The effect of chronic ankle instability on lower extremity frontal-plane kinematics and plantar pressure during a dynamic postural control task

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A Thesis

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The Effect of Chronic Ankle Instability on Lower Extremity Frontal-plane Kinematics and Plantar Pressure During a Dynamic Postural Control Task

By

Ara Wittwer, ATC

Submitted to the Graduate Faculty as partial fulfillment of the requirements for the Master of Science Degree in Exercise Science

______________________________

Dr. Phillip Gribble, Committee Chair

______________________________

Dr. Charles Armstrong, Committee Member:

______________________________

Dr. Brian Pietrosimone, Committee Member

______________________________

Dr. Patricia Komuniecki, Dean
College of Graduate Studies

The University of Toledo

May 2012
An Abstract of

The Effect of Chronic Ankle Instability on Lower Extremity Frontal-plane Kinematics and Plantar Pressure During a Dynamic Postural Control Task

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Objective: To assess the effects of CAI on frontal-plane kinematics of the hip, knee, and ankle as well as on plantar pressure distribution during the anterior reach of the Star Excursion Balance Test (SEBT) and identify possible relationship between altered kinematics and plantar pressure distribution. Design: A case control design with one between-subjects factor (Group) and one within-subjects factor (Side). Participants: Nine subjects with history of unilateral CAI and 9 healthy subjects. Methods: Subjects participated in one testing session and performed the anterior reach of the SEBT. Main Outcome Measures: Joint angles of the hip, knee, and ankle were quantified at the point of maximum SEBT reach. The medial to lateral (M:L) plantar pressure distribution was determined for the rearfoot, midfoot, and forefoot at the point of maximum reach. Normalized anterior reach distance was measured. Foot posture was assessed using the foot posture index 6 (FPI-6). Statistical Analysis: The means and standard deviations of the dependent variables at the point of maximum anterior reach distance for the 5 trials were used for comparison. A two-way analysis of variance was performed to determine if statistically significant interactions were present. An alpha level of .05 was set a priori.
Two-tailed t-tests were performed *post hoc* if significance was found to examine differences between each dependent variable within sides and between groups. Bivariate correlations were calculated using Pearson product moment correlations between all dependent variables on the involved side of the subjects with CAI, on the uninvolved side of the subjects with CAI, the involved side of the healthy subjects, on the uninvolved side of the healthy subjects. **Results:** The CAI group demonstrated more inversion at the ankle on the injured side (0.13 ± 4.48, *p* = 0.01) than the matched, healthy control (-12.21 ± 4.25) during the anterior reach of the SEBT. A less valgus angle was demonstrated at the knee of the CAI group (2.26 ± 6.46, *p* = 0.01) than the matched, healthy control (11.77 ± 11.00). Participants with CAI demonstrated a shorter normalized anterior reach distance on the injured side (59.06 ± 6.41, *p* = 0.036) than the matched, healthy control (66.98 ± 5.83). Although there were no statistically significant main effects or interactions for M:L plantar pressure distribution, the effect sizes for side by group interactions at the rearfoot (*d* = 1.07) and midfoot (*d* = 0.85) between the injured limb of the CAI group and matched limb of the control group were large. Pairwise correlations between kinematics, foot segments, and reach distance revealed that kinematics at the hip were significantly correlated with knee kinematics (*p* = 0.007) and that rearfoot plantar pressure was significantly correlated with forefoot plantar pressure (*p* = 0.046). **Conclusion:** We found altered kinematics in the frontal-plane at the knee and ankle. These findings support the conclusions of previous studies that suggest rehabilitation protocols following ankle sprain should incorporate proximal joint exercises.
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List of Abbreviations

ADL.................Activities of Daily Living

CAI .................. Chronic Ankle Instability
CNS.................Central Nervous System
COM.................Center of Mass

FADI ............Functional Ankle Disability Index
FI....................Functional Instability
FPI-6............Foot Posture Index- 6

GMD.................Gluteus Medius
GMX.................Gluteus Maximus

IT..................Iliotibial Band

MI..................Mechanical Instability
M:L..................Medial to Lateral Ratio

SEBT............Star Excursion Balance Test

TFL.................Tensor Fascia Lata
Chapter 1

Introduction

1.1 Introduction

Lateral ankle sprains are a very common injury.\textsuperscript{1} An epidemiological study from Nelson et al.\textsuperscript{2} reported a rate of 5.23 ankle injuries per 10,000 U.S. high school athletes. It has been estimated that as many as 80\% of these individuals will suffer recurrent ankle sprains and subsequent instability.\textsuperscript{3}

Chronic ankle instability (CAI) has been defined as “repetitive bouts of lateral ankle instability, resulting in numerous ankle sprains”\textsuperscript{4}. Lateral ankle instability results in lingering symptoms of an ankle sprain such as pain, swelling, and decreased function along with a subjectively described “giving way” sensation.\textsuperscript{5} Chronic ankle instability can be further separated into 2 categories: mechanical instability (MI) and functional instability (FI).\textsuperscript{4}

Anatomical changes at the ankle joint such as pathologic laxity and impaired or altered arthrokinematics result in the development of MI.\textsuperscript{4} These can contribute to altered position and mechanics of the ankle during movement. Functional instability is the result of alterations to the neuromuscular system: proprioception, muscle activation
patterns, strength, and postural control. Neuromuscular alterations are often attributed to damaged mechanoreceptors within the lateral ligaments of the ankle following lateral ankle sprain.

Inappropriate positioning of the foot and ankle may contribute to an increased risk of lateral ankle sprain. It has been previously demonstrated that participants with CAI have greater lateral plantar pressure distributions and a more lateral center of pressure during walking and running, suggesting that greater rearfoot inversion may place the lateral foot in greater contact with the floor: this is associated with the pathomechanical model related to a lateral ankle sprain. The excessive rearfoot inversion may result from alteration in foot positioning and pressure patterns not only distal to the ankle but also proximally up the kinetic chain.

Interestingly, alterations in proximal joint neuromuscular control and kinematics have been demonstrated in individuals with CAI. Alterations include decreased knee flexion of the stance leg during Star Excursion Balance Testing (SEBT) and during a jump landing task. CAI participants also demonstrated decreased knee flexor and extensor torque and increased facilitation of the quadriceps.

Additionally, there are alterations in hip neuromuscular control at the hip in those with CAI. The gluteal muscles have an important role in controlling foot placement during the stance phase of gait and supporting the pelvis during frontal-plane motion while performing a single-leg stance to prevent the contralateral side from dropping. Bullock-Saxton et al. assessed the sequence of activation of the gluteus maximus, hamstrings, and bilateral erector spinae on CAI and uninjured subjects performing active hip extension from prone lying. Researchers determined that a significant activation delay
occurred bilaterally in the gluteus maximus of CAI participants.\textsuperscript{20} Gribble et al. \textsuperscript{14} demonstrated a reduction in hip flexion angles in CAI participants during the SEBT compared with uninjured participants. Additionally, tensor fascia lata (TFL) muscle plays a role in maintaining stability of the knee and hip joint in the frontal plane.\textsuperscript{21} Zampagani et al. \textsuperscript{22} observed neuromuscular alterations in the TFL within the CAI population.

Altered neuromuscular control at the hip could be a contributing factor to altered foot positioning, ultimately resulting in hyper-supination at the foot and ankle joint complex. Although altered sagittal-plane kinematics in the proximal and distal limbs associated with CAI were evident \textsuperscript{22}, there is currently little evidence which has examined frontal-plane kinematics in the lower extremity as well as the entire relationship of lower extremity frontal-plane kinematics and foot position or pressure patterns in individuals with CAI. Understanding the relationship between hip and knee frontal plane positioning on the previously established pattern of increased lateral plantar pressure among CAI subjects may help illustrate the link between proximal and distal segments of the lower extremity and specifically what factors may be contributing to repetitive ankle instability.

1.2 Statement of Problem

Previous studies have suggested that alterations occur at proximal joints in response to CAI; however, the overall hip and knee kinematics associated with CAI have not been linked to changes in plantar pressure distribution. It is important for understanding injury mechanisms and functional deficits associated with CAI to identify altered lower extremity frontal-plane kinematic and plantar pressure distribution.

1.3 Statement of Purpose
The primary purpose of this study is to assess the effects of CAI on frontal-plane kinematics of the hip, knee, and ankle as well as plantar pressure distribution during a dynamic postural control task, the anterior reach of the SEBT. Our secondary purpose is to identify the relationship between lower extremity frontal-plane kinematics and plantar pressure distribution.

1.4 Hypotheses

1. It is hypothesized that increased lateral plantar pressure will be exhibited by CAI participants during SEBT.

2. Participants with CAI will demonstrate increased inversion at the ankle, increased varus angle at the knee, and increased hip abduction during SEBT compared to those without CAI.

3. Altered frontal-plane kinematics will be related to increased lateral plantar pressure in CAI participants at the point of maximum reach distance during SEBT.

4. Participants with CAI will exhibit a decreased normalized reaching distance in the anterior reaching direction.

1.5 Limitations

Individuals who have previously sustained ankle sprains and are currently experiencing CAI will be included in this study, thus making it retrospective. Therefore, confidently using the information from this study to predict injury mechanisms in the future will be limited.
The SEBT is dynamic in nature but is not necessarily a good representation of movements demanded during all athletic participation. However, this task has been demonstrated as reliable and is sensitive to detecting performance deficits in CAI participants.

