.22	1.37	1.24, 1.54	1.32 ± 0.27	1.34	1.08, 1.51	p = 0.489
Lower Leg TRANS	1.77 ± 0.21	1.81	1.55, 1.93	1.75 ± 0.24	1.81	1.55, 1.93	p = 0.779
Lower Leg CSA	4.55 ± 0.97	4.21	3.78, 5.08	4.59 ± 0.83	4.72	3.73, 5.17	p = 0.632 [a]

[a] *p-value calculated using Mann-Whitney U*

4.2.2 Range of Motion

There were significant differences ($p < 0.039$) between groups for all measurements related to ROM (Table 4), with CON having greater ROM for each measurement. The group differences for plantar flexion ($d = 0.554$) and dorsiflexion ($r = 0.348$) resulted in medium effect sizes. When plantar flexion and dorsiflexion values were combined to calculate a total ROM arc, the group differences provided a large effect size (d = 0.869).

Table 4. Range of Motion (ROM) of the Ankle and Total ROM

	CON (n = 29)			CAI-LAS (n = 29)			Group Comparison
	Mean ± SD	Median	IQR	Mean ± SD	Median	IQR	
Plantar flexion (°)	49.44 ± 8.50	48.67	42.17, 56.83	44.82 ± 8.17	44.00	38.17, 51.33	p = 0.039
Dorsiflexion (°)	13.77 ± 5.47	12.33	9.83, 18.50	10.14 ± 4.21	9.33	8.17, 11.33	p = 0.005 [a]
Total ROM (°)	63.21 ± 10.01	63.67	56.17, 70.33	54.96 ± 8.94	56.33	47.50, 62.83	p = 0.002

[a] *p-value calculated using Mann-Whitney U*

4.2.3 Threshold to Detect Passive Motion

There was a significant difference (p = 0.016) between groups for inversion during TTDPM testing (Table 5). For inversion testing, CAI-LAS had a median angle error that was 56.5% greater than CON. Although there was not a statistically significant difference for eversion (p = 0.181), CAI-LAS had 24.1% greater median angle error compared to CON.

Table 5. Threshold to Detect Passive Motion (TTDPM) for Ankle Inversion and Eversion

	CON (n = 29)			CAI-LAS (n = 29)			Group Comparison
	Mean ± SD	Median	IQR	Mean ± SD	Median	IQR	
Inversion (°)	2.65 ± 1.65	2.30	1.48, 3.23	3.77 ± 2.35	3.60	2.07, 4.23	p = 0.016 [a]
Eversion (°)	3.11 ± 1.92	2.90	1.53, 4.05	3.84 ± 2.21	3.60	2.10, 4.73	p = 0.181 [a]

[a] *p-value calculated using Mann-Whitney U*

4.2.4 Isometric Strength

There were no significant differences ($p \geq 0.152$) between groups for absolute or normalized isometric strength in either inversion or eversion directions (Table 6). Despite the lack of significance, normalized strength for both directions was roughly 8% lower in CAI-LAS.

Table 6. Isometric Strength: Average Peak Torque Over Three Trials in Each Direction (Inversion and Eversion) and the Strength Values Normalized to Body Mass

	CON (n = 29)			CAI-LAS (n = 29)			Group Comparison
	Mean ± SD	Median	IQR	Mean ± SD	Median	IQR	
Inversion Avg Peak Torque	17.87 ± 6.83	17.50	13.30, 24.20	15.50 ± 5.51	15.50	10.80, 19.20	p = 0.152
Inversion Normalized	22.97 ± 8.74	22.67	17.03, 28.20	20.09 ± 7.24	19.66	15.60, 23.44	p = 0.177
Eversion Avg Peak Torque	13.68 ± 4.12	13.00	11.60, 15.90	12.52 ± 3.82	11.90	10.20, 15.20	p = 0.269
Eversion Normalized	17.53 ± 4.70	17.88	14.42, 20.55	16.20 ± 4.87	15.32	13.45, 19.27	p = 0.295

4.2.5 Time to Peak Torque

There were no significant differences ($p \geq 0.382$) between the groups for TTPT in either inversion or eversion (Table 7). For both directions, CON did have 3.3-9.5% quicker TTPT values, but it was not a statistically significant difference.

Table 7. Time to Peak Torque (TTPT) for Ankle Inversion and Eversion During Isometric Strength Testing

	CON (n = 29)			CAI-LAS (n = 29)			Group Comparison
	Mean ± SD	Median	IQR	Mean ± SD	Median	IQR	
Inversion TTPT	372.64 ± 168.55	393.33	246.67, 461.67	411.95 ± 170.90	393.33	300.00, 515.00	p = 0.382
Eversion TTPT	319.77 ± 123.22	316.67	210.00, 416.67	330.86 ± 138.70	320.00	216.67, 403.33	p = 0.749

4.2.6 Star Excursion Balance Test

Data for SEBT were all normally distributed and reflected significant differences between groups for reaches in the anterior ($p = 0.040$) and posteromedial ($p = 0.016$) directions (Table 8). Normalized anterior reach ($d = 0.575$) and normalized posteromedial reach ($d = 0.672$) both had medium effect sizes. Posterolateral reach and its normalized measurement were not significantly different ($p \geq 0.096$) between the groups. The composite score of all three reaches was significantly greater ($p = 0.018$) in CON and had a medium effect size ($d = 0.637$).

Table 8. Star Excursion Balance Test (SEBT) Reach Distance (cm) for Each Direction and Reach Values Normalized (NORM) to Leg Length

	CON (n = 29)			CAI-LAS (n = 29)			Group Comparison
	Mean ± SD	Median	IQR	Mean ± SD	Median	IQR	
Anterior	83.26 ± 7.42	84.00	77.75, 88.67	78.84 ± 8.51	78.50	72.75, 85.00	p = 0.040
Posteromedial	82.34 ± 9.58	82.00	77.08, 88.33	75.76 ± 10.51	76.33	69.00, 84.25	p = 0.016
Posterolateral	90.68 ± 10.46	91.33	83.83, 98.75	86.37 ± 8.83	85.83	79.17, 92.75	p = 0.096
Normalized Anterior	8.72 ± 0.71	8.75	8.10, 9.17	8.30 ± 0.75	8.26	7.90, 8.92	p = 0.033
Norm Posteromedial	8.62 ± 0.87	8.50	8.18, 9.24	7.98 ± 1.03	8.01	7.35, 8.78	p = 0.014
Norm Posterolateral	9.49 ± 0.95	9.57	8.73, 10.19	9.11 ± 0.90	9.21	8.48, 9.65	p = 0.120
Composite Score	8.94 ± 0.74	8.90	8.36, 9.54	8.46 ± 0.76	8.46	8.09, 9.03	p = 0.018

4.2.7 Static Postural Stability

There were no significant differences between the groups for any of the variables related to static postural stability during trials with eyes open ($p \geq 0.103$) (Table 9) or with eyes closed ($p \geq 0.189$) (Table 10). Due to issues with the force plates during measurement of static postural stability, three subjects were removed from CON (Appendix C1 and C2) and one subject (Appendix C3 and C4) was removed from CAI-LAS during analysis of stdGRFz and CUGRF from the eyes open trials. Eight subjects were removed from CON (Appendix C5 and C6) and one subject (Appendix C7 and C8) was removed from CAI-LAS during analysis of stdGRFz and CUGRF from the eyes closed trials. Justification of removing the outliers is presented with box plots (Appendix C).

Table 9. Single-Leg Balance Test Scores During Static Postural Stability Assessments with Eyes Open – variables: Center of Pressure (COP), Ground Reactions Forces (GRF), and Sway

	CON (n = 29)			CAI-LAS (n = 29)			Group Comparison
	Mean ± SD	Median	IQR	Mean ± SD	Median	IQR	
stdCOPx (mm)	5.76 ± 1.26	5.43	4.81, 6.64	5.65 ± 1,48	5.27	4.86, 6.41	p = 0.527 [a]
stdCOPy (mm)	4.62 ± 1.70	4.42	3.78, 4.77	4.10 ± 0.85	3.98	3.48, 4.63	p = 0.103 [a]
stdGRFx (N)	2.56 ± 1.24	2.14	1.85, 2.94	2.42 ± 0.75	2.23	1.76, 2.88	p = 0.923 [a]
stdGRFy (N)	3.09 ± 1.44	2.61	1.91, 3.80	3.01 ± 1.21	2.49	2.14, 4.07	p = 0.886 [a]
stdGRFz (N) [#]	4.40 ± 1.78	3.73	2.96, 5.51	4.27 ± 3.99	3.99	2.79, 5.47	p = 0.945 [a]
CUGRF (N) [#]	5.79 ± 2.22	4.96	4.14, 7.08	5.70 ± 1.86	5.31	3.99, 7.53	p = 0.849 [a]
Total Sway length (m)	13.62 ± 2.31	13.89	12.42, 14.64	13.46 ± 3.19	13.27	11.16, 15.51	p = 0.834
Avg sway velocity	.449 ± .078	.456	.408, .482	.446 ± .107	.442	.364, .517	p = 0.912
Range_CoPx (m)	.031 ± .008	.029	.025, .035	.031 ± .007	.029	.026, .036	p = 0.793
Range_CoPy (m)	.028 ± .011	.025	.023, .028	.024 ± .005	.024	.022, .028	p = 0.122 [a]

[a] *p-value calculated using Mann-Whitney U*
[#] *n-size limited for CON (n = 26) and CAI-LAS (n = 28)*

Table 10. Single-Leg Balance Test Scores During Static Postural Stability Assessments with Eyes Closed – variables: Center of Pressure (COP), Ground Reactions Forces (GRF), and Sway

	CON (n = 29)			CAI-LAS (n = 29)			Group Comparison
	Mean ± SD	Median	IQR	Mean ± SD	Median	IQR	
stdCOPx (mm)	9.82 ± 1.78	9.96	8.48, 11.53	9.25 ± 1.78	9.46	7.94, 10.28	p = 0.227
stdCOPy (mm)	12.97 ± 4.94	12.48	9.30, 14.80	11.60 ± 3.73	11.06	9.03, 14.52	p = 0.300 [a]
stdGRFx (N)	6.85 ± 3.54	5.90	4.82, 7.94	5.82 ± 2.11	5.29	4.04, 7.82	p = 0.293 [a]
stdGRFy (N)	11.07 ± 4.40	10.25	8.29, 13.88	10.02 ± 4.81	8.86	6.57, 12.32	p = 0.246 [a]
stdGRFz (N) [#]	11.96 ± 4.22	11.76	8.87, 14.78	11.55 ± 5.46	9.90	7.73, 15.57	p = 0.431 [a]
CUGRF (N) [#]	16.46 ± 4.80	16.67	12.62, 18.61	16.48 ± 7.50	14.85	10.79, 20.89	p = 0.716 [a]
Total Sway length (m)	13.99 ± 2.28	13.64	13.02, 15.59	13.70 ± 3.06	13.59	11.30, 15.84	p = 0.683
Avg sway velocity	.459 ± .078	.455	.410, .517	.454 ± .105	.453	.371, .525	p = 0.829
Range_CoPx (m)	.064 ± .017	.064	.052, .072	.058 ± .015	.057	.047, .070	p = 0.189
Range_CoPy (m)	.088 ± .039	.092	.049, .119	.079 ± .031	.080	.053, .101	p = 0.335

[a] *p-value calculated using Mann-Whitney U*
[#] *n-size limited for CON (n = 21) and CAI-LAS (n = 28)*

4.2.7.1 *Sample Entropy*

There were no significant differences between groups for any of the variables related to the nonlinear analysis of static postural stability during trials with eyes open ($p \geq 0.060$) (Table 11) or with eyes closed ($p \geq 0.104$) (Table 12). As with the results for Static Postural Stability measures above, issues with force plate data resulted in the need to remove three subjects from CON (Appendix C9) and one subject from CAI-LAS (Appendix C10) for analysis. The group differences for SampEn with eyes open resulted in small to medium effect sizes (d = 0.422-0.525), but eyes closed trials had a smaller effect (d = 0.274-0.450).

Table 11. Nonlinear Analysis of Static Postural Stability with Eyes Open – Variables: Root Mean Square (RMS), Peak to Peak (P2P), Normalized Path Length (NPL), and Sample Entropy (SampEn) for x and y directions.

	CON (n = 26)			CAI-LAS (n = 28)			Group Comparison
	Mean ± SD	Median	IQR	Mean ± SD	Median	IQR	
RMSx	2.20 ± .525	2.13	1.82, 2.66	2.35 ± .643	2.18	1.76, 2.88	p = 0.365
RMSy	2.77 ± 1.05	2.46	1.91, 3.38	2.89 ± 1.01	2.47	2.13, 3.95	p = 0.588 [a]
P2Px	19.82 ± 7.41	17.32	15.47, 23.07	21.13 ± 5.99	19.84	16.88, 25.39	p = 0.181 [a]
P2Py	25.60 ± 12.25	19.74	15.60, 33.95	27.20 ± 10.99	25.18	17.07, 34.84	p = 0.414 [a]
NPLx	389.75 ± 65.08	413.75	319.69, 441.08	398.79 ± 80.62	443.97	303.44, 463.65	p = 0.340 [a]
NPLy	405.72 ± 69.00	435.20	329.38, 460.73	410.04 ± 80.19	458.07	312.09, 475.09	p = 0.465 [a]
SampEnx	1.08 ± .147	1.07	.973, 1.19	1.01 ± .183	.985	.871, 1.09	p = 0.085 [a]
SampEny	1.06 ± .145	1.05	.954, 1.16	.981 ± .156	1.01	.859, 1.13	p = 0.060

[a] *p-value calculated using Mann-Whitney U*

Table 12. Nonlinear Analysis of Static Postural Stability with Eyes Closed – Variables: Root Mean Square (RMS), Peak to Peak (P2P), Normalized Path Length (NPL), and Sample Entropy (SampEn) for x and y directions.