1.6 Significance

Alterations may be occurring in the lower extremity following lateral ankle sprain and analysis of lower extremity kinematics during a dynamic postural control task may illuminate these adaptations. Identification of deficiencies can benefit individuals who are recovering from ankle sprains with a comprehensive rehabilitation protocol that incorporates both the injured limb and the proximal joints and could lead to a decreased possibility of re-injury.

1.7 Operational Definitions

**Chronic Ankle Instability (CAI):** a condition characterized by the residual symptoms that persist after an ankle sprain. Symptoms include pain, swelling, and decreased function. Individuals report a sensation of the ankle “giving way”.  

**Mechanical Instability (MI):** a subset of CAI that involves measurably increased joint laxity. 

**Functional Instability (FI):** another subset of CAI that has been proposed as a method of explaining the persistent symptoms of CAI among individuals who do not experience the increased joint motion that characterizes MI.
Neuromuscular Control: unconscious activation of dynamic restraints occurring in preparation for and in response to joint motion and loading for the purpose of maintaining and restoring functional joint stability.

Dynamic Postural Control: the ability to maintain a stable base of support while purposefully moving multiple body segments.  

Star Excursion Balance Test (SEBT): a functional balance test used to assess dynamic postural control by utilizing a single leg stance at the center of a star (taped to the floor) and a maximal reach along each of the “points”.

Dominant Limb: determined to be the stance limb when kicking a soccer ball.15
Chapter 2

Literature Review

2.1 Lateral Ankle Sprain

Ankle stability is controlled by static restraints, including the congruity of the articulating surfaces and ligamentous complex, and dynamic stability provided by musculotendinous units. The ankle consists of 3 separate articulations: the subtalar joint, talocrural joint, and the distal tibiofibular syndesmosis. The motions of the rearfoot are produced at these joints: plantar flexion-dorsiflexion, inversion-eversion, internal rotation-external rotation and the combination movements of pronation-supination. Supination is a rearfoot movement that incorporates the movements of inversion and internal rotation; pronation is a combination of eversion and external rotation. These movements are initiated by synergistic contraction of the foot and ankle muscle groups. Dynamic stability is afforded through concentric and eccentric muscle activation. The peroneal muscles control eccentrically against excessive supination of the rearfoot while the muscles of the anterior compartment control concentrically against injury-causing degrees of forced supination, specifically the plantar flexion component. Lateral ligaments provide static support to the ankle and are damaged by a lateral ankle sprain:
these ligaments are the anterior talofibular (ATF), calcaneofibular, posterior talofibular, cervical, and lateral talocalcaneal.4

The most common mechanism of lateral ankle injury is excessive rearfoot supination combined with external rotation of the lower limb at the point of initial rearfoot ground contact. 25 It has been suggested that increased plantar flexion, in conjunction with supination, increases the risk of injury.4,25 These movements increase the load placed on the lateral ligament complex and can result in injury if the load exceeds ligamentous strength. Due to its position, the ATF ligament is the most susceptible to injury and is the often the first ligament damaged. Injury of this ligament allows for increased rearfoot instability (commonly referred to as rotational instability), possibly leading to damage of other ligaments. Injury to the ATF accounts for nearly 80% of all lateral ankle sprains.4 It has been theorized that mechanoreceptors of the lateral ligaments provide the proprioceptive input of the lateral ankle. 6,7,26

Increased magnitude and position of ground reaction forces (GRF) at foot contact may cause an increased supination moment at the ankle, resulting in ankle sprain.4,25 An unequal strength ratio between the lateral –medial and anterior –posterior muscles may be the contributing factor to the increased magnitude of GRF at the foot.4,25 Other considerations that could affect magnitude of GRF are decreased proprioception and poor postural control.4,27 Location of the GRF positioning may be altered by a medial shift of the center of pressure in relation to the subtalar joint.4

A lateral ankle sprain can interfere with sensory feedback, negatively affecting somatosensory control in the lower extremity. This may decrease an individual’s ability
to appropriately adjust to changes in movement. An injury that decreases the function of sensory receptors interferes with the feed forward-feedback loop that governs muscle function about the injured joint. Altered feed forward control may result in delayed anticipatory function and a change in feedback may cause inappropriate muscular response. These alterations may perpetuate the initial injury and/or lead to further injury. Previous studies have reported that altered feed forward and feedback control at the ankle, knee, and hip were demonstrated among a CAI population.

2.2 Chronic Ankle Instability

A definition of CAI is the development of repetitive ankle sprains and persistent, residual symptoms following an initial ankle sprain injury. The progression of acute lateral ankle sprains to chronic instability may be the result of poor or lack of treatment of the initial injury: about 55% of the individuals suffering from acute ankle sprains do not seek medical treatment from allied health professionals. The 2 contributing factors to CAI are: functional and mechanical instability.

2.2.1 Functional Instability

Functional instability was first described by Freeman in 1965 who postulated the theory that impaired balance associated with repeated ankle sprains is due to damaged articular mechanoreceptors in the lateral ligaments resulting in decreased proprioception. Functional instability may influence balance maintenance strategies. At rest, the mechanoreceptors in the foot and calf muscles function as plantar pressure receptors and, along with muscle spindles, respond to positional changes. In the event of a perturbation the sensory input reflexively activates the supporting musculature and
muscle synergies produce a correction. Minimal instability causes the central nervous system (CNS) to employ an ankle strategy: ground contact is maintained while plantar flexion and dorsiflexion occur at the ankle and the rest of the body sways. If a greater instability occurs, or the ankle joint/musculature is unable to respond appropriately, a hip strategy is employed by the CNS. As with the ankle strategy, the feet remain in contact with the ground but a greater translation of mass occurs at the hip. These strategies are used to maintain static and dynamic balance but if a disruption occurs at any level balance may be impaired.

Another explanation for loss of balance (other than deficits in proprioception) is altered neuromuscular control. Although impaired balance has been attributed solely to damaged mechanoreceptors, it seems more likely that it works in combination with the alterations in neuromuscular control associated with functional instability. Delahunt et al. investigated how neuromuscular control in FI participants affects ankle joint kinematics during walking. FI participants demonstrated decreased floor clearance and a more inverted ankle joint.

2.2.2 Mechanical Instability

Anatomical changes resulting from ankle sprain cause mechanical instability. These mechanical changes include pathologic laxity and impaired/altered arthrokine matics. These changes may lead to joint instability and increase the risk of re-injury when the foot is placed into a supinated position during athletic play. Damage incurred on the ATF and CF ligaments may cause rotational instability and increased anterior displacement of the talus, compounding the existing ligamentous laxity. Any of
the 3 joints previously mentioned may succumb to altered arthrokinematics: normal roll, glide, and translation. It has been suggested that the fibula may move anteriorly and inferiorly as a result of an ankle sprain resulting in a more taut ATF and greater degree of movement for the talus.\(^4\)

Mechanical instability may result in altered movement patterns during gait and cause a reaction up the kinetic chain at the knee and hip. A recent study analyzed plantar pressure distribution in runners with CAI and found that CAI participants had more lateral ratio (0.97 ± 0.12) when compared to the control (healthy) group (1.01 ± 0.13) and individuals who had sprained an ankle but did not have CAI (1.11 ± 0.13).\(^8\) Plantar pressure was measured using a TekScan plantar pressure mat at 66 frames per second during a (controlled speed) running gait.\(^8\) The authors of the study concluded that CAI subjects had a more lateral foot positioning and loading pattern.\(^8\) These data indicate that individuals with CAI are predisposed to supinate at the foot, thus increasing the load on the lateral ligaments. How this altered foot positioning translates up the limb remains to be seen; but it is possible that the knee and hip may be compensating for the increased lateral pressure.

### 2.3 Chronic Ankle Instability and the Knee

Gribble et al.\(^14\) investigated the influence of CAI on performance of the STAR Excursion Balance test (SEBT), a dynamic postural control task commonly used for assessment and rehabilitation of CAI. Hip- and knee- flexion angles were found to be decreased among the CAI group compared to the non-injured control.\(^14\) Robinson and Gribble\(^32\) examined the relationship between kinematics of the lower extremity and
normalized reach distance during performance of the SEBT. Hip flexion and knee flexion were found to account for 78.1% of anterior reach distance variance after the removal of hip rotation and hip abduction (variance of 0.2%) from the regression model.\textsuperscript{32} Results show internal consistency across the remaining reach directions, indicating that hip flexion and knee flexion are the greatest contributors (overall) to maximum reach distance during the SEBT.\textsuperscript{32} This data supports the conclusion by Hertel et al.\textsuperscript{33} that redundancy exists within the 8 reaches of the SEBT and it may be streamlined to a decreased number of reaches.\textsuperscript{32}

Knee kinematics and dynamic stability were assessed at ground impact of 10 jump landings in a study by Gribble and Robinson.\textsuperscript{15} Ankle plantar flexion, knee flexion, and hip flexion angles were measured in 38 participants (CAI= 19; non-injured= 19) using an electromagnetic tracking device and ground reaction force data were used to assess time to stabilization, a screening tool for CAI.\textsuperscript{15} Significantly decreased knee flexion prior to impact was noted in the CAI group as well as increased time to stabilization.\textsuperscript{15} Gribble et al. suggested that an altered location of center of mass (COM) because of the change in proximal joint position could be responsible for the decreased stabilization indicated by increased time to stabilization.\textsuperscript{15} Bilateral differences in knee flexion angle between groups were observed, suggesting that a central programming change had occurred.\textsuperscript{15}

Delahunt et al.\textsuperscript{11} examined differences in lower limb kinematics, kinetics, and muscle activity between 24 FI participants and 24 healthy participants. Participants with FI were noted to have less hip external rotation, decreased peroneus longus EMG, increased inversion of the ankle, and decreased dorsiflexion before (200ms- 55ms)
ground contact occurred from a single leg drop.\textsuperscript{11} These changes could affect positioning
of the body and location of COM, possibly resulting in increased stress transmitted to the
articular surfaces of the ankle joint.\textsuperscript{11}

Caulfield and Garrett \textsuperscript{16} found significant differences in lower extremity
biomechanical characteristics between CAI and healthy subjects during a single-leg
jumping task. Individuals were included into the FI group if there was a history of at least
2 ankle sprains to the joint in question and a subjective report of repeated episodes of
“giving way” during activity.\textsuperscript{16} The task was a jump landing onto the injured limb (CAI
participants) or onto the matched limb (uninjured participants) from a box (40 cm) onto a
force plate.\textsuperscript{16} Ground contact was determined by the force plate and the joint angular
displacement changes were identified pre and post landing and used to identify timing of
initiation of movements.\textsuperscript{16} A significant difference in knee joint displacement was found
prior to landing at -20ms (CAI, 18.0 ±0.7; Healthy, 13.3 ±1.6) and also at 20ms and 40ms
post landing.\textsuperscript{16} The altered position exhibited by CAI participants could be a learned
adaptation to protect the injured/damaged ligaments of the ankle. However, Konradsen et
al. argued interplay between a central programming change and peripheral feedback is
more likely to result in the changes seen before and after ground impact during a jump-
landing task.\textsuperscript{34}

2.4 Chronic Ankle Instability and the Hip

The muscles of the hip are integral in maintaining postural control during a
dynamic task. Dynamic postural control refers to the ability to respond to and correct for
disruptions of equilibrium during a task.\textsuperscript{24} This response is mitigated by a combination of
feed forward and feedback responses. The feed forward response is preparatory: the individual is aware of a disruption approaching and prepares for it. The feedback response functions as a reflexive response to an unexpected disruption. These responses utilize afferent information from visual, somatosensory, and vestibular sources to determine and make the necessary corrections to retain posture during a functional activity.

Postural control is essential because it helps to maintain joint stability, thereby preventing possible injury. The gluteus maximus and medius play a role in postural control due to their functions. The tensor fascia lata (TFL) influences knee stability via the iliotibial (IT) band. The gluteus maximus (GMX) and gluteus medius (GMD) are instrumental in controlling the translation of mass at the hip, much the same way as the ankle dorsiflexors and plantar flexors control the movement at the ankle. Following injury, de-afferentation of peripheral nerves in the ankle may lead to increased activation of hip musculature resulting in improved hip muscle recruitment during activity. Reimer and Wikstrom hypothesized that CAI may lead to re-organization within the CNS, reversing the order of strategies to hip first then ankle.

Zampagani et al. concluded that altered proprioception at the subtalar joint following an ankle sprain might induce inhibition of the TFL via the IT band. This study investigated the validity of 2 new procedures in reproducing contralateral TFL weakness from a stimulus applied at the subtalar joint of the ankle. Participants with a history of ankle sprains (determined by detailed medical history questionnaire) and a grade II or III on talar tilt and anterior drawer test (as determined by specialized orthopedic surgeon) were referred to as members of the ankle imbalance group (AIG) rather than as
experiencing CAI. Twenty-nine soccer players (15 CAI; 14 uninjured) were tested using a shock absorber test: a mechanical shock stimulus was applied to the subtalar joint followed by an isometric strength assessment of the TFL. The authors determined that the stimulus to the subtalar joint did result in contralateral TFL muscle weakness. The AIG experienced shorter muscle force duration than uninjured controls but no significant change in intensity was noted. These data implicate a change occurred in muscle activation time.

The coordination of the entire body may be required to achieve proper landing technique, and hip musculature may have a crucial role in controlling the pelvic motion in the frontal plane during perturbations. Many studies have analyzed the relationship between ankle joint pathology and hip dysfunction; however, these studies assessed different variables such as torque, muscle activation, functional testing, and strength. Gribble and Robinson examined torque at the ankle, knee, and hip joints iso-kinetically among 15 individuals with CAI and 15 without the pathology. Significant deficits in average peak torque (APT) were observed in the CAI population during knee flexion (p=0.03) and extension (p=0.03). Ankle plantar flexion (p=0.02) was decreased as compared to the subjects non-injured limb. The researchers concluded that changes about the knee suggested that neuromuscular adaptations may have occurred at the proximal joint due to changes at the distal joint: no APT deficits were observed at the hip.

Individuals coping with CAI may continue to perform in athletic activities and ADL’s at a high level. Demeritt et al. examined the relationship between CAI and performance during functional tests: co-contraction (resisted shuffle), shuttle run, and
agility hop. Twenty men with CAI were matched against 20 men with no history of injury and performed the three tests.\textsuperscript{40} No significant differences were found between the groups causing the authors to conclude that CAI does not negatively influence performance in spite of subjective complaints.\textsuperscript{40}

Bullock-Saxton et al.\textsuperscript{20} observed a delay in activation of the gluteus maximus during open-chain kinetic hip extension in CAI subjects. This study compared the onset of gluteus maximus, hamstring, and erector spinae muscle activations using surface electromyography during prone hip extension between 20 CAI subjects and 11 healthy.\textsuperscript{20} CAI participants demonstrated a delayed onset of activation in the gluteus maximus of both the injured and non-injured limbs compared to healthy subjects.

### 2.5 Star Excursion Balance Test

Assessment of dynamic postural control can be quantified through the use of the Star Excursion Balance Test (SEBT). This clinical tool is utilized by creating a star grid using tape on a solid surface: points of the star extend into 8 directions in 45° increments from the center.\textsuperscript{41,42} From the center of the star 3 of the points extend anteriorly, 2 extend laterally, and 3 extend posteriorly.\textsuperscript{41,42} The SEBT is performed with the subject in a single leg stance (testing limb) at the center of the star grid while attempting a maximum reach in the 8 directions.\textsuperscript{41,42} The maximum reach is marked by the examiner, measured, and normalized by dividing reach distance by limb length and multiplying by 100 (delivered in percentage of limb length).\textsuperscript{41}

Hertel et al.\textsuperscript{33} attempted a simplification of the SEBT by determining which of the 8 reaches was most highly correlated to chronic ankle instability and using this
information to decrease the number of reaches necessary to establish the presence of CAI. Forty-eight subjects performed 3 trials of the 8 reaches and a Pearson Product Moment Correlation determined that CAI subjects exhibited significantly decreased anteromedial, medial, and posteromedial reaches while balancing on the injured/matched limbs. The authors concluded that the posteromedial reach was highly representative of CAI performance of the SEBT (most highly correlated) while the anteromedial and medial reaches are useful clinically. Earl and Hertel also examined the contributions of the vastus medialis, vastus lateralis, medial hamstring, biceps femoris, anterior tibialis, and gastrocnemius during the SEBT and determined that all of these muscles were engaged during testing except the gastrocnemius. Use of all 8 directions during the SEBT allows for different lower-extremity muscle-activation patterns and may benefit neuromuscular control.

The SEBT was shown to be an effective tool in measuring reach differences between and within participants with CAI in a study by Olmsted et al. Reach tests were performed on both the injured and un-injured limbs for 20 CAI participants and matched against reach distances for matched un-injured control subjects. Significantly decreased reach distance as compared to control was demonstrated by the CAI group while standing on the injured limb. Further, reach distance while standing on the injured limb was significantly less than distance obtained while standing on the un-injured limb within the CAI group.

Reliability of the SEBT was investigated by Kinzey et al. Twenty healthy subjects performed 5 reaching trials in 4 of the SEBT directions during 2 testing sessions: ICC ranged from 0.67 to 0.87. The researchers suggest that 6 practice sessions could
increase the ICC above 0.86 and recommend that participants engage in a “learning period” before testing trials are initiated.  