	CON (n = 26)			CAI-LAS (n = 28)			Group Comparison
	Mean ± SD	Median	IQR	Mean ± SD	Median	IQR	
RMSx	6.13 ± 1.78	5.78	4.76, 7.98	5.75 ± 2.11	5.25	4.03, 7.51	p = 0.478
RMSy	10.16 ± 2.99	10.12	8.42, 11.87	9.98 ± 4.89	8.92	6.54, 12.35	p = 0.357 [a]
P2Px	69.13 ± 29.10	64.79	47.45, 88.17	63.55 ± 32.35	54.42	36.19, 81.17	p = 0.357 [a]
P2Py	93.45 ± 24.87	97.18	75.72, 112.02	89.43 ± 36.71	84.60	61.44, 108.26	p = 0.618
NPLx	413.21 ± 64.63	437.78	341.07, 469.80	416.18 ± 78.89	453.87	320.93, 478.69	p = 0.542 [a]
NPLy	440.48 ± 69.71	467.12	365.83, 495.90	439.92 ± 81.70	477.67	343.42, 498.57	p = 0.790 [a]
SampEnx	.993 ± .176	.969	.906, 1.08	.920 ± .147	.883	.815, .994	p = 0.104
SampEny	.841 ± .140	.810	.748, .892	.804 ± .130	.820	.704, .900	p = 0.326

[a] *p-value calculated using Mann-Whitney U*

4.2.8 Dynamic Postural Stability

There were no significant differences ($p \geq 0.161$) between the groups for any of the variables related to dynamic postural stability (Table 13). Due to issues with the force plates during measurement of dynamic postural stability, three subjects were removed from CON prior to analysis (Appendix C11 and C12). Justification of removing outliers is presented with box plots. (Appendix C) For both directions, CON did have lower values for each variable, indicating better postural stability based on traditional interpretation, but there was not a statistically significant difference. The AP jumps saw CON have between 2.24% and 6.45% lower values than CAI-LAS, and during ML jumps, CON had lowers scores than CAI-LAS ranging from 1.20% and 9.77%.

Table 13. Dynamic Postural Stability Index (DPSI) and its Component Measures (APSI, MLSI, VSI) for Jumps in the Anterior-Posterior (AP) and Medial-Lateral (ML) Directions

	CON (n = 26)			CAI-LAS (n = 29)			Group Comparison
	Mean ± SD	Median	IQR	Mean ± SD	Median	IQR	
AP_APSI	.140 ± .009	.138	.133, .147	.144 ± .012	.144	.138, .148	p = 0.206 [a]
AP_MLSI	.031 ± .006	.030	.027, .035	.033 ± .008	.032	.027, .039	p = 0.280
AP_VSI	.326 ± .029	.330	.298, .342	.334 ± .044	.336	.303, .365	p = 0.459
AP_DPSI	.357 ± .028	.360	.328, .372	.365 ± .041	.370	.333, .393	p = 0.371
ML_APSI	.037 ± .007	.036	.033, .041	.039 ± .007	.040	.033, .043	p = 0.298
ML_MLSI	.126 ± .008	.127	.120, .132	.130 ± .009	.131	.124, .138	p = 0.161
ML_VSI	.307 ± .039	.308	.272, .343	.310 ± .045	.305	.278, .352	p = 0.798
ML_DPSI	.334 ± .037	.335	.300, .369	.338 ± .043	.329	.305, .378	p = 0.702

[a] *p-value calculated using Mann-Whitney U*

5.0 DISCUSSION

While previous research has examined the role of CAI on various neuromuscular deficiencies related to ankle injury risk factors, this study was unique in its wide array of assessments in athletes with CAI-LAS. Additionally, this was one of the first studies to assess TTDPM at the ankle using an isokinetic dynamometer

The purpose of this study was to examine if differences in laboratory measures of ankle flexibility, proprioception, strength, and postural stability existed in soccer players, with and without CAI-LAS. A total of 58 male soccer players completed the study. All subjects completed each component of the study, however, several data points were omitted from the final analysis due to equipment issues resulting in spurious outliers.

It was hypothesized that CON would have better performance in all assessments, reflected in: greater ankle ROM and performance on the SEBT; larger musculature size, smaller TTDPM, greater strength, and quicker TTPT; and lower postural stability values. Results from this study did support some of the original hypotheses with significant differences being detected for ROM, SEBT, and TTDPM. Not all hypotheses were found to be true, however, as results for musculature size, strength, TTPT, and postural stability failed to detect significant differences between the groups. Subject characteristics, variables collected as part of the study's specific aims, significance of the study, study limitations, and future research directions are discussed with more detail in the following sections.

5.1 SUBJECT CHARACTERISTICS

5.1.1 Demographic Data

Subject data for age, height, weight, body fat percentage, and limb length of the test leg were collected to ensure there were no significant differences, aside from injury history, between CAI-LAS and CON groups. The statistical analyses showed that groups did not have any statistical differences in any of the collected demographic measures.

5.1.2 Cumberland Ankle Instability Tool

A significant difference between the two groups did exist in CAIT scores, which was to be expected. Subjects were not enrolled in the CAI-LAS group if their CAIT score was above a 24, and subjects were excluded from participating in the CON group if their CAIT score was below a 27, resulting in an expected statistical difference between the groups. The validity of CAIT was furthered by a significant correlation ($p < 0.001$) to time since last LAS. Previous studies have utilized the CAIT and reported 100% accuracy in identifying individuals with CAI and providing an average score of 23,[102] which is only slightly higher than the 22.83 in the current study.

5.2 RANGE OF MOTION AND FLEXIBILITY

The first aim of this project was to examine the differences in ROM and flexibility in athletes with or without CAI-LAS. It was hypothesized that individuals with CAI-LAS would exhibit less ROM at the ankle joint and perform more poorly on the SEBT compared to CON.

5.2.1 Range of Motion

The literature is inconsistent regarding the relation between ROM and lower extremity injury,[27, 33, 93] likely due to slightly varying methods and different populations. Soderman et al.[140] did not find ankle dorsiflexion ROM to be a risk factor for lower extremity injury in female soccer players s (OR = 2.50, 95% CI = 1.11 to 5.61), and Twellaar et al.[162] found no significant differences in ROM about the ankle between physical education students who sustained lower extremity injuries and those who did not. Similarly, Wiesler et al.[166] did not find a relation between ankle ROM and injury rate in dancers, and Barrett et al.[4] reported no relation between plantar and dorsiflexion ROM and ankle injury among basketball players. However, Leanderson et al.[78] showed that basketball players with a history of LAS had significantly less ROM (3.6°) than healthy controls (17.9°), and Wiesler et al.[166], despite a lack of relation in ROM and injury rate, showed previously injured dancers to have a reduced passive dorsiflexion value compared to healthy controls. Hertel [57] reported that diminished dorsiflexion following LAS is thought to contribute to functional instability of the ankle following LAS, and Thalman [156] cited a lack of dorsiflexion as one of the biggest contributing factors to CAI after LAS.

The results of the current study agree with studies stating that ROM is a detectable risk factor for ankle injuries, as CAI-LAS reported significantly lower ROM than CON, particularly for dorsiflexion. While values for plantar flexion and total ROM arc were significantly lower in the CAI-LAS group by 9.4% and 13.1%, respectively, median dorsiflexion for CAI-LAS was 24.3% lower than median dorsiflexion for CON. The findings of the current study would further the argument for the inclusion of ankle ROM in similar future investigations as well as in screening measures for athletes that may be at risk for lower extremity injuries. The use of a standard goniometer does not require much training and the technique implemented in this study has shown to have excellent reliability (ICC = 0.741-0.931), and the measurements are quick to assess, adding to the argument of its usefulness as a screening measure in athletes and individuals recovering from LAS.

5.2.2 Star Excursion Balance Test

The SEBT has been shown to be a reliable and valid measure as a dynamic test to predict risk of lower extremity injury,[49, 92] and the literature is fairly consistent in showing that people with CAI perform worse on the SEBT than uninjured people.[52, 59] Because of this, the SEBT was considered for the current study as a means of ensuring a measure to differentiate the groups. If the SEBT could detect a difference in CAI-LAS and CON, and if SEBT was correlated to other variables measured, further clarification could be employed in the interpretation of results. Further, the SEBT has been shown to be responsive to training programs in both healthy people and people with injuries to the lower extremity, making it a strong tool for clinicians and researchers looking for a functional test of the lower extremity.[49] For this reason, SEBT was included to help the overall goal of the current study.

The results verified the aim's hypothesis in that CAI-LAS had worse performance in all three reach distances, with statistically significant deficits reflected in the anterior and posteromedial directions. On average, CAI-LAS had 4.8% less normalized reach in the anterior direction and 7.4% less reach in the posteromedial direction. The results of the current study are consistent with Olmsted et al.,[97] who reported an average reach of 78.6 cm in the CAI group and 82.8 cm in the healthy group. The composite score, which Plisky et al.[105] verified as a measure able to differentiate heightened injury risk in basketball players, was 5.4% lower in the CAI-LAS group. The results of this study are consistent with the literature and further validate that SEBT is a sound measurement tool to detect differences in individuals with and without CAI.

5.2.3 Summary

Subjects with CAI-LAS has significantly worse values for ROM and SEBT compared to CON. These findings support the argument for inclusion of assessing ROM as a screening tool in athletes as a means of monitoring injury risk and implementing ROM as a clinical measure to help determine progression of recovery from injury. Because both the passive and dynamic measures were significant, a further argument could be made to select either ROM or SEBT, rather than utilizing both measures, to reduce redundancy. The results of this project lead to the recommendation of utilizing ROM, as it is easy to administer, a reliable measure, and requires less space and time to conduct than SEBT.

5.3 MUSCULATURE SIZE, PROPRIOCEPTION, AND STRENGTH

The second aim of this project was to examine differences in musculature size, ankle proprioception, and ankle strength in athletes with or without CAI-LAS. It was hypothesized that individuals with CAI-LAS would have smaller lower leg musculature, greater (worse) TTDPM at the ankle, less isometric strength, and longer TTPT values during strength testing compared to CON. Results from the study supported the TTDPM hypothesis, but results for musculature size, strength, and TTPT did not have statistical significance.

5.3.1 Musculature Size

Ultrasound images were collected to assess the size of the tibialis anterior muscle group and the peroneal muscle group in all subjects. It was desired to see if a significant difference existed in musculature size between CAI-LAS and CON, but the results did not support the hypothesis. For the tibialis anterior muscle group, for which images were scanned from the proximal 20% along a line between the fibular head and lateral malleolus, the groups were nearly identical. The cross-sectional area for CAI-LAS was slightly larger than CON, which was unexpected. Because this is believed to be one of the first investigations to use ultrasound to compare musculature size between CAI-LAS and CON, it is unknown if this is a common occurrence. For the peroneal muscle group, which was scanned at the distal 40% along a line between the fibular head and lateral malleolus, there was also no significant differences between the groups. Longitudinal and transverse images were, on average, slightly smaller in CAI-LAS, but the cross-sectional area was again larger for CAI-LAS.

For the current study, ultrasound measurements were reported as raw values for each subject, but during collection, visual differences were noticed for individuals who were taller, had longer legs, or had more body fat. To determine if varying body type influenced the ultrasound measurements, secondary analysis was performed to assess if normalization of ultrasound data would alter interpretations. Ultrasound measurements were normalized for height, weight, body fat percentage, and limb length. Despite visual differences during data collections, results of the normalization further indicated no significant differences between CAI-LAS and CON.

Murphy et al.[93] suggested radiographic techniques such as computed tomography scans as the only way to accurately measure limb girth, a technique not common in the literature. The findings of the current study suggest further research is needed to see if ultrasound is a sound means of assessing limb size as part of screening for injury risk. The results of the current study are in line with Bennell et al.,[8] who found that there was no association between gastrocnemius girth and ankle injury in male subjects, although there was an association seen in female subjects. Perhaps if the current study had included female subjects, more significance would have been noted in the measurements. Although the current study did not include circumference measurements of the lower leg, there is a chance the results of cross-sectional area measurements are in line with Milgrom et al.,[90] who showed that subjects with larger circumference of the gastrocnemius had a higher incidence of LAS. The larger calf-to-ankle ratio may indicate a larger mass over a smaller ankle that results in greater difficulty in stabilizing or a delayed ability to control the mass over the ankle. Cross-sectional area was, on average, higher in CAI-LAS for both scan locations, but the results were not statistically significant. Future inclusion of circumferences measurements of the calf and ankle may help clarify this difference in size.

5.3.2 Threshold to Detect Passive Motion

It has been shown that proprioceptive abilities are adversely affected by LAS.[57] Further, there is an increased risk of sustaining LAS re-injury for individuals with CAI who have more significant alterations in ankle joint position sense and kinesthesia.[76] Hertel et al.[59] attributed the alterations in proprioception to the impact of LAS on "conscious perception of afferent somatosensory information, reflex responses, and efferent motor control deficits present with ankle instability," but stated the specific origin of these deficits has yet to be fully elucidated. What is clear, however, is that both the feedback and feedforward mechanisms of motor control are affected by CAI-LAS due to the disruption of static ligamentous structures.[59, 119] Testing TTDPM as part of the battery proposed in the current study was believed to assess the level of impairment in injured ankles.[42, 81]

While the various methods of assessing ankle proprioception may contribute to the inconsistencies in findings, the results of the current study supported the hypothesis and findings reported in the literature. Lentell et al.[79] noted an increase of 1° when comparing inversion threshold in previously injured ankles and uninjured ankles in 42 subjects. In the current study, degree of error for inversion was 1.3° higher in CAI-LAS. Although there was only statistical significance for inversion, TTDPM performance for eversion also appeared to be affected by a history of LAS, as CAI-LAS had 24.1% greater median angle error compared to CON.

Utilization of TTDPM testing as a screening tool for injury risk has merit, and proprioception training as a preventive tool has been recommended as a means of reducing injury risk.[157] A small number of studies have suggested that balance and coordination training can restore some of the deficits in proprioception that result from LAS, returning error values to near normal levels.[76] Strength training specific to the ankle in subjects with a history of unilateral CAI demonstrated improvements in proprioceptive measures,[69, 70] a finding attributed to enhancements in muscle-spindle activity.[29] If TTDPM is used as a screening tool, it may highlight individuals at an added risk of injury, allowing for corrective balance and strength training to be implemented as a means of preventing injury occurrence.

5.3.3 Isometric Strength

Ankle strength is important to test and analyze following an ankle injury and can be a beneficial screening measure, as it has been shown that eversion strength may not be back to full strength even 12 weeks following LAS.[76] Peroneal muscle weakness can persist in individuals with unilateral ankle injury history,[159] and less evertor strength has been reported for male athletes who had suffered a LAS compared to a healthy control.[16, 176] Additionally, inversion strength has been shown to have a decrement in individuals with a history of LAS. Wilkerson et al.[172] demonstrated significantly greater invertor deficits than evertor deficits for both peak torque and average power. The findings suggest that a lateral ankle ligament injury may be associated with an invertor muscle performance deficiency.

The results, however, did not support the hypotheses with any statistical significance. Subjects with CAI-LAS did have lower values for all strength measures, but it was not significant. The results were not entirely surprising, as the literature is inconsistent on the role of strength in relation to ankle injuries or injury history.[10]

One interesting consideration came from Baumhauer et al.[5] who reported that individuals with a muscle strength imbalance as measured by an elevated eversion-to-inversion ratio exhibited a higher incidence of inversion ankle sprains. The results of the current study agree with this notion, as CAI-LAS subjects had an eversion-to-inversion ratio, calculated from the normalized strength data, of 0.806. The CON group had a ratio of 0.763, which may indicate a clinical significance in the strength data, despite the lack of statistical significance.