Originally, it was proposed that 6 practice trials were necessary to remove a learning effect on SEBT results: Hertel et al.\textsuperscript{45} determined that after 6 trials participants exhibited significantly greater reach distances and the practice trials were included to minimize the learning effect. Changes in administration of the SEBT prompted Robinson et al.\textsuperscript{46} to attempt a reduction of the number of practice trials necessary prior to testing. The rationale behind this reduction was to maximize the efficiency of the SEBT as it relates to a clinician’s time investment.\textsuperscript{46} Twenty healthy participants participated in 6 practice trials and 3 testing trials in all 8 directions of the SEBT.\textsuperscript{46} Maximum reach distance was achieved within the first 4 reaches leading the researchers to conclude that a reduction in practice trials from 6 to 4 reaches was acceptable.\textsuperscript{46}

2.6 Foot Posture Index-6

Individual foot type has been associated with increased risk of lower extremity injury during athletic participation. A number of foot type classification tools exist although none has set a gold standard for prediction of injury based on foot type. A number of factors have been proposed to predict an increased risk including: arch height, amount of pronation/supination, and degree of rearfoot valgus/varus.\textsuperscript{47} Extreme scores obtained through the use of the foot posture index-6 (FPI-6) have been associated with an increased injury risk.\textsuperscript{48,49}

2.6.1 Description of the Foot Posture Index-6 (FPI-6)
The FPI-6 was developed by identifying clinical measures of foot posture. Indicators were included based on cost, ease of use, and production of quantifiable data.\textsuperscript{47} The FPI-6 is a tool used to classify a foot as neutral, supinated, or pronated based on several criteria using a numerical system that ranges -2 to +2.\textsuperscript{47} Negative values indicate a more supinated foot while positive values are indicative of a more pronated foot.\textsuperscript{47} Position of the forefoot and rearfoot are taken into account using six criteria. Criteria used to determine rearfoot scores are: amount of talar head palpation, degree of curve above and below the malleoli, and calcaneal inversion/eversion.\textsuperscript{47} Forefoot scores are determined by analyzing talo-navicular congruence, medial arch height, and forefoot abduction/ adduction.\textsuperscript{47} Palpation of the talar dome and still frame photos from the posterior, posteromedial, and medial aspects of the ankle during double limb stance are used to apply the criteria. A relaxed double limb stance is achieved by marching in place for several steps.

**2.6.2 Reliability of the FPI-6**

A study by Cornwall et al.\textsuperscript{50} assessed the reliability of the FPI in predicting foot type among 46 individuals: both feet were analyzed separately so a total of 92 feet were assessed. Three researchers of varying levels of experience performed the assessment: a first year physical therapy student, a physical therapist with 9 years of general experience, and a physical therapist with more than 30 years of foot and ankle clinical experience\textsuperscript{51}. The primary goal of the study was to determine if 3 different raters could use the FPI-6 to agree on the shape of a foot; secondarily, the influence of previous experience with the index was assessed\textsuperscript{51}. Absolute error and ICCs were calculated separately for the first and last 20 feet evaluated to determine the impact of familiarity
with the FP I-6. Intra-rater reliability was high but inter-rater reliability was only moderate; therefore, the authors concluded that the test should be used with extreme caution. A learning curve is associated with increased reliability so it is suggested in the test protocol (and supported by the results of this study) to perform 30 practice trials before use in a research study.
Chapter 3

Materials and Methods

3.1 Experimental Design

A case control study design was used to determine if lower extremity frontal-plane kinematic and foot pressure pattern differences exist between participants with and without CAI during an anterior reach of the SEBT.

3.2 Participants

Eighteen participants between the ages of 18 and 35 years were recruited from the University of Toledo community. All participants were recreationally active, defined as participating in at least 30 minutes of exercise a minimum of 3 times a week. All participants were free of any diagnosed balance or vestibular disorders or concussion within the past 6 months. All participants volunteered and signed an informed consent form approved by University Institutional Review Board.

Participants were allocated to 2 groups: healthy (control) or CAI. The control group included participants who had not sustained any musculoskeletal and/or neurovascular injury to the lower extremity. We excluded participants with history of low
back pain in the previous six months. An independent t test was used to compare
demographic data in both groups and no statistically significant difference was found.

The CAI group included participants with a history of at least one acute lateral
ankle sprain which resulted in pain, swelling, and loss of function with multiple episodes
of the ankle “giving way” in the past 6 months (but none in the 3 months prior to testing),
a history of at least two repeated episodes of “giving way” in three months, no history of
any musculoskeletal and neurological injury or disorder in the lower extremity other than
the ankle in the previous two years, no history of low back pain in the previous six
months, and no previous fractures or surgery in the lower extremity in the previous two
years.

Group designation will be confirmed by administration of the Functional Ankle
Disability Index (FADI) and Functional Ankle Disability Index Sports Scale (FADI
Sport). Participants scoring less than 80% on the FADI and 90% on the FADI Sport will
be included into the CAI group. 52 Nine healthy participants and nine CAI participants
were included in data testing and analysis.

3.3 Instrumentation

Frontal-plane kinematic data were collected with an electromagnetic tracking
system (Flock of Birds; Ascension Technology Corp, Burlington, VT) using
MotionMonitor software (version 7.0; Innsport Inc, Chicago, IL). The TekScan MatScan
plantar pressure system including the sensor mat, transmitter, and software (Tekscan, Inc,
South Boston, MA) was used to measure plantar pressure distribution during the task.
The 5 mm thick mat (432 x 368 mm) is comprised of 2288 resistive sensors will sample
data at a frequency of 40 Hz which was transmitted to a Dell Optiplex GX 530 computer
(Dell Inc, Round Rock, TX) via a USB cable. The Tekscan software, F-Scan Research 6.34, was used to produce a visual output of the pressure applied to the sensors by each participant’s foot. The visual plantar pressure “movie” was accompanied by video of the participant performing the task recorded using a Sony camcorder (Sony Electronics Inc.). Still frame photos were taken using a Kodak (Kodak) camera.

3.4 Procedures

Upon arrival to the testing site, the participant was asked to read and sign a consent form. Participant height, weight, and limb dominance was assessed. Leg length was measured on the stance (injured/matched) leg for normalization purposes. Testing procedure was explained to the participant. The participant was instructed to perform 5 marching steps then stand in a relaxed posture while photos were taken of the posterior, posteromedial, and medial foot. Sensors were attached to the dorsum of the foot, mid-calf, mid-thigh, and sacrum of the participant. Digitization was performed using the Flock of Birds. The TekScan Mat was calibrated by balancing on the mat on the stance leg. The participant was allowed four practice trials of the anterior reach of the SEBT to minimize the learning effect. During performance of the SEBT, the subject stood at the base of a line of tape and reached as far as possible down the line to lightly touch the line with the most distal part of the reaching foot. The participant minimized the shift of any body weight from the stance leg, kept hands on the hips, and the sole of the stance-leg foot on the flat.14 The participant performed 5 anterior reaching trials. The trial was discarded and repeated if the researcher determined that the subject used the reaching leg for a substantial amount of support at any time, the support limb was moved from the center of the line, or the participant was unable to maintain balance on the support limb.14
During SEBT, electromagnetic sensors were placed over the sacrum, lateral mid-thigh, lateral mid-shank, and the dorsal surface of foot of the testing leg using Velcro straps, and were secured to the skin using a double-side tape and a non-adhesive elastic tape. A fifth sensor was attached to a stylus and used for the digitizing process of the lower extremity segments. Following placement of the sensors, the participant stood in a neutral position during the digitizing process. The following bony landmarks were palpated and digitized with the fifth sensor attached to a plastic stylus: the distal portions of the medial and lateral condyles of the femur, the distal portions of the medial and lateral malleoli, distal tip of the second phalanx in the foot and the right and left ASIS and PSIS.

3.5 Data Collection and Processing

Kinematic data was sampled at 100 Hz. Frontal-plane kinematics at the hip, knee, and ankle were calculated with the Grood/Suntay angle orientation function in the MotionMonitor software.\textsuperscript{13,15} We used the segment definition, calculations of the location of each joint center, and sensor/coordinate system set-up previously described. Raw data was filtered with a low-pass third-order Butterworth filter with a cutoff frequency of 20 Hz.\textsuperscript{13} All kinematic variables were collected at the point of maximum reach distance during the SEBT trials. An external event marker synched with the MotionMonitor software was depressed by the participant when the subject touches down at maximum reach in order to designate this point in the software to determine the time point for kinematic assessment.

Foot pressures were collected at a rate of 40 Hz and processed within the F-scan Research 6.34 software. The peak pressure at the point of maximum reach distance were
calculated by the software and presented on an output display of the plantar surface of the participant’s foot. A grid was created over the plantar surface of the output display with a longitudinal line through the 2nd metatarsal, a horizontal line across the metatarsal heads, and a horizontal line across the heel. The template will be visually checked for each trial and adjusted, if necessary, to fit appropriately on the foot. The foot was bisected into medial and lateral rearfoot with vertical line drawn by the F-scan Research software’s template, and divided into the rearfoot, midfoot, and forefoot with the horizontal line. The pressures at the point of maximum reach distance were quantified for following six areas of the foot: (1) lateral rearfoot, (2) lateral midfoot, (3) lateral forefoot, (4) medial rearfoot, (5) medial midfoot, and (6) medial forefoot. Medial-to-lateral (M:L) pressure ratios were calculated for rearfoot, midfoot, and forefoot. The M:L pressure ratios of 1.0 indicate equal pressure distribution of medial and lateral foots, whereas the ratios less than 1.0 indicate increased lateral pressure distribution compared with medial pressure. The ratios greater than 1.0 indicate high pressure on the lateral side of the foot relative to the medial side. Plantar pressure at the point of maximum reach was determined using video (within the F-Scan software) of the participant performing the SEBT.

3.6 Statistical Analysis

The dependent variables included hip, knee, and ankle frontal-plane kinematic position, the M:L pressure ratios of the rearfoot, midfoot, and forefoot at the point of maximum reach, the normalized maximum reach distances, and the FPI-6 results. The means and standard deviations of the dependent variables at the point of maximum anterior reach distance for the 5 trials were used for comparison. A two-way analysis of
variance was performed to determine if statistically significant interactions were present between dependent variables. An alpha level of .05 was set a priori. A pairwise comparison with Bonferroni adjustment was performed if significant interaction was revealed to examine differences between each dependent variable within sides and between groups with the Statistical Package for the Social Sciences for Windows (version17.0; SPSS Inc, Chicago, IL). An alpha level of .05 was set a priori.

Cohen’s $d$ effect sizes and associated 95% confidence interval (CI) was calculated using the pooled standard deviations to determine the magnitude of differences in dependent variables between groups. The strength of effect sizes was interpreted as weak ($d \leq 0.4$), moderate ($0.40 < d \leq 0.7$), and strong ($d > 0.7$) 53.

Bivariate Pearson Product Moment Correlation was used to determine the relationship between lower extremity frontal-kinematics and M:L pressure ratios. A correlation coefficient is considered weak ($0 \leq r < 0.4$), moderate ($0.4 \leq r < 0.7$), or strong ($0.7 < r \leq 1.0$).
Chapter 4

Results

4.1 Demographic Information

There were no statistically significant group-differences in age, height, or mass (Table 4-1). Scores on the FADI and FADI Sport instruments were significantly lower in the CAI group than the control group, verifying the presence of the targeted pathology (Table 4-1).

<table>
<thead>
<tr>
<th></th>
<th>CAI</th>
<th>Control</th>
<th>T</th>
<th>df</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>23 ± 2</td>
<td>22 ± 2</td>
<td>-1.031</td>
<td>16</td>
<td>0.138</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>169.16 ± 14.70</td>
<td>173.29 ± 10.06</td>
<td>0.691</td>
<td>16</td>
<td>0.499</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>70.87 ± 17.10</td>
<td>73.28 ± 12.32</td>
<td>0.342</td>
<td>16</td>
<td>0.737</td>
</tr>
<tr>
<td>FADI</td>
<td>100</td>
<td>73.09 ± 23.89</td>
<td>-3.379</td>
<td>16</td>
<td>0.004*</td>
</tr>
<tr>
<td>FADI- Sport</td>
<td>100</td>
<td>56.93 ± 27.75</td>
<td>-4.655</td>
<td>16</td>
<td>0.000*</td>
</tr>
</tbody>
</table>

* Significant difference in FADI and FADI Sport between groups (p<0.05).
For foot posture, as assessed by the FPI-6, a total of five participants had a pronated foot (Table 4-2). Two CAI participants demonstrated the pronated foot on the involved side while one CAI participant had the pronated foot on the uninvolved side. In the control group, one participant exhibited pronated foot type on the matched-involved side, and one participant did on the matched-uninvolved side. No participants had bilateral pronation or demonstrated supination.

The mean and standard deviation of FPI-6 raw score are provided in Table 4-3. There was no significant group by side interaction ($F_{1,16} = 0.171, p = 0.685$), side main effect ($F_{1,16} = 1.154, p = 0.299$), or group main effect ($F_{1,16} = 0.474, p = 0.501$) for the FPI-6 score.

### Table 4-2. CAI and Control Participants with a Pronated Foot Posture.

<table>
<thead>
<tr>
<th></th>
<th>Involved</th>
<th>Uninvolved</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAI</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Control</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

### Table 4-3. FPI-6 Raw Scores By Limb for the CAI Group and Control Group (Mean ± SD).

<table>
<thead>
<tr>
<th></th>
<th>Involved/ Matched Limb</th>
<th>Non-involved</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAI</td>
<td>3.44 ± 2.01</td>
<td>3.89 ± 2.20</td>
</tr>
<tr>
<td>Control</td>
<td>2.66 ± 2.00</td>
<td>3.67 ± 2.18</td>
</tr>
</tbody>
</table>
No statistically significant correlations between FPI-6 raw score and foot pressure variables were found in either the involved or uninvolved limb for all 18 participants (Table 4-4).

Table 4-4. Pearson Correlations Between Foot Pressure Variables and FPI-6 Raw Score on the Involved Side and on the Non-involved Side for all 18 Participants.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Involved Correlation Coefficient</th>
<th>Involved p</th>
<th>Non-involved Correlation Coefficient</th>
<th>Non-involved p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rearfoot</td>
<td>-0.360</td>
<td>0.142</td>
<td>-0.100</td>
<td>0.694</td>
</tr>
<tr>
<td>Midfoot</td>
<td>-0.177</td>
<td>0.481</td>
<td>0.013</td>
<td>0.959</td>
</tr>
<tr>
<td>Forefoot</td>
<td>-0.311</td>
<td>0.209</td>
<td>0.307</td>
<td>0.215</td>
</tr>
</tbody>
</table>

4.2 Kinematics

4.2.1 Ankle

A statistically significant group by side interaction was observed in frontal-plane kinematics at the ankle (F1,16 = 9.42; p = 0.007) (Table 4-5, Figure 4-1). A post hoc test revealed that the CAI group had a greater inversion angle in the involved ankle at the point of maximum anterior reach distance of the SEBT compared to the matched limb of the healthy control (F1,16 = 36.01; p < 0.001) and compared to the uninvolved limb of the CAI group (F1,16 = 18.89; p = 0.001). A large effect size supported the difference between the involved limb of the CAI group and the matched limb of the Control group (d = 2.93; 95% CIs: 1.42, 3.97). There were statistically significant side (F1,16 = 9.47, p = 0.007) and group (F1,16 = 6.45, p = 0.022) main effects for ankle kinematics. The effect sizes for side and group main effects were large, with 95% CIs that did not crossed zero (Figure 4-1).

4.2.2 Knee
A statistically significant group by side interaction was observed for frontal-plane kinematics at the knee ($F_{1,16} = 9.19; p = 0.008$) (Table 4-5 and Figure 4-1). A post hoc test revealed that the CAI group demonstrated significantly less valgus on the involved limb compared to the matched-involved limb of the control group ($F_{1,16} = 5.74, p = 0.029$) and the uninvolved limb of the CAI group ($F_{1,16} = 17.50, p = 0.001$). A large effect size supported the difference between the involved limb of the CAI group and the matched limb of the Control group ($d = -1.13; 95\% \text{ CIs: } -2.07, -0.09$). There was no significant group main effect for frontal-plane kinematics at the knee ($F_{1,16} = 0.72, p = 0.409$) with a weak effect size of -0.37 (95% CIs = -1.29, 0.58). A significant side main effect was observed for knee kinematics ($F_{1,16} = 8.32, p = 0.011$) with a moderate effect size of -0.53 and 95% CIs that crossed zero (95% CIs = -1.19, 0.14) (Table 4-5 and Figure 4-1).

4.2.3 Hip

There was no statistically significant group by side interaction in frontal-plane hip kinematics ($F_{1,16} = 0.90, p = 0.357$) (Table 4-5). There were no statistically significant side main effects ($F_{1,16} = 3.26, p = 0.090$) or group main effects ($F_{1,16} = 0.001, p = 0.979$) at the hip either.
Table 4-5. Hip, knee, and ankle kinematic positions at the point of maximum anterior reach of the SEBT for the CAI and control groups.

<table>
<thead>
<tr>
<th>Kinematic position</th>
<th>Group main effect</th>
<th>Side main effect</th>
<th>Group by side interaction</th>
<th>CAI Injured side</th>
<th>Non-injured side</th>
<th>“Injured” side</th>
<th>Control Injured side</th>
<th>Non-injured side</th>
<th>“Non-injured” side</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ankle</td>
<td>$F_{1,16}$ = 6.449</td>
<td>$F_{1,16}$ = 9.462</td>
<td>$F_{1,16}$ = 9.422</td>
<td>0.13 ± 4.48</td>
<td>-11.19 ± 11.39</td>
<td>-12.21 ± 4.25</td>
<td>-12.22 ± 4.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$P = 0.022^*$</td>
<td>$P = 0.007^*$</td>
<td>$P = 0.007^*$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Power = 0.665</td>
<td>Power = 0.823</td>
<td>Power = 0.821</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>95% CI (0.02, 1.98)</td>
<td>95% CI (0.02, 1.36)</td>
<td>95% CI (1.42, 3.97)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee</td>
<td>$F_{1,16}$ = 0.720</td>
<td>$F_{1,16}$ = 8.317</td>
<td>$F_{1,16}$ = 9.192</td>
<td>2.26 ± 6.46</td>
<td>11.77 ± 11.00</td>
<td>10.21 ± 7.56</td>
<td>9.97 ± 7.93</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$P = 0.409$</td>
<td>$P = 0.011^*$</td>
<td>$P = 0.008^*$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Power = 0.126</td>
<td>Power = 0.773</td>
<td>Power = 0.812</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>95% CI (-1.29, 0.58)</td>
<td>95% CI (-1.19, 0.14)</td>
<td>95% CI (-2.07, -0.09)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hip</td>
<td>$F_{1,16}$ = 0.001</td>
<td>$F_{1,16}$ = 3.264</td>
<td>$F_{1,16}$ = 0.901</td>
<td>-9.45 ± 7.03</td>
<td>-7.71 ± 5.38</td>
<td>-11.32 ± 5.48</td>
<td>-5.73 ± 5.08</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$P = 0.979$</td>
<td>$P = 0.090$</td>
<td>$P = 0.357$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Power = 0.050</td>
<td>Power = 0.397</td>
<td>Power = 0.145</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>95% CI (-0.93, 0.92)</td>
<td>95% CI (-1.30, 0.04)</td>
<td>95% CI (-0.65, 1.21)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Statistical significance (p < 0.05)
Ankle: (+) values = Inversion, (-) values = Eversion; Knee: (+) values = Valgus, (-) values = Varus; Hip: (+) values = Abduction, (-) values = Adduction

Figure 4-1. Effect Sizes and 95% Confidence Intervals for Frontal-Plane Kinematics.
4.3 SEBT

A significant group main effect was observed for %MAXD (F_{1,16} = 5.247, p = 0.036), with the CAI group demonstrating less %MAXD (58.83 ± 7.44%) compared to the control group (66.28 ± 6.45%), supported by a large effect size and 95% CIs that did not cross zero (d = -1.07; 95% CIs: -2.0, -0.04). There was not a statistically significant group by side interaction (F_{1,16} = 0.616, p = 0.444) or side main effect (F_{1,16} = 2.420, p = 0.139) for %MAXD. The effect sizes for side main effect and group by side interaction are found in Table 4-6.