Secondary analysis was performed to see if time since last LAS had any relationship to ankle strength values. With Konradsen et al.[76] suggesting isometric eversion strength is still not 100% of the contralateral side after three months, the relationship of time and injury was warranted. Although no subject in the current study had sustained an LAS within three months of their visit, it was still speculated that a time effect may exist. Results of the secondary analysis, however, did not indicate any significant correlations ($p \geq 0.139$) between time since last injury (11.97 ± 8.18 months) and strength values.

5.3.4 Time to Peak Torque

The collection of TTPT was simultaneous with collection of strength measures and was believed to provide an additional variable of interest in the current study. Utilization of HA and custom protocol are unique to this study, making connections to existing literature difficult. Previous research is limited but has indicated a trend that muscle reaction to perturbations may be compromised as a result of LAS, reducing joint stability and leading to a heightened risk of re-injury.[10, 93] Utilizing EMG analysis during an inversion perturbation, Beynnon et al.[11, 76] showed that the tibialis anterior and peroneals had reactions to perturbations that were 6.4% slower in individuals with a history of ankle injuries when compared to healthy controls.

While a trend did exist in the data for both inversion and eversion TTPT, there was no significant difference between groups. The average inversion TTPT value for subjects with CAI-LAS were 10.5% slower than CON. This is in agreement with Beynnon et al.,[11] who did not find statistically significant differences between male subjects but did see a trend for slower muscle activation in their female subjects.

5.3.5 Summary

Subjects with CAI-LAS had significantly lower values for TTDPM, allowing for the argument to be made that ankle proprioception with HA can be a valuable component to a pre-season screening or as a means of monitoring rehabilitation. Despite the lack of significant differences for strength and TTPT values, there was a noticeable trend in the data. For all strength and TTPT variables, CAI-LAS displayed deficiencies in line with their respective hypotheses. Strength values were lower and TTPT values were higher for CAI-LAS. While the lack of significance limits the ability to recommend implementation of the methods utilized in the current study, it is suggested for alternate methods to be investigated to pinpoint a reliable means of assessment for strength and TTPT, as they both appear to be near a point of delineating between the two groups. A clinical significance may exist as the trend in the direction of results is in line with the hypothesized differences expected between the two groups. Assessments for musculature size did not result in any significant differences, nor did the data appear to provide any consistent interpretations. It is not recommended to utilize musculature size via sonomyography as a measure of screening for injury risk.

It is interesting that individuals with worse ROM would also require more displacement of their ankle to detect passive motion, but it is believed the same neuromuscular deficiencies that result in limited ROM are present in diminished TTDPM. By implementing both measures as a screening tool, a higher likelihood of detecting heightened injury risk in individuals will be possible. If an athlete displays adequate ROM but displays subpar TTDPM, focused balance and proprioceptive training can be implemented as a means of preventing injury. Similarly, if an athlete has average TTDPM but limited ROM, training can be tailored to improve flexibility and

ROM for that individual. If used in clinical settings, return-to-play criteria can be enhanced as multiple factors will need to be satisfied.

5.4 STATIC AND DYNAMIC POSTURAL STABILITY

The third aim of this project was to examine differences in postural stability in athletes with or without CAI-LAS. It was hypothesized that individuals with CAI-LAS would have worse static postural stability, exhibit a more deterministic center of pressure (CoP) SampEn, and perform more poorly during a task of dynamic postural stability compared to CON.

5.4.1 Static Postural Stability

Although the literature is inconsistent in findings relating static postural stability to injury risk, the studies indicating postural sway as a predictor of injury occurrence and postural stability decrement because of injury,[13, 87, 117, 173] led to the inclusion of static postural stability in the current study. Assessments of CoP and postural sway are commonly used in assessing risk or determining severity of decrement, but these measures have been met with skepticism due to the inability for CoP measures to consistently assess subjects with CAI.[76, 101] Investigations utilizing quantification of GRF during postural stability trials attempted to correct the inconsistencies. Ross et al.[128] showed that the standard deviation of medial/lateral GRF was a more accurate measure than CoP displacement in discriminating between subjects with and without CAI. Ground reaction forces in the anterior/posterior direction were also shown to be highly reliable.

Due to the inconsistencies of CoP and GRF, the current study included both measures in the analysis, and it was hypothesized that subjects in the CAI-LAS group would have worse static postural stability that CON, exhibited in higher values. The results of the current study did not support the hypothesis for either the eyes open static postural stability task or the eyes closed task. While the values reported are consistent with those measured in other studies,[100, 101] the inability to detect a significant difference between the two groups, unfortunately, is also something common in the literature.

Additional analysis was conducted to see if CoP measurements were correlated with GRF measurements to determine if there was redundancy in the measures.[67, 71] The CoP and GRF values were significantly correlated for both the x ($p = 0.046$, $r = 0.263$) and y ($p = 0.046$, $r = 0.263$) directions during the eyes open trials. Both CoPx ($p < 0.001$, $r = 0.515$) and CoPy ($p < 0.001$, $r = 0.538$) were strongly correlated to cumulative GRF during the 30-second trials. The correlations between CoP and GRF were stronger for x ($p < 0.001$, $r = 0.649$) and y ($p <0.001$, $r = 0.757$) during the eyes closed trials. The correlations to cumulative GRF was also stronger for both CoPx ($p < 0.001$, $r = 0.764$) and CoPy ($p < 0.001$, $r = 0.691$) during the eyes closed trials. These correlations would seem to indicate that both CoP and GRF are acceptable measures of postural stability. The lack of statistical significance, however, does not help satisfy the argument as to which variable is more appropriate in discerning individuals with and without CAI-LAS.

Additional criticism of the measures discussed above are that they involve independent dimension – anterior/posterior and medial/lateral, and while metrics such as path length consider both dimensions, they only quantify the magnitude of the CoP movement.[113] Because this movement is technically a vector quantity with both magnitude and direction, Rhea et al.[113] argued for the direction of displacement, or heading change, to be assessed for further insight into static postural stability because it allows for a more holistic analysis of postural control. Lower complexity of movement, as evidenced by lower SampEn values, can be a possible indicator that the control systems may be more vulnerable to stressors.[84] This can be valuable screening information for CAI-LAS in attempts to avoid re-injury.

5.4.1.1 *Sample Entropy*

The current study also investigated static postural stability with a nonlinear assessment, resulting in variables: RMS, P2P, NPL, and SampEn. The rationale for doing so was because research has begun to suggest that traditional biomechanical models of postural stability are not complete representations of postural stability.[17] Traditional postural stability assessments define postural stability as the ability to maintain a desired orientation around a fixed base of support, assuming deviations around the orientation are a negative feature. However, the framework of nonlinear dynamics suggests that postural stability is an interaction of individual physiological systems, so there must be an element of adaptability, flexibility, and unpredictability in a constantly evolving environment.[145] Rather than viewing deviations in CoP as negative, it is argued that oscillation in postural steadiness are part of a physiological rhythm, just as heart beat and respiration are bodily rhythms, associated with the postural control system.[17]

This seeming randomness reflects the readiness of the system to rapidly respond to a perturbation, and in clinical populations, this interconnection between system components is compromised, reducing the complexity of the system.[17] There is an optimal state of variability for healthy and functional movement, and the variability has an organization characterized by a chaotic structure.[146] The variability refers to the ability of the motor system to reliably perform in a variety of different environmental and task constraints, while stability refers to the ability to offset external perturbations.[145] When interpreting variability of CoP, it is important to attempt differentiating the degree of change that is due to the neuromotor system and how much is a function of the data processing technique used.[114]

Several considerations were made in the analysis of the SampEn data. A proper selection of *m* and *r* values is essential for proper interpretation of the data,[181] however, no guidelines exist for optimizing their values.[77] In SampEn calculations, the parameter *m* is known as the template length of compared runs,[145] and *r* is the tolerance level.[113]

Yentes et al.[181] suggested investigators to examine several *r* values before selecting final parameters, as choosing the appropriate value is the most difficult aspect of SampEn analysis. A higher *r* prevents more noticeable features in the data to be distinguished,[77] and Rhea et al.[113] suggested using an *r* equal to 0.07xSD when the independent analysis of both the AP and ML time series is desired.

Additionally, Yentes et al.[181] suggested using an *m* value of 2, which was consistent in the literature. In selecting an *m* of 2, the analysis tool compared two consecutive data points to another set of consecutive data points, which lowered the number of self-matches in the experimental data.[181] While an *m* of 3 is also appropriate,[77] Yentes et al.,[181] recommend examining the data with *m*=2 and *m*=3. Both options were conducted for a small sample of the current study's subjects, and an *m* of 2 resulted in more plausible outcomes.

A final consideration was sampling frequency. The static postural stability data was collected at 1200 Hz for a 30-second trial. This resulted in 36,000 data points per trial, which surpasses the recommended maximum of 20,000 in SampEn analysis.[109] To correct for this, cropping the middle 10 seconds, which would equate to 12,000 data points, was attempted as a means of making the data more manageable.[115] Because this method would overlook two-thirds of the data, down-sampling the trials to 120 Hz was attempted in order to retain data from the entire 30-second trial. Ramdani et al.[109] reported the analysis of raw data does not result in detectable significant differences between visual conditions ($p > 0.05$), however, down-sampled data did ($p \leq 0.040$). Further rationale for down-sampling was provided by Rhea et al.[115] who found that higher sampling rates led to artificially lower SampEn values.[109]

With proper parameters in place and trials appropriately down-sampled, findings of the current study were similar to the SampEn values reported by Ramdani et al.,[109] who showed higher SampEn values in an eyes open condition (1.05-1.11) compared to eyes closed (0.90-0.93). It was believed CAI-LAS would have lower SampEn values as abnormal physiology is associated with more regularity while normal physiology is associated with greater complexity.[103] The reduction in SampEn values between eyes open and closed conditions and between CON and CAI-LAS was consistent with the theory that a loss of complexity in physiological and behavioral systems is a result of the reduction of the number of structural components.[109] Terada et al.[154] found that participants with CAI had lower SampEn values for frontal-plan kinematics during walking compared to healthy controls and that the decreased variability in walking patterns may be associated with a less adaptable sensorimotor system.

The lack of significant differences existing between CAI-LAS and CON could be due to subjects being fully recovered from their last LAS. The lower entropy values during the eyes closed condition and in CAI-LAS compared to CON, despite the lack of statistical significance, is in line with Cavanaugh et al.[17] who suggested the removal of sensory feedback made it more difficult for individuals to precisely control their body position. This was manifested in artificially constrained interactions among control system components, resulting in less complex oscillations in system output.[17] Lower SampEn values reflect a reduction in complexity, resulting in a more deterministic system. Deterministic systems are those whose evolving properties are completely determined by its current state and history. Such a system has a predictable behavior at any future time.[145] The ability to detect lowered complexity in individuals may allow for individualized training to be implemented as a means of preventing future injury.[154]

5.4.2 Dynamic Postural Stability

Due to a lack of a strong correlation between static and dynamic measures of postural stability,[134] the current study aimed to assess if differences in performance of a jump-landing task were detectable. Dynamic postural stability is the preferred measurement to evaluate postural stability in physically active subjects due to its resultant ground reaction forces that closely resemble those incurred during sporting activities.[13, 167] Wikstrom et al.[171] demonstrated DPSI as a measure that closely mimics functional activities, and DPSI has been able to detect differences in individuals with and without CAI, with the latter having lower measures.[171] While the results of the current study did not support the hypotheses with any statistical significance, overall DPSI and its component measures were higher for CAI-LAS during both the anterior/posterior and medial/lateral jumping tasks. On average, the four variables for the anterior/posterior jump were 3.5% higher for CAI-LAS, and during medial/lateral jumps, CAI-LAS had values that were 4.9% higher than CON.

The results indicate that DPSI may be able to detect a trend in values, but it is hard to determine if it is strong enough to merit consideration as part of a consistent battery of tests used for screening individuals for injury risk.

5.4.3 Summary

Similar to the strength data, results from the postural stability assessments did not display significant differences between the two test groups. However, trends in the data did give indication as to the merit of the values for future investigations. The traditional static postural stability measurements did not show any consistent findings in terms of differentiating between the groups. In fact, CAI-LAS appeared to have better performance under the interpretation that lower values are indicative of better postural stability. The interpretation of lower values being better during linear static balance assessments can be seen when comparing the eyes open and eyes closed conditions. All variables for the eyes closed condition were higher for both groups compared to the eyes open condition.

The non-linear analysis, while also lacking in statistical significance, did indicate a trend in the data similar to what is reported in the literature for eyes open and eyes closed conditions,[109] providing rationale for its implementation in further investigations. For SampEn measures, it appears the interpretation of values is the opposite for linear assessments of static postural stability, in that lower values are indicative of diminished ability. The interpretation can be seen in the fact that eyes closed values for SampEn are lower in both groups compared to their respective values during the eyes open condition. With this interpretation in mind, CAI-LAS has lower ability than CON during static balance trials, providing the argument that non-linear analysis of static postural stability may be a more sensitive analysis tool than traditional linear measures of static postural stability.

For dynamic postural stability, the results lacked statistical significance but did show a trend between groups that is similar to what had been reported in the literature in regard to lower values being indicative of lower injury risk. While further investigations are necessary to substantiate this claim and allow for the argument to be made that the test can discriminate between CAI-LAS and CON, all variables were lower for individuals without neuromuscular deficiencies related to LAS.

The lower ROM and worse TTDPM seen in CAI-LAS may be related to the trends seen in postural stability data. The lower SampEn measures and higher DPSI scores could be a result of less control over a fixed surface and a delayed ability to correct for a landing perturbation, respectively. If SampEn and DPSI measurements can be fine-tuned to be more sensitive assessments, their inclusion into a pre-season screening would add a valuable component for coaches and clinicians to tailor training as a means of preventing injury. Teasing out whether previous injury for CAI-LAS resulted in lower SampEn or if the lower SampEn was already present and contributed to the initial injury will benefit from future longitudinal investigations. Based on the current study, the bottom 25th percentile of CON had lower SampEn values than half of CAI-LAS during the eyes open condition, which could be an indicator of injury risk. Such a conclusion could be elucidated with longitudinal assessments, which might also be able to determine threshold values in SampEn values, enhancing its usefulness as a screening tool.

5.5 CORRELATIONS

Correlations were assessed post hoc for all collected variables in all subjects to see if certain measures provided redundancy in the battery or if any measures were correlated to other components of the testing. For ROM, interesting correlations were present with strength values and SEBT. Dorsiflexion ROM was significantly correlated ($p \leq 0.005$) with inversion strength values ($r \leq 0.438$) and plantar flexion ROM was significantly correlated ($p \leq 0.002$) with eversion strength ($r \leq 0.429$). Only dorsiflexion ROM was significantly correlated ($p \leq 0.012$) with SEBT, but only for the anterior and posteromedial directions. In addition to the correlations mentioned above, the anterior reach of the SEBT was significantly correlated ($p \leq 0.025$) with most the static postural stability measures during the eyes closed trials ($r \leq 0.410$). The positive correlation between these two tasks is intuitive as the SEBT is a single-leg task.

All ultrasound scans were found to be significantly correlated ($p \leq 0.007$) with eversion average peak torque ($r \leq 0.474$). This correlation is not surprising as the scans were taken on the lateral portion of the leg, which is associated with evertor muscles. The lack of correlation to normalized strength was interesting, however. All ultrasound scans were also significantly negatively correlated ($p \leq 0.014$) with total sway length ($r \leq -0.455$) and average sway velocity ($r \leq -0.441$) for both the eyes open and eyes closed trials of static postural stability. This would indicate that larger musculature resulted in less sway during single-leg balance. The only notable correlation that existed for TTDPM was that it was significantly correlated ($p \leq 0.005$) with MLSI ($r \leq 0.393$) during the AP jumps. Inversion strength values were significantly correlated ($p \leq 0.045$) to all SEBT measures ($r \leq 0.417$).

The best correlations for both postural stability assessments were to themselves. For static eyes open trials were strongly correlated to eyes closed trials, and for dynamic tasks, AP numbers were correlated with ML values. While each of the four tasks do examine various aspects of stability, the argument against redundancy could be made if a team trainer or clinician were limited in their testing time.

5.6 STUDY SIGNIFICANCE

Although some of the hypotheses were rejected in this study, the results contribute useful information to the scientific literature. No studies have investigated the full battery of tests implemented in this study. The significant difference detected for ROM, SEBT, and TTDPM, as well as trends detected in the data, may provide a foundation for future research in multiple areas, and serve as a guideline for injury prevention and maintenance of team physicians and rehabilitation clinicians. The findings related to TTDPM are pivotal in that a valid and reliable means of measuring ankle proprioception has been shown to be sensitive enough to detect differences in CAI-LAS and CON. Proprioception is a key contributor to injury risk, and having a sound means of screening for deficiencies in proprioception can be gleaned from this study. Changes may be made in future research protocols to enhance and refine the research questions and methodologies based upon findings from this study. Specific changes in future research are described below.

5.7 STUDY LIMITATIONS

This study has a few potential limitations. Although the groups did not have any statistically significant differences and were relatively homogenous demographically, subjects did vary in their playing level, playing history, position, and injury history. Future studies that may be able to control for each of these aspects, may find further significant differences in the collected variables.

Analysis of ultrasound measurements may have been strengthened if limb girth was also collected at the two scan locations. The current study was proposing to use ultrasound as a better means of assessing musculature size but did not include circumference measurements, which are more common in the literature.

Limitations were also present with TTDPM testing, particularly with the subject set up. While the padding under the foot was adopted from Lim et al.,[83] the altered test angle created by HA, necessitated for the foot to be secured with a strap. This may have provided tactile feedback for the subject, although a large tube sock was worn to dissipate any cueing sensations provided by the strap. Future investigations should assess TTDPM differences with HA both with and without the footplate strap being applied.

While eversion and inversion strength are more commonly reported in the literature related to LAS, there were some instances where plantar flexion and dorsiflexion strength values were reported. Testing for those directions may offer further information on the role of ankle strength in the current study.

The TTPT collection method on the Biodex is flawed in several ways. It can be compromised by the subject engaging too soon or not maintaining true isometric contractions throughout the five-second trial, resulting in spurious or multiple TTPT curves that make interpretation difficult. While the current study aimed to eliminate these issues by providing verbal cues at the appropriate time to the subjects, future collection of TTPT should aim to create strict test criteria when aiming to implement this measure, especially during repeated trials within a single collection session.

Data related to dynamic postural stability were potentially limited by a couple factors. The first may have been subjects performing the task in self-selected footwear,[152, 165] and the second may be the protocol itself. Currently ongoing research has suggested performance of jump-landing tasks while barefoot are more consistent than when shod,[132] and a protocol that controls for jump height rather than jump distance may be a better indicator of postural stability.[125]

5.8 FUTURE DIRECTIONS

Further research directed at identifying predictors of ankle injury neuromuscular characteristics can potentially use the limitations and findings of the present work to guide future study design.

The validity of ultrasound assessments can be furthered by investigating side-to-side differences in individuals as well as incorporating female subjects into the investigation. Collecting ultrasound scans and circumference measurements in the same individuals will also help clarify if one measurement method is preferred or if the two present a different picture altogether. Such an investigation will help further the argument for implementation of ultrasound as a measure of muscle size or provide evidence to solidify its removal from consideration.

Utilizing the Biodex to collect maximum ROM values is possible with HA. While those measures were not recorded for this study, analyzing those values along with strength values and TTPT might provide further information on the role of ROM in ankle injury history. This would be an important concurrent measure, as the ROM values in the current study were measured separate from the Biodex and were in a different plane of motion. Incorporating more extensive strength measures would make future research efforts stronger. Incorporating strength and ROM measurements in the same direction would be beneficial, for example assessing plantar flexion strength and comparing it to its corresponding ROM values to see if either is related or has a more predictive effect. Also, while this study opted to not assess side-to-side differences, comparing strength decrements in the injured limb compared to the contralateral leg would provide interesting information when coupled with data related to time since the last injury.

Prospective investigations utilizing TTDPM measures are warranted. Payne et al.[99] showed that proprioceptive deficits at the ankle can be used to predict ankle injury in college basketball players. However, Payne et al.[99] used joint position sense testing, segueing into the need for a similar study to use TTDPM testing to detect if the deficit in kinesthesia is caused by a predisposition, the result of repeated LAS, or the result of a single LAS that was never rehabilitated.[76] A prospective investigation with TTDPM using HA that can show a relationship between deficits in proprioception and injury occurrence will further the argument of the need to include TTDPM as part of a pre-season screening of injury risk.

Training intervention studies would also be a very interesting progression of the current study. Since it has been shown that balance and strength training can help restore proprioceptive abilities following LAS,[29, 76] conducting a study where half the subjects undergo regular balance and strength training and half represent a control group would allow for the benefits of the training to be elucidated by using TTDPM as a pre- and post-intervention measure. Again, this would further the argument for the implementation of HA when testing the ankle.

Since a noticeable trend in the current results were evident, future studies should look to validate alternative TTPT measurements at the ankle and whether utilizing HA on an isokinetic dynamometer is a reliable means of doing so. Incorporating surface electromyography to create visual representations of the muscle activity patterns during the task will be an interesting addition to the interpretation of TTPT values as well.

Regarding postural stability and SampEn measurements, future research should utilize SampEn as a screening tool in assessing athletes' return-to-play criteria when recovering from LAS. Future investigations may also want to incorporate EMG analysis of muscle activation with SampEn assessment to quantify muscle activity as it correlates to varying entropy values for a further understanding of stochastic and deterministic values.

Lastly, a future investigation of the ability to predict injury risk with an assessment of dynamic postural stability is warranted. Single-leg balance trials have been shown to be predictors of injury occurrence,[173] but there is no known prospective analysis of dynamic postural stability and injury occurrence. If such an investigation were to find significant relationships between dynamic postural stability indices and injury occurrence, the argument for the utilization of a dynamic postural stability task in sports medicine research would be further validated.

5.9 CONCLUSION

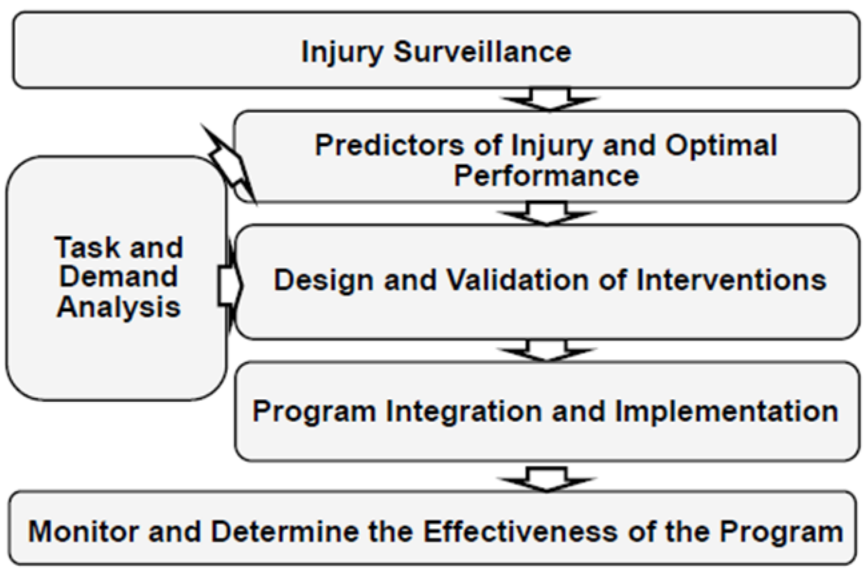
The purpose of this study was to examine if differences in laboratory measures of ankle flexibility proprioception, strength, and postural stability existed in athletes, with or without CAI-LAS, highlighting which laboratory measures could be utilized to help clinicians and team personnel reduce risk of re-injury. It was hypothesized that individuals with CAI-LAS would have: less ankle ROM and worse performance on the SEBT; smaller musculature size, worse TTDPM, weaker strength, and slower TTPT; and worse postural stability values. Results from this study did support some of the original hypotheses, but not all hypotheses were found to be true.

Significant differences between the two groups were found and the hypotheses were supported for ROM, TTDPM, and SEBT assessments. There was not a statistically significant difference between CAI-LAS and CON for musculature size or static postural stability. Additionally, no significant difference was seen between groups for isometric strength, TTPT, or dynamic postural stability, however, trends in the results were in agreement with the hypotheses.

These results indicate that the laboratory measures related to musculature size and static postural stability are not sensitive enough to discriminate between CAI-LAS and CON. While the current study did not support the argument for a test battery to include all the measures described herein, the results from this study should help provide the foundation for future research. There is apparent value in using ROM, SEBT, and TTDPM in assessing individuals to determine injury risk or monitor rehabilitation from injury. Despite the lack of statistical significance, there is potential clinical significance and merit to consider including strength, TTPT, and dynamic postural stability assessments in future analyses. More investigations need to be conducted to assess the value of ultrasound measurements as a screening tool, but static postural stability does not seem to have the same value as the other functional measures examined.

APPENDIX A

UNIVERSITY OF PITTSBURGH INJURY PREVENTION AND PERFORMANCE OPTIMIZATION MODEL



APPENDIX B

CUMBERLAND ANKLE INSTABILITY TOOL

The Cumberland Ankle Instability Tool
Please tick the ONE statement in EACH question that BEST describes your ankles.

	LEFT	RIGHT	SCORE
1. I have pain in my ankle			
Never	☐	☐	5
During sport	☐	☐	4
Running on uneven surfaces	☐	☐	3
Running on level surfaces	☐	☐	2
Walking on uneven surfaces	☐	☐	1
Walking on level surfaces	☐	☐	0
2. My ankle feels UNSTABLE			
Never	☐	☐	4
Sometimes during sport (not every time)	☐	☐	3
Frequently during sport (every time)	☐	☐	2
Sometimes during daily activity	☐	☐	1
Frequently during daily activity	☐	☐	0
3. When I make SHARP turns, my ankle feels UNSTABLE			
Never	☐	☐	3
Sometimes when running	☐	☐	2
Often when running	☐	☐	1
When walking	☐	☐	0
4. When going down the stairs, my ankle feels UNSTABLE			
Never	☐	☐	3
If I go fast	☐	☐	2
Occasionally	☐	☐	1
Always	☐	☐	0
5. My ankle feels UNSTBLE when standing on ONE leg			
Never	☐	☐	2
On the ball of my foot	☐	☐	1
With my foot flat	☐	☐	0
6. My ankle feels UNSTABLE when			
Never	☐	☐	3
I hop from side to side	☐	☐	2
I hop on the spot	☐	☐	1
When I jump	☐	☐	0
7. My ankle feels UNSTABLE when			
Never	☐	☐	4
I run on uneven surfaces	☐	☐	3
I jog on uneven surfaces	☐	☐	2
I walk on uneven surfaces	☐	☐	1
I walk on a flat surface	☐	☐	0
8. TYPICALLY, when I start to roll over (or twist) on my ankle, I can stop			
Immediately	☐	☐	4
Often	☐	☐	3
Sometimes	☐	☐	2
Never	☐	☐	1
I have never rolled over on my ankle	☐	☐	0
9. After a TYPICAL incident of my ankle rolling over, my ankle returns to "normal "			
Almost immediately	☐	☐	4
Less than one day	☐	☐	3
1-2 days	☐	☐	2
More than 2 days	☐	☐	1
I have never rolled over on my ankle	☐	☐	0