4.4 Plantar Pressure

A statistically significant side main effect was found for the rearfoot M:L ratio (F_{1,16} = 11.54; p = 0.004). The effect size was large for the side-difference in rearfoot M:L ratio, with 95% CIs that did not cross zero. There were no significant interactions or main effects for the other plantar pressure measurements (Table 4-6). The effect size for M:L ratio in the midfoot and forefoot ranged from -0.10 to 0.71, with associated 95% CIs that crossed zero. However, the midfoot M:L ratio was approaching statistical significance (p = 0.083) with a large effect size (d = 0.71), but the associated 95% CIs crossed zero (-0.27, 1.63).
Table 4-6. %MAXD and plantar pressure measurements at the point of maximum reach for the CAI and control groups.

<table>
<thead>
<tr>
<th></th>
<th>Group Main Effect</th>
<th>Side Main Effect</th>
<th>Side by Group Interactions</th>
<th>CAI Injured Side</th>
<th>CAI Non-Injured Side</th>
<th>Control “Injured” Side</th>
<th>Control “Non-Injured” Side</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rearfoot Plantar Pressure</td>
<td>$F_{1,16} = 0.496$</td>
<td>$p = 0.491$</td>
<td>$F_{1,16} = 11.544$</td>
<td>$p = 0.004^*$</td>
<td>$F_{1,16} = 0.592$</td>
<td>$p = 0.453$</td>
<td>$F_{1,16} = 11.544$</td>
</tr>
<tr>
<td></td>
<td>$\text{Power}= 0.102$</td>
<td>$\text{ES}= 0.28$</td>
<td>$\text{Power}= 0.890$</td>
<td>$\text{ES}= 0.95$</td>
<td>$\text{Power}= 0.112$</td>
<td>$\text{ES}= 0.40$</td>
<td>$\text{Power}= 0.890$</td>
</tr>
<tr>
<td>Midfoot Plantar Pressure</td>
<td>$F_{1,16} = 0.800$</td>
<td>$p = 0.384$</td>
<td>$F_{1,16} = 2.357$</td>
<td>$p = 0.144$</td>
<td>$F_{1,16} = 3.411$</td>
<td>$p = 0.083$</td>
<td>$F_{1,16} = 2.357$</td>
</tr>
<tr>
<td></td>
<td>$\text{Power}= 0.134$</td>
<td>$\text{ES}= 0.36$</td>
<td>$\text{Power}= 0.303$</td>
<td>$\text{ES}= 0.39$</td>
<td>$\text{Power}= 0.412$</td>
<td>$\text{ES}= 0.71$</td>
<td>$\text{95%CI} (-0.28, 1.04)$</td>
</tr>
<tr>
<td>Forefoot Plantar Pressure</td>
<td>$F_{1,16} = 0.143$</td>
<td>$p = 0.710$</td>
<td>$F_{1,16} = 0.124$</td>
<td>$p = 0.729$</td>
<td>$F_{1,16} = 0.470$</td>
<td>$p = 0.503$</td>
<td>$F_{1,16} = 0.124$</td>
</tr>
<tr>
<td></td>
<td>$\text{Power}= 0.065$</td>
<td>$\text{ES}= 0.15$</td>
<td>$\text{Power}= 0.063$</td>
<td>$\text{ES}= -0.10$</td>
<td>$\text{Power}= 0.099$</td>
<td>$\text{ES}= -0.05$</td>
<td>$\text{95%CI} (-0.75, 0.56)$</td>
</tr>
<tr>
<td>%MAXD</td>
<td>$F_{1,16} = 5.247$</td>
<td>$p = 0.036^*$</td>
<td>$F_{1,16} = 2.420$</td>
<td>$p = 0.139$</td>
<td>$F_{1,16} = 0.616$</td>
<td>$p = 0.444$</td>
<td>$F_{1,16} = 5.247$</td>
</tr>
<tr>
<td></td>
<td>$\text{Power}= 0.576$</td>
<td>$\text{ES}= -1.07$</td>
<td>$\text{Power}= 0.310$</td>
<td>$\text{ES}= 0.12$</td>
<td>$\text{Power}= 0.114$</td>
<td>$\text{ES}= -1.29$</td>
<td>$\text{95%CI} (-2.24, -0.22)$</td>
</tr>
</tbody>
</table>

*Statistical significance (p < 0.05)

4.5 Pairwise Correlations

Pearson product moment correlations between the outcome variables for the CAI group on the involved side are found in Table 4-7. There were significant and strong correlations between frontal-plane hip and knee kinematics ($r = 0.822$, $R^2 = 0.676$, $p = 0.007$) and between frontal-plane hip and forefoot plantar pressure ($r = -0.787$, $R^2 = 0.619$, $p = 0.012$) in the CAI group.
Pearson product moment correlations among variables for CAI group on the uninvolved side are found in Table 4-8. There were significant correlations between frontal-plane ankle and knee kinematics ($r = -0.714$, $p = 0.031$) and between rearfoot and forefoot plantar pressure ($r = 0.676$, $p = 0.046$).

### Table 4-8. Correlations between dependent variables obtained from uninvolved side of the CAI group.

<table>
<thead>
<tr>
<th></th>
<th>Ankle Pearson Correlation (r)</th>
<th>Knee</th>
<th>Hip Pearson Correlation (r)</th>
<th>Knee</th>
<th>Rearfoot Pearson Correlation (r)</th>
<th>Midfoot Pearson Correlation (r)</th>
<th>Forefoot Pearson Correlation (r)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee</td>
<td>$-0.714$</td>
<td></td>
<td>$0.031^*$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hip</td>
<td>$0.078$</td>
<td>$0.250$</td>
<td>$0.516^*$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rearfoot</td>
<td>$-0.058$</td>
<td>$0.318$</td>
<td>$0.383$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Midfoot</td>
<td>$0.082$</td>
<td>$-0.090$</td>
<td>$0.819$</td>
<td>$0.531$</td>
<td>$0.142^*$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forefoot</td>
<td>$0.124$</td>
<td>$0.302$</td>
<td>$0.430$</td>
<td>$0.406^*$</td>
<td>$0.046^*$</td>
<td>$0.166$</td>
<td>$0.670$</td>
</tr>
<tr>
<td>Anterior Reach</td>
<td>$-0.608$</td>
<td>$0.480$</td>
<td>$-0.146$</td>
<td>$0.406$</td>
<td>$0.034^*$</td>
<td>$0.023$</td>
<td></td>
</tr>
</tbody>
</table>

*Statistical significance ($p < 0.05$)

Pearson product moment correlations among variables for the control group on the involved side are found in Table 4-9. There was a significant negative correlation between frontal-plane hip kinematics and rearfoot plantar pressure ($r = -0.763$, $p = 0.017$).
Pearson product moment correlations among variables for the control group on the uninvolved side are found in Table 4-10. There were significant correlations between frontal-plane hip and knee kinematics (r = -0.664, p = 0.051).

Table 4-10. Correlations between dependent variables obtained from uninvolved side of the control group.

<table>
<thead>
<tr>
<th>Knee</th>
<th>Ankle</th>
<th>Knee</th>
<th>Hip</th>
<th>Rearfoot</th>
<th>Midfoot</th>
<th>Forefoot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ankle</td>
<td>-0.316</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee</td>
<td>0.408</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hip</td>
<td>-0.172</td>
<td>0.664</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rearfoot</td>
<td>0.658</td>
<td>0.051*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Midfoot</td>
<td>0.200</td>
<td>0.918</td>
<td>0.657</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forefoot</td>
<td>0.098</td>
<td>0.577</td>
<td>0.393</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anterior</td>
<td>0.367</td>
<td></td>
<td></td>
<td>0.657</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reach</td>
<td>0.331</td>
<td></td>
<td></td>
<td></td>
<td>0.657</td>
<td></td>
</tr>
<tr>
<td>*Statistical significance (p &lt;0.05)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Discussion

5.1 Discussion

This study was conducted to assess the effects of CAI on frontal-plane kinematics of the hip, knee, and ankle as well as on plantar pressure distribution during a dynamic postural control task, the anterior reach of the SEBT. Our secondary purpose was to identify the relationship between lower extremity frontal-plane kinematics and plantar pressure distribution. Identification of a link between frontal-plane kinematics and plantar pressure distribution may provide a deeper understanding of the pathomechanical model for CAI. The most important finding of this study was that participants with CAI exhibited altered frontal-plane kinematics at the involved ankle and knee along with a shorter anterior reach distance of the SEBT. To our knowledge, this study is the first to examine the effect of CAI on frontal-plane kinematics in the lower extremity during the SEBT.