APPENDIX C

BOX PLOTS TO SHOW DIFFERENCES WITH THE REMOVAL OF OUTLIERS

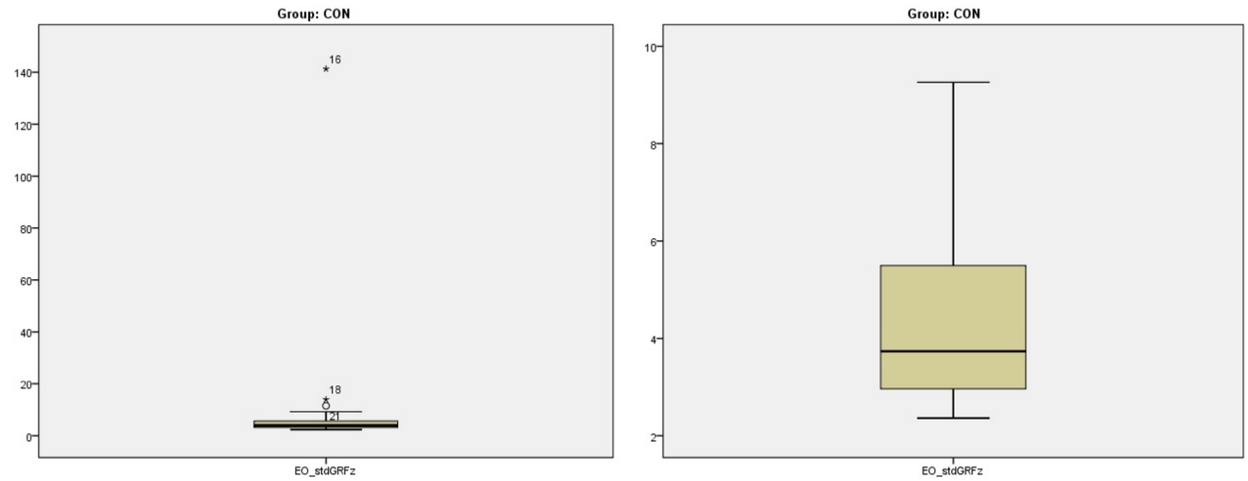


Figure C1. Box Plot to Show Removal of Three Outliers for EO_stdGRFz in CON

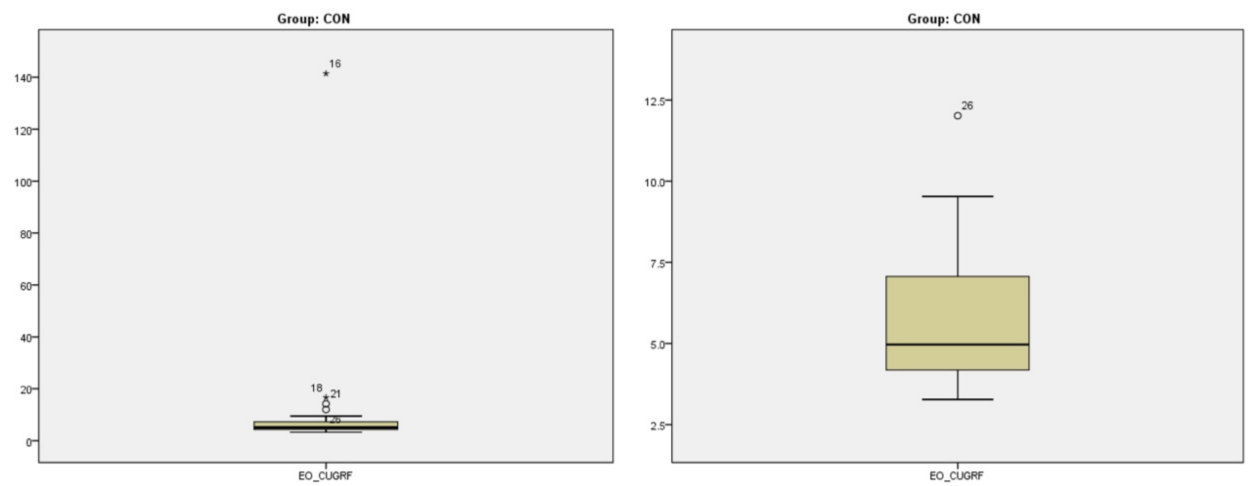


Figure C2. Box Plot to Show Removal of Three Outliers for EO_CUGRF in CON

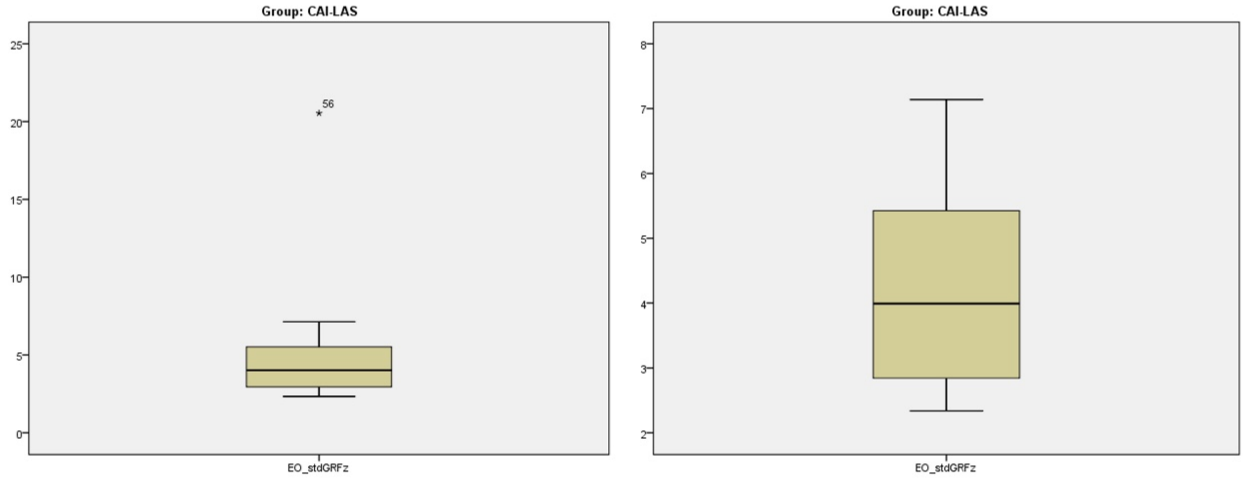


Figure C3. Box Plot to Show Removal of One Outlier for EO_stdGRFz in CAI-LAS

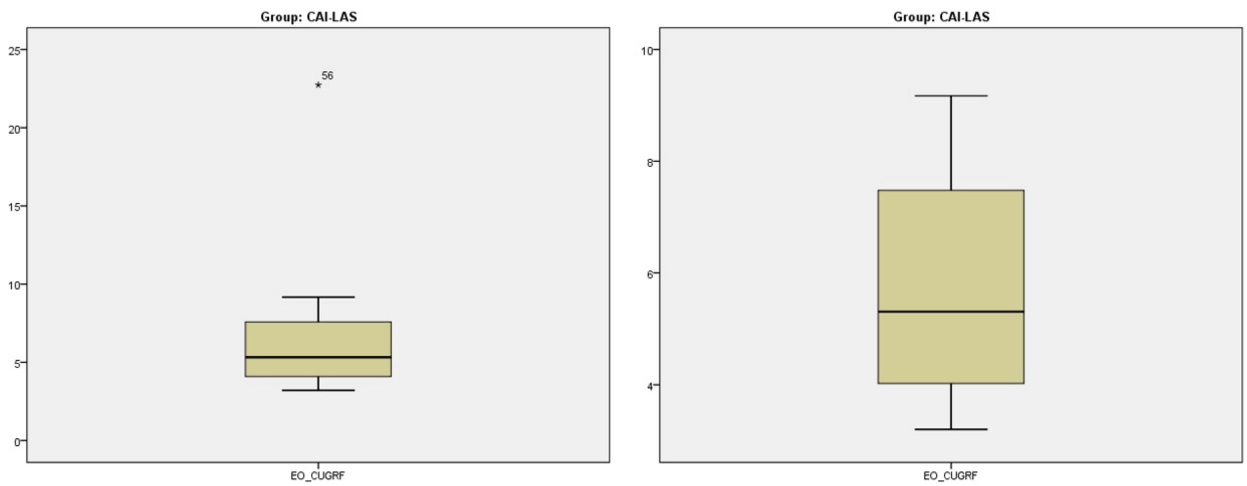


Figure C4. Box Plot to Show Removal of One Outlier for EO_CUGRF in CAI-LAS

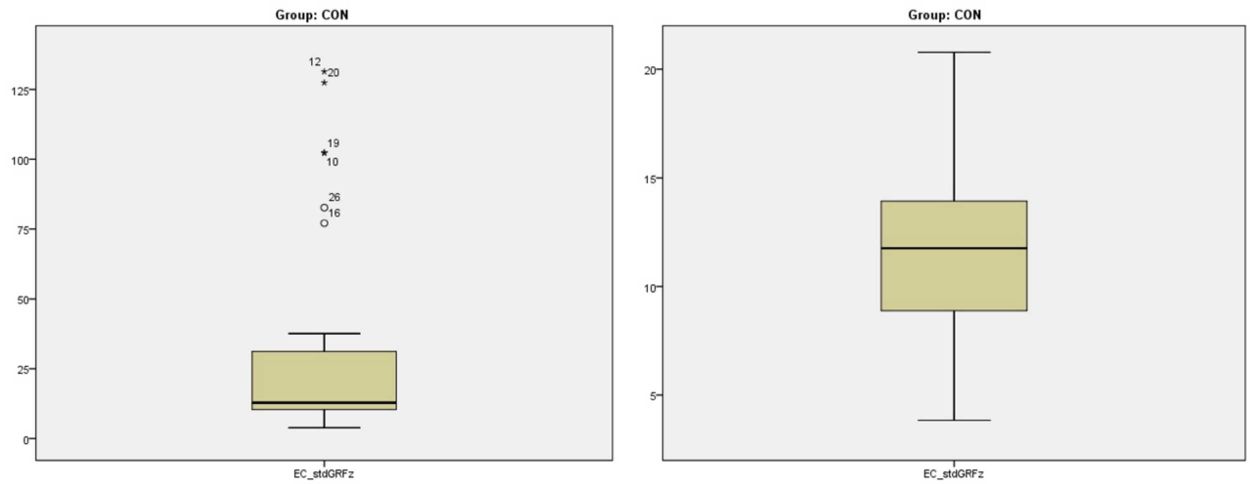


Figure C5. Box Plot to Show Removal of Eight Outliers for EC_stdGRFz in CON

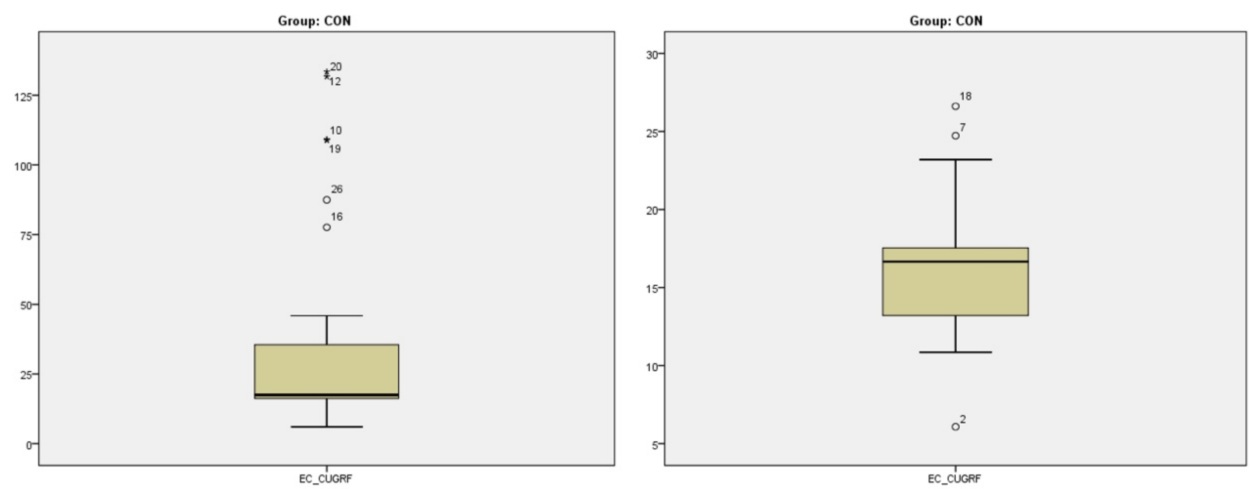


Figure C6. Box Plot to Show Removal of Eight Outliers for EC_CUGRF in CON

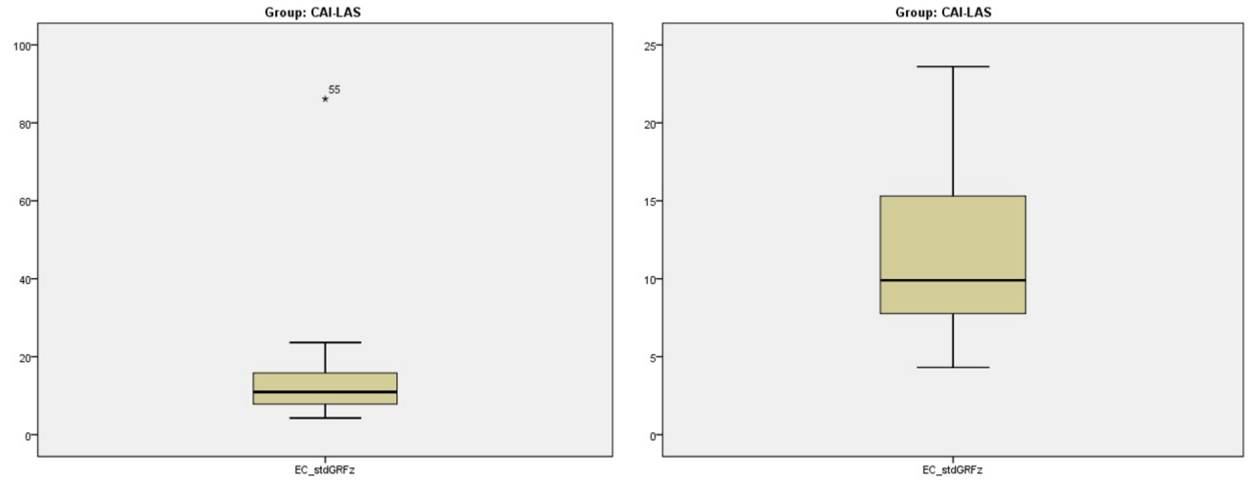


Figure C7. Box Plot to Show Removal of One Outlier for EC_stdGRFz in CAI-LAS

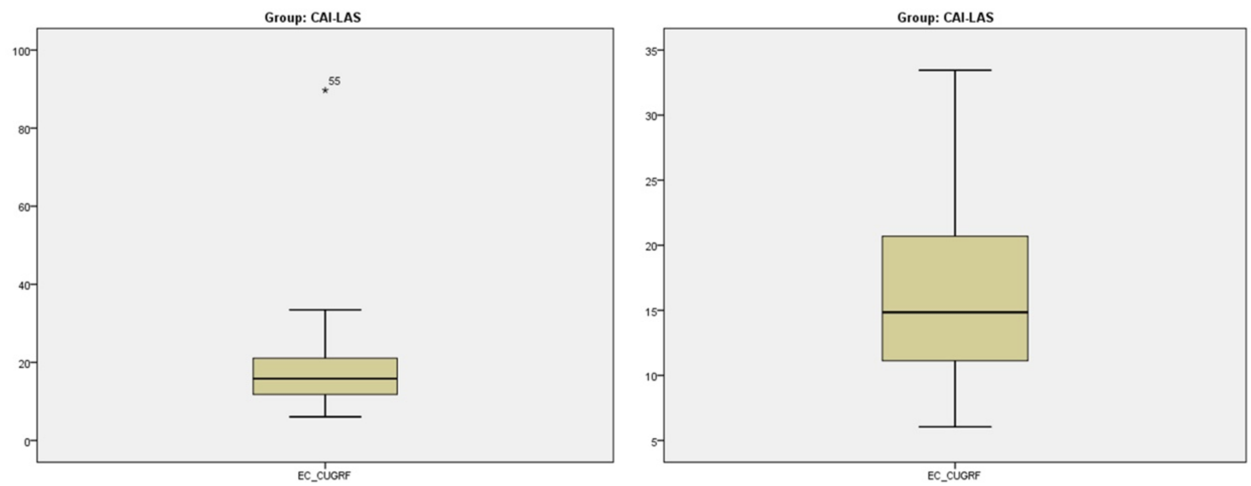


Figure C8. Box Plot to Show Removal of One Outlier for EC_CUGRF in CAI-LAS

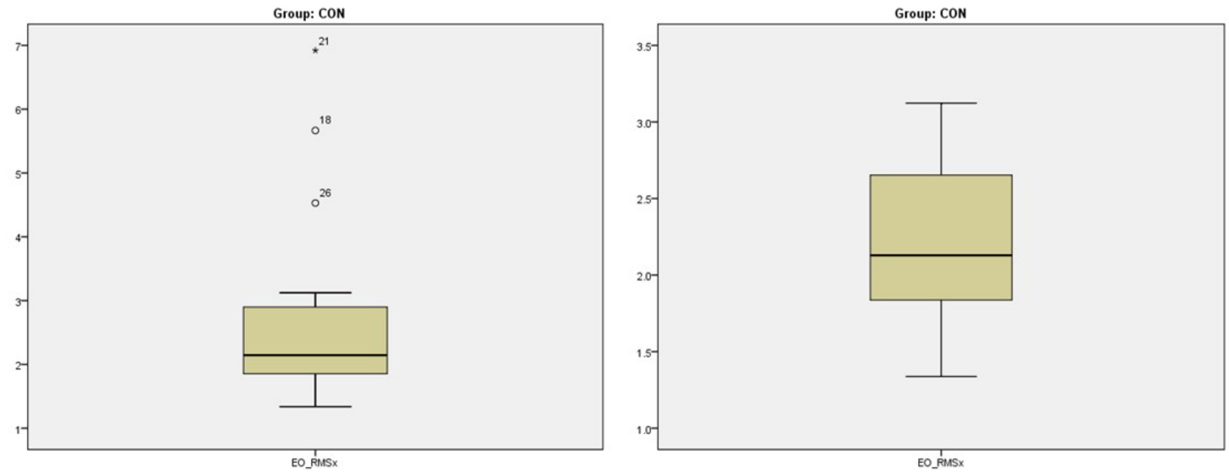


Figure C9. Box plot to show removal of three outliers for EO_RMSx in CON

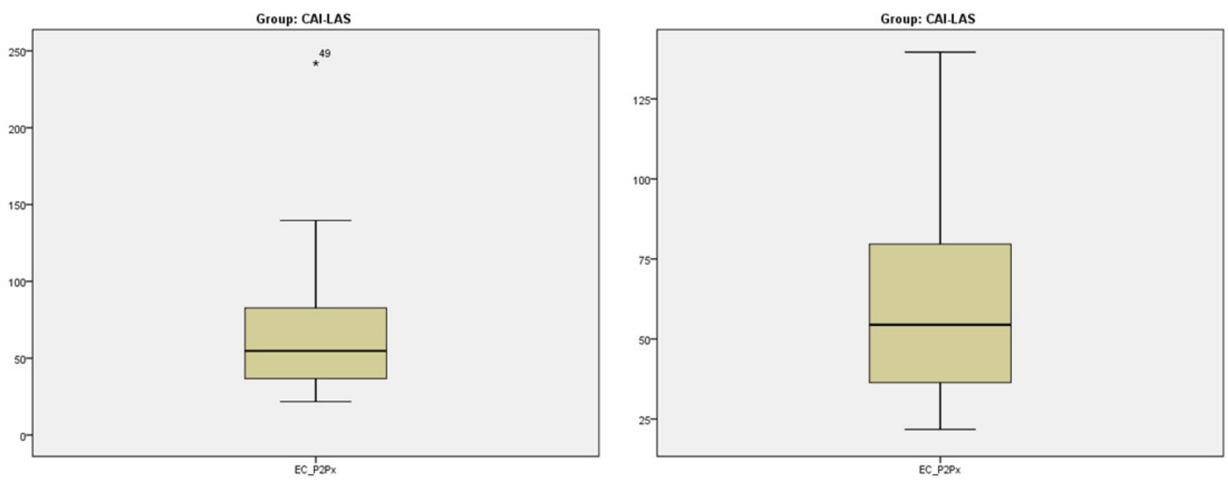


Figure C10. Box plot to show removal of one outlier for EC_P2Px in CAI-LAS

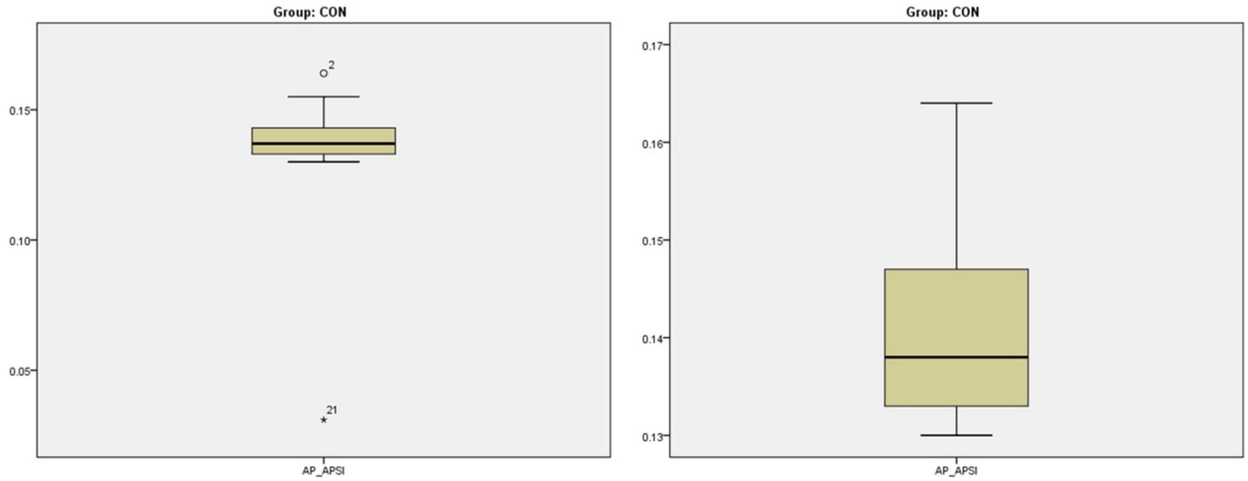


Figure C11. Box Plot to Show Removal of Outliers for AP_DPSI in CON

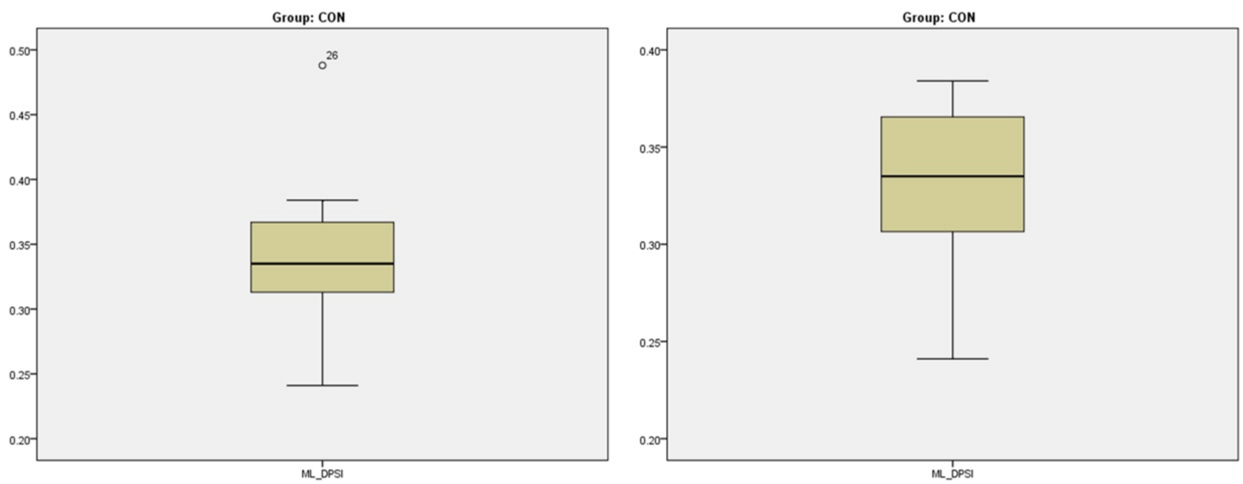


Figure C12. Box Plot to Show Removal of Outliers for ML_DPSI in CON

BIBLIOGRAPHY

1. Abbot B. *The Relationship Between Two Tasks of Dynamic Postural Stability*. Pittsburgh, PA: School of Health and Rehabilitation Sciences, University of Pittsburgh; 2015.

2. Arnason A, Sigurdsson SB, Gudmundsson A, Holme I, Engebretsen L, Bahr R. Risk factors for injuries in football. *Am J Sports Med.* 2004;32(1 Suppl):5S-16S.

3. Ashton-Miller JA, Ottaviani RA, Hutchinson C, Wojtys EM. What best protects the inverted weightbearing ankle against further inversion? Evertor muscle strength compares favorably with shoe height, athletic tape, and three orthoses. *Am J Sports Med.* 1996;24(6):800-809.

4. Barrett JR, Tanji JL, Drake C, Fuller D, Kawasaki RI, Fenton RM. High- versus low-top shoes for the prevention of ankle sprains in basketball players. A prospective randomized study. *Am J Sports Med.* 1993;21(4):582-585.

5. Baumhauer JF, Alosa DM, Renstrom AF, Trevino S, Beynnon B. A prospective study of ankle injury risk factors. *The American journal of sports medicine.* 1995;23(5):564-570.

6. Baumhauer JF, Alosa DM, Renstrom AF, Trevino S, Beynnon B. A prospective study of ankle injury risk factors. *Am J Sports Med.* 1995;23(5):564-570.

7. Beggs I, Bianchi S, Bueno A, et al. Chapter VI. Ankle. In: European_Society_of_MusculoSkeletal_Radiology, ed. *Musculoskeletal Ultrasound Technical Guidelines*. Vienna, Austria: ESSR; 2016.

8. Bennell KL, Malcolm SA, Thomas SA, et al. Risk factors for stress fractures in track and field athletes. A twelve-month prospective study. *Am J Sports Med.* 1996;24(6):810-818.

9. Bennett JE, Reinking MF, Pluemer B, Pentel A, Seaton M, Killian C. Factors contributing to the development of medial tibial stress syndrome in high school runners. *J Orthop Sports Phys Ther.* 2001;31(9):504-510.

10. Beynnon BD, Murphy DF, Alosa DM. Predictive Factors for Lateral Ankle Sprains: A Literature Review. *J Athl Train.* 2002;37(4):376-380.

11. Beynnon BD, Renstrom PA, Alosa DM, Baumhauer JF, Vacek PM. Ankle ligament injury risk factors: a prospective study of college athletes. *Journal of orthopaedic research : official publication of the Orthopaedic Research Society.* 2001;19(2):213-220.