The SEBT has been developed to assess dynamic postural control by requiring individuals to maintain stability while simultaneously reaching maximally without compromising the base of support.\textsuperscript{54-57} It has been consistently demonstrated in the
literature that decreased dynamic postural control, as measured with the SEBT, is associated with CAI.\textsuperscript{54,58-60} Olmsted et al.\textsuperscript{60} observed diminished dynamic postural control measured with the SEBT in individuals with CAI. Gribble et al.\textsuperscript{59} examined lower extremity kinematics in an attempt to identify factors that underlie dynamic postural control deficits during SEBT performance in individuals with CAI. They showed that those with CAI had decreased reach distance of the SEBT while displaying decreased knee and hip flexion angles. We found that participants with CAI demonstrated a statistically significant decreased reach distance (p = 0.036) with a large effect size of -1.07 (95% CIs = -2.0, -0.04) compared to the control group. Therefore, the finding of our study provided consistent evidence that the anterior reach direction of the SEBT can identify altered dynamic postural control in individuals with CAI. In addition, we found an increased inversion angle at the involved ankle of the CAI group (d = 2.93; 95% CIs 1.42, 3.97) and a decreased valgus angle at the involved knee of the CAI group compared to the control (d = -1.13; 95% CIs -2.07, -0.09) during the SEBT in the anterior reach direction. Together, these findings indicate that sensorimotor and neuromuscular alterations of the lower extremity joints manifested as altered frontal-plane kinematics at the ankle and knee in conjunction with decreased dynamic stability during the SEBT in the anterior reaching direction.

Alterations in sensorimotor function and neuromuscular control of the lower extremity joints have been consistently observed in individuals with CAI.\textsuperscript{58,61-63} Delahunt et al.\textsuperscript{63} observed that participants with CAI demonstrated greater ankle inversion and a significant decrease in peroneus longus EMG during a jump-landing task. Drewes et al.\textsuperscript{64} observed that individuals with CAI exhibited more rearfoot inversion coupled with more
external rotation of the shank during walking and jogging. The peroneal muscles have been considered important joint stabilizers that provide dynamic stability through concentric contraction during weight-bearing activity. \(^65\) Palmieri-Smith et al. \(^66\) identified impaired dynamic peroneal activity in functionally unstable ankles, which may contribute to CAI. Moreover, Gribble and Robinson\(^62\) observed less knee flexion before and at ground contact with diminished dynamic stability during a jump-landing in individuals with CAI. In our current study, we confirmed the findings from these previous studies that participants with CAI have increased ankle inversion, altered knee kinematics, and diminished dynamic postural control while performing another dynamic task, the SEBT. Future research should incorporate electromyography (EMG) assessments with the kinematics during the SEBT in order to fully illustrate the alterations in sensorimotor and neuromuscular control of the lower extremity joints associated with CAI.

While Gribble et al.\(^54\) reported that knee and ankle kinematic changes in the sagittal-plane were associated with the SEBT performance in individuals with CAI, we did not observe a significant correlation between SEBT performance and frontal-plane kinematics in the CAI group, suggesting that the decreased performance on the SEBT may not be associated with the altered frontal-plane kinematics. In a recent investigation\(^67\), maximum weight-bearing ankle dorsiflexion was significantly associated with anterior %MAXD of the SEBT and explained 28% of variance in anterior %MAXD of the SEBT, indicating that decreased performance on the anterior reach distance may be indicative of restricted ankle dorsiflexion. It is possible that sagittal-plane kinematics at the knee and hip and the availability of ankle dorsiflexion range of motion have greater influence on the SEBT performance in the anterior reach direction. Greater eversion is
produced at the ankle due to improved muscular stabilization from peroneal activation in the healthy control group. Delahunt et al. demonstrated that reaching the closed-pack position of the subtalar joint was less efficient in CAI participants than healthy participants. An increased valgus position at the knee will lower the COM. These factors lead to a more stable base of support thus a greater reach distance in the healthy control group than the CAI group. Further investigation should perform the comprehensive regression analysis to determine which plane of kinematics influence the SEBT performance the most. Furthermore, it has been shown that CAI is associated with deficits in strength, static postural control, spinal excitability, and laxity which may contribute to decreased performance on the SEBT. However, it is currently unclear what factors have an impact individually and in combination on the SEBT performance. Therefore, further study should examine potential contributing factors to SEBT performance to determine the source of the observed alterations in lower extremity kinematics and postural control associated with CAI.

The involved knee of the CAI group was in a relatively less valgus position compared to the control group at the point of maximal reach. We found a significant positive correlation between knee and hip frontal-hip kinematics on the involved side of the CAI group ($r = 0.822, R^2 = 0.676, p = .007$). However, no significant difference in frontal-plane kinematics at the hip was noted between groups. These findings may be influenced by hip abductor strength or altered activation patterns. Previous studies observed decreased hip abductor strength as well as prolonged onset times and shorter durations of gluteus medius activity. The main function of the gluteus muscles is stabilization of the pelvis rather than active abduction of the thigh. During the SEBT,
perhaps the CAI participants shifted the center of mass (COM) over the stance limb rather than contracting the gluteal muscles to stabilize the pelvis to compensate for hip abductor weakness or altered muscle activation patterns, thereby placing the knee in a less valgus position. Shifting the COM changes motions about the hip during the SEBT but may not have necessitated enough of a mechanical contribution to produce a significant group-difference. Therefore, the hip frontal-plane motion was not different between the CAI and control group, but it was associated with the knee frontal-plane kinematics. However, we did not quantify the gluteus muscles activation pattern and the location of the COM during the SEBT. Future studies should examine the location of COM and the relationship between the COM location and lower extremity kinematics during the SEBT.

In our study, there were no significant differences in any plantar pressure distribution variables between the CAI and control groups. However, the midfoot M:L ratio was approaching statistical significance (p = 0.083) between the CAI and control groups, with a large effect size (d = 0.71), indicating that the midfoot plantar pressures were likely more medially distributed in the CAI group at the point of maximum anterior reach during the SEBT compared to the control group. Morrison et al. observed that individuals with CAI had more lateral planter pressure distributions during initial loading phases of running, suggesting greater rearfoot inversion and less eversion in the CAI group. In contrast, we observed that participants with CAI had greater ankle inversion and greater medial plantar pressure distribution at the point of maximum reach during the SEBT compared to those without CAI. It is important to address that we quantified kinematics only of the ankle-rearfoot complex but not kinematics of the forefoot and
midfoot. In general, with the rearfoot supinating, the midfoot and forefoot must simultaneously twist into relative pronation in order for the foot to remain in the full contact with the ground. The observed frontal-plane kinematics in the ankle and the greater midfoot plantar pressure distribution may be functioning under normal mechanics orchestrated through a closed kinetic interaction among the ankle, rearfoot, midfoot, and forefoot with the foot fixed on the ground. Although we found that frontal-plane kinematics at the ankle were not correlated with M:L ratio of the midfoot and the M:L ratio at the forefoot was positively correlated to the M:L ratio of the midfoot in the involved limb of the CAI group, we cannot definitively speculate on the mechanisms underlying the relationships between frontal-plane kinematics and plantar pressure distribution in the absence of the kinematics at the subtalar, transverse tarsal, metatarsophalangeal joints as well as joint coupling analysis among joints. Lastly, foot and ankle posture has been shown to affect plantar pressure distribution. We found no correlations between the foot and ankle posture as assessed with the FPI-6 and any plantar pressure variables.

We did not separate individuals within the CAI group into MAI or FAI. It has been suggested that separating into these groups may provide better explanation for CAI due to structural and pathological differences in MAI and FAI. Additionally, previous investigation found differences in movement patterns and dynamic stability between individuals with CAI and those that did not develop it after an initial injury. A comparison in the CAI group with a “coper” group may help researchers to understand the underlying mechanisms of development of instability following an initial ankle
sprain. Therefore, future studies should assess sensorimotor differences among the CAI, FAI, MAI, and “coper” groups during the SEBT.

5.2 Limitations

Results from this study should be interpreted with caution due to the number of limitations. Target sample size was calculated using our own pilot work. A priori sample size calculation indicated that we needed to recruit 25 participants for each group to achieve a desired power of 0.80. Because of time constraints and availability of participants, we could include only 9 participants for each group. This small sample size may pose the possibility of Type I and II error. By increasing the number of participants it may be possible to better define the statistical relationships in plantar pressure measurements because some of the plantar pressure variables were approaching statistical significance with large effect sizes.

Because of the retrospective nature of this study, it is possible that the observed alterations in frontal-plane knee and hip kinematics during the SEBT may be influenced by other factors that are not directly associated with CAI, such as muscle flexibility and strength in the lower extremity, which were not quantified in this study. Also, it is not possible to determine whether alterations were present prior to injury in the CAI group.