12. Boyle J, Negus V. Joint position sense in the recurrently sprained ankle. *Australian Journal of Physiotherapy.* 1998;44(3):159-163.

13. Brown CN, Mynark R. Balance deficits in recreational athletes with chronic ankle instability. *J Athl Train.* 2007;42(3):367-373.

14. Bruggemann G, Potthast W, Braunstein B, Niehoff A. Effect of increased mechanical stimuli on foot muscles functional capacity. *In: Proceedings of International Society of Biomechanics XXth Congress*. Cleveland, Ohio; 2005:553.

15. Burks RT, Morgan J. Anatomy of the lateral ankle ligaments. *Am J Sports Med.* 1994;22(1):72-77.

16. Bush KW. Predicting ankle sprain. *Journal of Manual & Manipulative Therapy.* 1996;4(2):54-58.

17. Cavanaugh JT, Guskiewicz KM, Stergiou N. A nonlinear dynamic approach for evaluating postural control. *Sports Medicine.* 2005;35(11):935-950.

18. Clark NC. *Predictors of Knee Functional Joint Stability in Uninjured Physically Active Adults*. Pittsburgh, PA: School of Health and Rehabilitation Sciences, University of Pittsburgh; 2014.

19. Cleland JA, Mintken PE, McDevitt A, et al. Manual physical therapy and exercise versus supervised home exercise in the management of patients with inversion ankle sprain: a multicenter randomized clinical trial. *J Orthop Sports Phys Ther.* 2013;43(7):443-455.

20. Cohen J. Statistical power analysis for the behavioral sciences (revised ed.): New York: Academic Press; 1977.

21. Cohen J. Statistical power analysis. *Current directions in psychological science.* 1992;1(3):98-101.

22. Darnell ME. *Effect of Carbohydrate-Electrolyte Feedings on Knee Biomechanics and Postural Stability During Intermirrtent High-Intensity Exercise to Fatigue*. Pittsburgh, PB: School of Health and Rehabilitation Sciences, University of Pittsburgh; 2015.

23. de Jong A, Kilbreath SL, Refshauge KM, Adams R. Performance in different proprioceptive tests does not correlate in ankles with recurrent sprain. *Arch Phys Med Rehabil.* 2005;86(11):2101-2105.

24. de Loes M, Goldie I. Incidence rate of injuries during sport activity and physical exercise in a rural Swedish municipality: incidence rates in 17 sports. *Int J Sports Med.* 1988;9(6):461-467.

25. de Noronha M, Refshauge KM, Herbert RD, Kilbreath SL, Hertel J. Do voluntary strength, proprioception, range of motion, or postural sway predict occurrence of lateral ankle sprain? *Br J Sports Med.* 2006;40(10):824-828; discussion 828.

26. Dekker R, Kingma J, Groothoff JW, Eisma WH, Ten Duis HJ. Measurement of severity of sports injuries: an epidemiological study. *Clin Rehabil.* 2000;14(6):651-656.

27. Denegar CR, Hertel J, Fonseca J. The effect of lateral ankle sprain on dorsiflexion range of motion, posterior talar glide, and joint laxity. *J Orthop Sports Phys Ther.* 2002;32(4):166-173.

28. Docherty CL, Moore JH, Arnold BL. Effects of strength training on strength development and joint position sense in functionally unstable ankles. *Journal of athletic training.* 1998;33(4):310-314.

29. Docherty CL, Moore JH, Arnold BL. Effects of strength training on strength development and joint position sense in functionally unstable ankles. *Journal of athletic training.* 1998;33(4):310.

30. Donovan L, Hertel J. A new paradigm for rehabilitation of patients with chronic ankle instability. *The Physician and sportsmedicine.* 2012;40(4):41-51.

31. Ekstrand J, Gillquist J. Soccer injuries and their mechanisms: a prospective study. *Med Sci Sports Exerc.* 1983;15(3):267-270.

32. Ekstrand J, Tropp H. The incidence of ankle sprains in soccer. *Foot Ankle.* 1990;11(1):41-44.

33. Elveru RA, Rothstein JM, Lamb RL. Goniometric reliability in a clinical setting. Subtalar and ankle joint measurements. *Phys Ther.* 1988;68(5):672-677.

34. Engström BK, Renström PA. How can injuries be prevented in the World Cup soccer athlete? *Clinics in sports medicine.* 1998;17(4):755-768.

35. Faul F, Erdfelder E, Lang AG, Buchner A. G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav Res Methods.* 2007;39(2):175-191.

36. Federolf P, Zandiyeh P, von Tscharner V. Time scale dependence of the center of pressure entropy: What characteristics of the neuromuscular postural control system influence stabilographic entropic half-life? *Exp Brain Res.* 2015;233(12):3507-3515.

37. Ferran NA, Maffulli N. Epidemiology of sprains of the lateral ankle ligament complex. *Foot Ankle Clin.* 2006;11(3):659-662.

38. Fong DT, Hong Y, Chan LK, Yung PS, Chan KM. A systematic review on ankle injury and ankle sprain in sports. *Sports Med.* 2007;37(1):73-94.

39. Forkin DM, Koczur C, Battle R, Newton RA. Evaluation of kinesthetic deficits indicative of balance control in gymnasts with unilateral chronic ankle sprains. *J Orthop Sports Phys Ther.* 1996;23(4):245-250.

40. Freeman MA. Instability of the foot after injuries to the lateral ligament of the ankle. *The Journal of bone and joint surgery. British volume.* 1965;47(4):669-677.

41. Garn SN, Newton RA. Kinesthetic awareness in subjects with multiple ankle sprains. *Phys Ther.* 1988;68(11):1667-1671.

42. Glencross D, Thornton E. Position sense following joint injury. *J Sports Med Phys Fitness.* 1981;21(1):23-27.

43. Goldie P, Bach T, Evans O. Force platform measures for evaluating postural control: reliability and validity. *Archives of physical medicine and rehabilitation.* 1989;70(7):510.

44. Goldie P, Evans O, Bach T. Steadiness in one-legged stance: development of a reliable force-platform testing procedure. *Archives of physical medicine and rehabilitation.* 1992;73(4):348.

45. Goldie PA, Evans OM, Bach TM. Postural control following inversion injuries of the ankle. *Arch Phys Med Rehabil.* 1994;75(9):969-975.

46. Gribble P, Hertel J. Considerations for normalizing measures of the Star Excursion Balance Test. *Measurement in physical education and exercise science.* 2003;7(2):89-100.

47. Gribble PA, Bleakley CM, Caulfield BM, et al. 2016 consensus statement of the International Ankle Consortium: prevalence, impact and long-term consequences of lateral ankle sprains. *British journal of sports medicine.* 2016;50(24):1493-1495.

48. Gribble PA, Bleakley CM, Caulfield BM, et al. Evidence review for the 2016 International Ankle Consortium consensus statement on the prevalence, impact and long-term consequences of lateral ankle sprains. *British journal of sports medicine.* 2016;50(24):1496-1505.

49. Gribble PA, Hertel J, Plisky P. Using the Star Excursion Balance Test to assess dynamic postural-control deficits and outcomes in lower extremity injury: a literature and systematic review. *J Athl Train.* 2012;47(3):339-357.

50. Gribble PA, Terada M, Beard MQ, et al. Prediction of Lateral Ankle Sprains in Football Players Based on Clinical Tests and Body Mass Index. *Am J Sports Med.* 2016;44(2):460-467.

51. Gross MT. Effects of recurrent lateral ankle sprains on active and passive judgements of joint position. *Phys Ther.* 1987;67(10):1505-1509.

52. Hale SA, Hertel J, Olmsted-Kramer LC. The effect of a 4-week comprehensive rehabilitation program on postural control and lower extremity function in individuals with chronic ankle instability. *J Orthop Sports Phys Ther.* 2007;37(6):303-311.

53. Hall EA, Docherty CL, Simon J, Kingma JJ, Klossner JC. Strength-Training Protocols to Improve Deficits in Participants With Chronic Ankle Instability: A Randomized Controlled Trial. *Journal of athletic training.* 2014.

54. Harman E, Pandorf C. Principles of test selection and administration. *Essentials of Strength Training and Conditioning. 2nd ed. Champaign, IL: Human Kinetics.* 2000:275-307.

55. Heebner NR. *The effect of jump didtance on biomechanical risk factors for ACL injury during landing and their relationship with sensorimotor characteristics at the knee*. Pittsburgh, PB: School of Health and Rehabilitation Sciences, University of Pittsburgh; 2015.

56. Heit EJ, Lephart SM, Rozzi SL. The effect of ankle bracing and taping on joint position sense in the stable ankle. *Journal of Sport Rehabilitation.* 1996;5:206-213.

57. Hertel J. Functional instability following lateral ankle sprain. *Sports Med.* 2000;29(5):361-371.

58. Hertel J. Functional Anatomy, Pathomechanics, and Pathophysiology of Lateral Ankle Instability. *Journal of athletic training.* 2002;37(4):364-375.

59. Hertel J. Sensorimotor deficits with ankle sprains and chronic ankle instability. *Clinics in sports medicine.* 2008;27(3):353-370, vii.

60. Hertel J, Braham RA, Hale SA, Olmsted-Kramer LC. Simplifying the star excursion balance test: analyses of subjects with and without chronic ankle instability. *Journal of Orthopaedic & Sports Physical Therapy.* 2006;36(3):131-137.

61. Hiller CE, Refshauge KM, Bundy AC, Herbert RD, Kilbreath SL. The Cumberland ankle instability tool: a report of validity and reliability testing. *Archives of physical medicine and rehabilitation.* 2006;87(9):1235-1241.

62. Hiller CE, Refshauge KM, Herbert RD, Kilbreath SL. Balance and recovery from a perturbation are impaired in people with functional ankle instability. *Clin J Sport Med.* 2007;17(4):269-275.

63. Hollis JM, Blasier RD, Flahiff CM. Simulated lateral ankle ligamentous injury. Change in ankle stability. *Am J Sports Med.* 1995;23(6):672-677.

64. Holmer P, Sondergaard L, Konradsen L, Nielsen PT, Jorgensen LN. Epidemiology of sprains in the lateral ankle and foot. *Foot Ankle Int.* 1994;15(2):72-74.

65. Hootman JM, Dick R, Agel J. Epidemiology of collegiate injuries for 15 sports: summary and recommendations for injury prevention initiatives. *J Athl Train.* 2007;42(2):311-319.

66. Hosea TM, Carey CC, Harrer MF. The gender issue: epidemiology of ankle injuries in athletes who participate in basketball. *Clin Orthop Relat Res.* 2000(372):45-49.

67. Hubbard TJ, Kramer LC, Denegar CR, Hertel J. Correlations among multiple measures of functional and mechanical instability in subjects with chronic ankle instability. *J Athl Train.* 2007;42(3):361-366.

68. Jacobson JA. *Fundamentals of Musculoskeletal Ultrasound: Expert Consult-Online*: Elsevier Health Sciences; 2012.

69. Kaminski TW, Hartsell HD. Factors Contributing to Chronic Ankle Instability: A Strength Perspective. *J Athl Train.* 2002;37(4):394-405.

70. Kaminski TW, Hertel J, Amendola N, et al. National Athletic Trainers' Association position statement: conservative management and prevention of ankle sprains in athletes. *J Athl Train.* 2013;48(4):528-545.

71. Karlsson A, Frykberg G. Correlations between force plate measures for assessment of balance. *Clin Biomech (Bristol, Avon).* 2000;15(5):365-369.

72. Kinzey SJ, Armstrong CW. The reliability of the star-excursion test in assessing dynamic balance. *J Orthop Sports Phys Ther.* 1998;27(5):356-360.

73. Kjaersgaard-Andersen P, Wethelund JO, Helmig P, Nielsen S. Effect of the calcaneofibular ligament on hindfoot rotation in amputation specimens. *Acta Orthop Scand.* 1987;58(2):135-138.

74. Koepsell TD. Selecting a Study Design for. *Injury control: a guide to research and program evaluation.* 2001:89.

75. Konradsen L. Factors Contributing to Chronic Ankle Instability: Kinesthesia and Joint Position Sense. *Journal of athletic training.* 2002;37(4):381-385.

76. Konradsen L, Olesen S, Hansen HM. Ankle sensorimotor control and eversion strength after acute ankle inversion injuries. *Am J Sports Med.* 1998;26(1):72-77.

77. Lake DE, Richman JS, Griffin MP, Moorman JR. Sample entropy analysis of neonatal heart rate variability. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology.* 2002;283(3):R789-R797.

78. Leanderson J, Wykman A, Eriksson E. Ankle sprain and postural sway in basketball players. *Knee Surg Sports Traumatol Arthrosc.* 1993;1(3-4):203-205.

79. Lentell G, Baas B, Lopez D, McGuire L, Sarrels M, Snyder P. The contributions of proprioceptive deficits, muscle function, and anatomic laxity to functional instability of the ankle. *J Orthop Sports Phys Ther.* 1995;21(4):206-215.

80. Lephart SM, Pincivero DM, Giraldo JL, Fu FH. The role of proprioception in the management and rehabilitation of athletic injuries. *Am J Sports Med.* 1997;25(1):130-137.

81. Lephart SM, Pincivero DM, Rozzi SL. Proprioception of the ankle and knee. *Sports Med.* 1998;25(3):149-155.

82. Lephart SM, Riemann B, Fu F, eds. *Introduction to the sensorimotor system*. Champaign, IL: Human Kinetics; 2000. Lephart S, Fu F, eds.

83. Lim EC, Tan MH. Side-to-side difference in joint position sense and kinesthesia in unilateral functional ankle instability. *Foot & ankle international.* 2009;30(10):1011-1017.

84. Manor B, Costa MD, Hu K, et al. Physiological complexity and system adaptability: evidence from postural control dynamics of older adults. *Journal of Applied Physiology.* 2010;109(6):1786-1791.

85. Martinson H, Stokes MJ. Measurement of anterior tibial muscle size using real-time ultrasound imaging. *European journal of applied physiology and occupational physiology.* 1991;63(3-4):250-254.

86. McCreesh K, Egan S. Ultrasound measurement of the size of the anterior tibial muscle group: the effect of exercise and leg dominance. *Sports medicine, arthroscopy, rehabilitation, therapy & technology : SMARTT.* 2011;3:18.

87. McGuine T, Greene J, Best T, Leverson G. Balance as a predictor of ankle injuries in high school basketball players. *Clinical journal of sport medicine: official journal of the Canadian Academy of Sport Medicine.* 2000;10(4):239.

88. McKay GD, Goldie PA, Payne WR, Oakes BW. Ankle injuries in basketball: injury rate and risk factors. *Br J Sports Med.* 2001;35(2):103-108.

89. Michelson JD, Hutchins C. Mechanoreceptors in human ankle ligaments. *J Bone Joint Surg Br.* 1995;77(2):219-224.

90. Milgrom C, Shlamkovitch N, Finestone A, et al. Risk factors for lateral ankle sprain: a prospective study among military recruits. *Foot Ankle.* 1991;12(1):26-30.

91. Miller CD, Shelton WR, Barrett GR, Savoie FH, Dukes AD. Deltoid and syndesmosis ligament injury of the ankle without fracture. *Am J Sports Med.* 1995;23(6):746-750.

92. Munro AG, Herrington LC. Between-session reliability of the star excursion balance test. *Phys Ther Sport.* 2010;11(4):128-132.

93. Murphy DF, Connolly DA, Beynnon BD. Risk factors for lower extremity injury: a review of the literature. *British journal of sports medicine.* 2003;37(1):13-29.

94. Nagai T, Sell TC, Abt JP, Lephart SM. Reliability, precision, and gender differences in knee internal/external rotation proprioception measurements. *Phys Ther Sport.* 2012;13(4):233-237.

95. Nagai T, Sell TC, House AJ, Abt JP, Lephart SM. Knee proprioception and strength and landing kinematics during a single-leg stop-jump task. *J Athl Train.* 2013;48(1):31-38.

96. Nema S, Kowalczyk P, Loram I. Complexity and dynamics of switched human balance control during quiet standing. *Biol Cybern.* 2015;109(4-5):469-478.

97. Olmsted LC, Carcia CR, Hertel J, Shultz SJ. Efficacy of the star excursion balance tests in detecting reach deficits in subjects with chronic ankle instability. *Journal of athletic training.* 2002;37(4):501.

98. Olsen OE, Myklebust G, Engebretsen L, Holme I, Bahr R. Exercises to prevent lower limb injuries in youth sports: cluster randomised controlled trial. *BMJ.* 2005;330(7489):449.

99. Payne KA, Berg K, Latin RW. Ankle injuries and ankle strength, flexibility, and proprioception in college basketball players. *J Athl Train.* 1997;32(3):221-225.

100. Pederson J. *Investigating the Relationship Between FAI Questionnaires and Measures of Static and Dynamic Postural Stability*. Pittsburgh, PA: School of Health and Rehabilitation Sciences, University of Pittsburgh; 2011.

101. Pederson JJ, Abt JP, Keenan KA, et al. Altered ground reaction forces during anterior jump landing in subjects with functional ankle instability. Paper presented at: International Ankle Symposium; October 17, 2012, 2012; Lexington, KY.

102. Pederson JJ, Abt JP, Keenan KA, et al. Ankle Questionnaires Correlate with Dynamic Postural Stablity in Subjects with Functional Ankle Instability. Paper presented at: National Athleteic Trainers Association Annual Meeting and Clinical Symposia; June 26, 2012, 2012; St. Louis, MO.

103. Pincus SM, Goldberger AL. Physiological time-series analysis: what does regularity quantify? *American Journal of Physiology-Heart and Circulatory Physiology.* 1994;266(4):H1643-H1656.

104. Plisky PJ, Gorman PP, Butler RJ, Kiesel KB, Underwood FB, Elkins B. The reliability of an instrumented device for measuring components of the star excursion balance test. *N Am J Sports Phys Ther.* 2009;4(2):92-99.

105. Plisky PJ, Rauh MJ, Kaminski TW, Underwood FB. Star Excursion Balance Test as a predictor of lower extremity injury in high school basketball players. *J Orthop Sports Phys Ther.* 2006;36(12):911-919.

106. Portney LG, Watkins MP. *Foundations of clinical research: applications to practice.* Vol 2: Prentice Hall Upper Saddle River, NJ; 2000.

107. Powden CJ, Hogan KK, Wikstrom EA, Hoch MC. The Effect of Two Forms of Talocrural Joint Traction on Dorsiflexion Range of Motion and Postural Control in Those With Chronic Ankle Instability. *J Sport Rehabil.* 2015.

108. Prajapati B, Dunne M, Armstrong R. Sample size estimation and statistical power analyses. *Optomoetry today.* 2010;July.

109. Ramdani S, Seigle B, Lagarde J, Bouchara F, Bernard PL. On the use of sample entropy to analyze human postural sway data. *Medical engineering & physics.* 2009;31(8):1023-1031.

110. Refshauge KM, Kilbreath SL, Raymond J. The effect of recurrent ankle inversion sprain and taping on proprioception at the ankle. *Med Sci Sports Exerc.* 2000;32(1):10-15.

111. Refshauge KM, Kilbreath SL, Raymond J. Deficits in detection of inversion and eversion movements among subjects with recurrent ankle sprains. *Journal of Orthopaedic & Sports Physical Therapy.* 2003;33(4):166-176.

112. Refshauge KM, Raymond J, Kilbreath SL, Pengel L, Heijnen I. The effect of ankle taping on detection of inversion-eversion movements in participants with recurrent ankle sprain. *Am J Sports Med.* 2009;37(2):371-375.

113. Rhea CK, Kiefer AW, Haran FJ, Glass SM, Warren WH. A new measure of the CoP trajectory in postural sway: dynamics of heading change. *Med Eng Phys.* 2014;36(11):1473-1479.

114. Rhea CK, Kiefer AW, Wright WG, Raisbeck LD, Haran FJ. Interpretation of postural control may change due to data processing techniques. *Gait Posture.* 2015;41(2):731-735.

115. Rhea CK, Silver TA, Hong SL, et al. Noise and complexity in human postural control: interpreting the different estimations of entropy. *PloS one.* 2011;6(3):e17696.

116. Richman JS, Moorman JR. Physiological time-series analysis using approximate entropy and sample entropy. *Am J Physiol Heart Circ Physiol.* 2000;278(6):H2039-2049.

117. Riemann BL. Is There a Link Between Chronic Ankle Instability and Postural Instability? *J Athl Train.* 2002;37(4):386-393.

118. Riemann BL, Lephart SM. The sensorimotor system, part I: the physiologic basis of functional joint stability. *Journal of athletic training.* 2002;37(1):71-79.

119. Riemann BL, Lephart SM. The Sensorimotor System, Part II: The Role of Proprioception in Motor Control and Functional Joint Stability. *Journal of athletic training.* 2002;37(1):80-84.

120. Riemann BL, Myers JB, Lephart SM. Sensorimotor system measurement techniques. *J Athl Train.* 2002;37(1):85.

121. Rivara FP, Cummings P, Koepsell TD. *Injury control: a guide to research and program evaluation*: Cambridge University Press; 2009.

122. Robbins S, Hanna A. Running-related injury prevention through barefoot adaptations. *Medicine and science in sports and exercise.* 1987;19(2):148.

123. Roerdink M, Hlavackova P, Vuillerme N. Center-of-pressure regularity as a marker for attentional investment in postural control: a comparison between sitting and standing postures. *Hum Mov Sci.* 2011;30(2):203-212.

124. Rosenthal R. *Meta-analytic procedures for social research.* Vol 6: Sage; 1991.

125. Ross S, Guskiewicz K. Examination of static and dynamic postural stability in individuals with functionally stable and unstable ankles. *Clinical journal of sport medicine: official journal of the Canadian Academy of Sport Medicine.* 2004;14(6):332.

126. Ross SE, Guskiewicz K. Time to stabilization: a method for analyzing dynamic postural stability. *Athl Ther Today.* 2003;8(3):37-39.

127. Ross SE, Guskiewicz KM. Examination of static and dynamic postural stability in individuals with functionally stable and unstable ankles. *Clinical journal of sport medicine : official journal of the Canadian Academy of Sport Medicine.* 2004;14(6):332-338.

128. Ross SE, Guskiewicz KM, Gross MT, Yu B. Balance measures for discriminating between functionally unstable and stable ankles. *Med Sci Sports Exerc.* 2009;41(2):399-407.

129. Ross SE, Guskiewicz KM, Yu B. Single-leg jump-landing stabilization times in subjects with functionally unstable ankles. *Journal of athletic training.* 2005;40(4):298-304.

130. Ross SE, Guskiewicz KM, Yu B. Single-leg jump-landing stabilization times in subjects with functionally unstable ankles. *Journal of Athletic Training.* 2005;40(4):298.

131. Sawkins K, Refshauge K, Kilbreath S, Raymond J. The placebo effect of ankle taping in ankle instability. *Med Sci Sports Exerc.* 2007;39(5):781-787.

132. Schmitz JL. *Comparison and Correlation of Dynamic Postural Stability Indicies Obtained During Different Dynamic Landing Tasks and with Different Footwear Conditions*. Pittsburgh, PA: School of Health and Rehabilitation Sciences, University of Pittsburgh; 2017.

133. Sell TC. An examination, correlation, and comparison of static and dynamic measures of postural stability in healthy, physically active adults. *Phys Ther Sport.* 2012;13(2):80-86.

134. Sell TC. An examination, correlation, and comparison of static and dynamic measures of postural stability in healthy, physically active adults. *Physical therapy in sport : official journal of the Association of Chartered Physiotherapists in Sports Medicine.* 2012;13(2):80-86.

135. Sell TC, Abt JP, Crawford K, et al. Warrior Model for Human Performance and Injury Prevention: Eagle Tactical Athlete Program (ETAP) Part I. *Journal of Special Operations Medicine.* 2010;10(4):2-21.

136. Sell TC, Pederson JJ, Abt JP, et al. The addition of body armor diminishes dynamic postural stability in military soldiers. *Military medicine.* 2013;178(1):76-81.

137. Shambaugh JP, Klein A, Herbert JH. Structural measures as predictors of injury basketball players. *Med Sci Sports Exerc.* 1991;23(5):522-527.

138. Shumway-Cook A, Horak F. Assessing the influence of sensory interaction of balance. Suggestion from the field. *Phys Ther.* 1986;66(10):1548.

139. Sitler M, Ryan J, Wheeler B, et al. The efficacy of a semirigid ankle stabilizer to reduce acute ankle injuries in basketball. A randomized clinical study at West Point. *Am J Sports Med.* 1994;22(4):454-461.

140. Soderman K, Alfredson H, Pietila T, Werner S. Risk factors for leg injuries in female soccer players: a prospective investigation during one out-door season. *Knee Surg Sports Traumatol Arthrosc.* 2001;9(5):313-321.

141. Son SM, Kang KW, Lee NK, Nam SH, Kwon JW, Kim K. Influence of Isokinetic Strength Training of Unilateral Ankle on Ipsilateral One-legged Standing Balance of Adults. *Journal of physical therapy science.* 2013;25(10):1313-1315.

142. Squadrone R, Gallozzi C. Effect of a five-toed minimal protection shoe on static and dynamic ankle position sense. *The Journal of sports medicine and physical fitness.* 2011;51(3):401.

143. Stacoff A, Steger J, Stussi E, Reinschmidt C. Lateral stability in sideward cutting movements. *Med Sci Sports Exerc.* 1996;28(3):350-358.

144. Stephens MM, Sammarco GJ. The stabilizing role of the lateral ligament complex around the ankle and subtalar joints. *Foot Ankle.* 1992;13(3):130-136.

145. Stergiou N. *Innovative analyses of human movement*: Human Kinetics Publishers; 2004.

146. Stergiou N, Decker LM. Human movement variability, nonlinear dynamics, and pathology: is there a connection? *Human movement science.* 2011;30(5):869-888.

147. Stergiou N, Decker LM. Human movement variability, nonlinear dynamics, and pathology: is there a connection? *Hum Mov Sci.* 2011;30(5):869-888.

148. Stiffler MR, Sanfilippo JL, Brooks MA, Heiderscheit BC. Star Excursion Balance Test Performance Varies by Sport in Healthy Division I Collegiate Athletes. *J Orthop Sports Phys Ther.* 2015;45(10):772-780.

149. Stormont DM, Morrey BF, An KN, Cass JR. Stability of the loaded ankle. Relation between articular restraint and primary and secondary static restraints. *Am J Sports Med.* 1985;13(5):295-300.

150. Surve I, Schwellnus MP, Noakes T, Lombard C. A fivefold reduction in the incidence of recurrent ankle sprains in soccer players using the Sport-Stirrup orthosis. *The American Journal of Sports Medicine.* 1994;22(5):601-606.

151. Takebayashi T, Yamashita T, Minaki Y, Ishii S. Mechanosensitive afferent units in the lateral ligament of the ankle. *J Bone Joint Surg Br.* 1997;79(3):490-493.

152. Tammaro M, Schmitz J, Darnell M, Whitehead P. Habitual Users of Minimalist Footwear Display Better Dynamic Postural Stability During a Jump Landing Task. Paper presented at: ACSM Mid-Altantic Regional Chapter Annual Meeting, 2016; Harrisburg, PA.

153. Tankevicius G, Lankaite D, Krisciunas A. Test-retest reliability of biodex system 4 pro for isometric ankle-eversion and -inversion measurement. *Journal of Sport Rehabilitation.* 2013;22(3):212-215.

154. Terada M, Bowker S, Thomas AC, et al. Alterations in stride-to-stride variability during walking in individuals with chronic ankle instability. *Human movement science.* 2015;40:154-162.

155. Thacker SB, Stroup DF, Branche CM, Gilchrist J, Goodman RA, Weitman EA. The prevention of ankle sprains in sports A systematic review of the literature. *The American journal of sports medicine.* 1999;27(6):753-760.

156. Thalman LA. The Effects of Whole Body Vibration on Dorsiflexion in Chronic Ankle Instability. 2011.

157. Tomaszewski D. T-band kicks ankle proprioception program. *Athl Train J Natl Athl Train Assoc.* 1991;26:216-217,219.

158. Tourny C, Sangnier S, Cotte T, Langlois R, Coquart J. Epidemiologic study of young soccer player's injuries in U12 to U20. *J Sports Med Phys Fitness.* 2014;54(4):526-535.

159. Tropp H. Pronator muscle weakness in functional instability of the ankle joint. *Int J Sports Med.* 1986;7(5):291-294.

160. Tropp H, Askling C, Gillquist J. Prevention of ankle sprains. *Am J Sports Med.* 1985;13(4):259-262.

161. Tumilty D. Physiological characteristics of elite soccer players. *Sports Med.* 1993;16(2):80-96.

162. Twellaar M, Verstappen FT, Huson A, van Mechelen W. Physical characteristics as risk factors for sports injuries: a four year prospective study. *Int J Sports Med.* 1997;18(1):66-71.

163. Viladot A, Lorenzo JC, Salazar J, Rodriguez A. The subtalar joint: embryology and morphology. *Foot Ankle.* 1984;5(2):54-66.

164. Watson AW. Ankle sprains in players of the field-games Gaelic football and hurling. *J Sports Med Phys Fitness.* 1999;39(1):66-70.

165. Whitehead P. Better Dynamic Postural Stability While Wearing Minimalist Footwear in Physically-Active Male Adults. Paper presented at: ACSM Mid-Atlantic Regional Chapter Annual Meeting, 2014; Harrisburg, PA.

166. Wiesler ER, Hunter DM, Martin DF, Curl WW, Hoen H. Ankle flexibility and injury patterns in dancers. *Am J Sports Med.* 1996;24(6):754-757.

167. Wikstrom EA, Tillman MD, Borsa PA. Detection of dynamic stability deficits in subjects with functional ankle instability. *Med Sci Sports Exerc.* 2005;37(2):169-175.

168. Wikstrom EA, Tillman MD, Chmielewski TL, Cauraugh JH, Borsa PA. Dynamic postural stability deficits in subjects with self-reported ankle instability. *Medicine and science in sports and exercise.* 2007;39(3):397-402.

169. Wikstrom EA, Tillman MD, Kline KJ, Borsa PA. Gender and limb differences in dynamic postural stability during landing. *Clinical journal of sport medicine : official journal of the Canadian Academy of Sport Medicine.* 2006;16(4):311-315.

170. Wikstrom EA, Tillman MD, Schenker S, Borsa PA. Failed jump landing trials: deficits in neuromuscular control. *Scandinavian journal of medicine & science in sports.* 2008;18(1):55-61.

171. Wikstrom EA, Tillman MD, Smith AN, Borsa PA. A new force-plate technology measure of dynamic postural stability: the dynamic postural stability index. *J Athl Train.* 2005;40(4):305.

172. Wilkerson GB, Pinerola JJ, Caturano RW. Invertor vs. evertor peak torque and power deficiencies associated with lateral ankle ligament injury. *Journal of Orthopaedic & Sports Physical Therapy.* 1997;26(2):78-86.

173. Willems T, Witvrouw E, Delbaere K, Mahieu N, De Bourdeaudhuij I, De Clercq D. Intrinsic risk factors for inversion ankle sprains in male subjects: a prospective study. *The American journal of sports medicine.* 2005;33(3):415.

174. Willems T, Witvrouw E, Verstuyft J, Vaes P, De Clercq D. Proprioception and Muscle Strength in Subjects With a History of Ankle Sprains and Chronic Instability. *J Athl Train.* 2002;37(4):487-493.

175. Willems TM, Witvrouw E, Delbaere K, Philippaerts R, De Bourdeaudhuij I, De Clercq D. Intrinsic risk factors for inversion ankle sprains in females--a prospective study. *Scand J Med Sci Sports.* 2005;15(5):336-345.

176. Witchalls J, Blanch P, Waddington G, Adams R. Intrinsic functional deficits associated with increased risk of ankle injuries: a systematic review with meta-analysis. *British journal of sports medicine.* 2012;46(7):515-523.

177. Wojtys EM, Huston LJ, Taylor PD, Bastian SD. Neuromuscular adaptations in isokinetic, isotonic, and agility training programs. *The American journal of sports medicine.* 1996;24(2):187-192.

178. Wong P, Hong Y. Soccer injury in the lower extremities. *Br J Sports Med.* 2005;39(8):473-482.

179. Woods C, Hawkins R, Hulse M, Hodson A. The Football Association Medical Research Programme: an audit of injuries in professional football: an analysis of ankle sprains. *Br J Sports Med.* 2003;37(3):233-238.

180. Yagi S, Muneta T, Sekiya I. Incidence and risk factors for medial tibial stress syndrome and tibial stress fracture in high school runners. *Knee Surg Sports Traumatol Arthrosc.* 2013;21(3):556-563.

181. Yentes JM, Hunt N, Schmid KK, Kaipust JP, McGrath D, Stergiou N. The appropriate use of approximate entropy and sample entropy with short data sets. *Annals of biomedical engineering.* 2013;41(2):349-365.