Participants included in this study were members of a young and physically active adult population performing a single-limb balance reaching activity. Therefore, the findings of our study may be limited to a similar population and task. Kinematic data was collected using sensors placed on the skin and held in place using elastic tape, which may induce measurement errors in assessing the true joint motions due to movement of the sensors.
5.3 Clinical Implication

We found an increased ankle inversion angle and less knee adduction on the involved side of the CAI group compared to the matched involved side of the control group. These findings support the results from previous studies\(^{63,64,54,62}\) that demonstrated altered kinematic patterns in the knee and ankle as well as diminished dynamic postural stability across other tasks. Most current ankle rehabilitation protocols focus on regaining and improving function at the ankle while some studies have suggested incorporating exercises at the hip following an ankle injury. The findings of this current study may help clinicians to develop more effective therapeutic applications to modify frontal-plane kinematic patterns in those with CAI. Proximal joint rehabilitation can help to correct kinematic alterations that result in mal-positioning of the foot/ankle complex during activity. Future research should consider this information as it may be used to develop more effective interventions to target these potentially modifiable frontal-plane kinematic patterns in those with CAI.

5.4 Conclusions

This study assessed the effect of unilateral CAI on frontal-plane kinematics and plantar pressure distribution during the SEBT in the anterior direction. The observed frontal-plane kinematic changes in the ankle and knee of an individual that has suffered CAI in association with decreased postural control during the SEBT may be indicating alterations in sensorimotor and neuromuscular controls manifesting in a joint proximal to the ankle. The decreased valgus angle at the knee may lead to the improper positioning of the foot that is resulting in increased inversion at the ankle. Addressing the altered kinetic chain relationship in the entire lower extremity can provide a more comprehensive and
significant insight to more effective intervention strategies for CAI. Additional kinetic and EMG variables are needed to determine if the kinetic relationship among these variables provides insight regarding existing ankle pathology.
References


81. Teyhen D, Stoltenberg, BE, Eckard, TG, Doyle, PM, Boland, DM, Feldtmann, JJ, McPoil, TG, Christie, DS, Molloy, JM, Goffar, SL. Static foot posture associated

Appendix A

Human Subjects Informed Consent Form

EFFECTS OF CHRONIC ANKLE INSTABILITY ON LOWER EXTREMITY FRONTAL-PLANE KINEMATICS AND FOOT PRESSURE DISTRIBUTION DURING A DYNAMIC POSTURAL CONTROL TASK

Principal Investigator: Phillip Gribble, Ph.D., ATC
Other Staff (identified by role): Ara Wittwer, ATC, Co-investigator
Masafumi Terada, MS, ATC, Co-investigators
Contact Phone number(s): Dr. Phillip Gribble: (419) 530-2691
Ara Wittwer: (906)250-5936
Masafumi Terada: (308)293-3302

What you should know about this research study:

- We give you this consent/authorization form so that you may read about the purpose, risks and benefits of this research study. All information in this form will be communicated to you verbally by the research staff as well.

- Routine clinical care is based upon the best-known treatment and is provided with the main goal of helping the Individual patient.

- The main goal of research studies is to gain knowledge that may help future patients.

- We cannot promise that this research will benefit you. Just like routine care, this research can have side effects that can be serious or minor.

- You have the right to refuse to take part in this research, or agree to take part now and change your mind later.

- If you decide to take part in this research or not, or if you decide to take part now but change your mind later, your decision will not affect your routine care.

Please review this form carefully. Ask any questions before you make a decision about whether or not you want to take part in this research. If you decide to take part in this
research, you may ask any additional questions at any time. Your participation in this research is voluntary.
PURPOSE (WHY THIS RESEARCH IS BEING DONE)

You are being asked to take part in a research study that examines neuromuscular and biomechanical characteristics in the lower extremity associated with chronic ankle instability (CAI) during a dynamic postural control balance test. Once an individual has sustained an ankle sprain, the likelihood for re-occurrence is very high, potentially leading to CAI. The purposes of the study are (1) to assess the effects of CAI on frontal-plane kinematics of the hip, knee, and ankle as well as plantar pressure distribution during a dynamic postural control task, the anterior reach of the SEBT, (2) to identify the relationship between lower extremity frontal-plane kinematics and plantar pressure distribution, and (3) to examine hip muscle activation patterns. This study may help illustrate the link between proximal and distal segments of the lower extremity and specifically what factors may be contributing to repetitive ankle instability by understanding the relationship between lower extremity frontal plane positioning on the foot pressure pattern in CAI population.

You were selected as someone who may want to take part in this study because you meet the following criteria:

You will be in the CAI group if you:
- Would like to voluntarily participate in this study
- Are between the ages 18 and 35 years
- Participate in at least 20 minutes of vigorous activity, three or more days per week
- Are free of any diagnosed balance or vestibular disorders and head injury
- Have
  1. A previous history of at least one acute lateral ankle sprain which caused swelling, pain, and temporary loss of function
  2. A history of at least two repeated episodes of "giving way" in the past 12 months but not within the post three months
  3. No history of any musculoskeletal and neurovascular injury in the lower extremity other than the ankle in the previous two years, and (4) no previous fractures or surgery in the lower extremity
  4. No history of low back pain and sacroiliac joint dysfunction in the previous six months
- Report a score of < 90% on the Functional Ankle Disability Index (FADI) and < 80% on the FADI Sport Subscale 157

You will be in the control (healthy) group if you:
- Would like to voluntarily participate in this study
- Are between the ages 18 and 35 years
- Participate in at least 20 minutes of vigorous activity, three or more days per week
- Are free of any diagnosed balance or vestibular disorders and head injury
- Have no history of any self-reported musculoskeletal and neurovascular injury and disorder in the lower extremity, no history of low back pain and sacroiliac joint dysfunction in the previous six months, and no history of surgery in the lower extremity.
- Have a score of ≥ 100% on the FADI and the FADI Sport Subscale
We will be enrolling a total of 50 participants. This research study will be conducted in the Athletic Training Research Laboratory and Motion Analysis Laboratory in the Health Science and Human Services building at the University of Toledo.

**DESCRIPTION OF THE RESEARCH PROCEDURES AND DURATION OF YOUR INVOLVEMENT**

If you decide to take part in this study, you will be asked to complete one testing session. The session will take approximately 60 minutes. At the beginning of the session, your pre-participation screening will be conducted.

After reading and signing the informed consent, you will be asked to complete a health history questionnaire and an ankle questionnaire, called as Functional Ankle Disability Index (FADI) including daily activity and sport sections, to allow us to better understand your history of the lower extremity injury.

Following completion of questionnaire, your leg length, height, weight, and foot posture (subtalar pronation) will be assessed using the Foot Posture Index.

After the pre-participation screen, disposable electromyography (EMG) electrodes will be placed on your skin of the hip muscles (gluteus maximus, gluteus medius, tensor fascia lata) in order to record your muscle activity levels. You will be informed which side of your limb will be tested. These electrodes are used for recording purposes of the electrical activity produced during a muscle contraction. You will not feel any sensations from these electrodes any differently than wearing a band-aid. Before EMG electrodes are attached onto your skin, skin will be cleaned with an alcohol swab and shaved if necessary to eliminate any object (e.g., hair) which may cause the electrodes to come off. After completing the preparation for EMG, electromagnetic sensors will be placed over the skin of the lower back (sacrum), outer mid-thigh, outer mid-lower leg, and the top of foot. These sensors will record the position of your ankle, knee, and hip as you perform tasks. The sensors will pick up a signal from an electromagnetic field that will be created from a black transmitter. The sensors will be secured on your skin using non-adhesive elastic tape and hook-and-loop straps. The sensors are connected by the cords to a computer, and the cords will be secured to your skin with a non-adhesive elastic tape or a strap to prevent the cords from interfering with your motions. You will be asked to stand in a relaxed posture while anatomical landmarks on the hip, knee, ankle, and foot will be digitized by palpation using a stylus attached to a fifth electromagnetic sensor for creating digital representation of your testing leg. You will not feel anything from these sensors during a testing session. Furthermore, you will not see or feel the electromagnetic field and it does not cause any harm to you. The signal from the sensors will be transmitted to a computer which will provide us a stick-figure of the position and movement patterns of your joints.

After completing preparation for EMG and electromagnetic sensors, you will be asked to stand on a foot pressure mat that will monitor the pressure distribution of your foot during testing. Then, you will be asked to perform the Star Excursion Balance Test.
which consists of single leg squat with bare feet with your hands on the hip. You will be instructed to reach into the forward direction along the tape measure, using the toes of the non-standing leg to make a touch as lightly as possible, and then return to the starting point with double-leg stance. The reaching distance will be marked and measured in centimeters. You will be allowed to complete four practice trials to eliminate the learning effect. Following a five-minute rest, you will perform five forward direction reaches. Each trial will be separated by 30 seconds of rest. You will be asked to repeat the trial if the stance foot is lifted while reaching, let your non-standing foot touch the mat, or if you lose balance during the trials. After all this is completed on one leg, the procedures will be repeated for your other leg. Before you begin the testing procedures, the investigator will inform you which leg you will start with.

**RISKS AND DISCOMFORTS YOU MAY EXPERIENCE IF YOU TAKE PART IN THIS RESEARCH**

When participating in any research study, you may encounter some risks. Although the risk for taking part in this study is very low, you may experience one or more of the following:

1. Because you are performing functional activities, there is a slight chance of falling. However, you will be given instruction on how to perform the task and as much practice as you need to become comfortable with the task. Finally, an investigator will be standing nearby in the unlikely event that you need assistance.

2. You may experience minor muscle soreness following the study as you would after exercising. To minimize this risk, you will be given rest periods between test trials to make sure you don't get tired.

3. Adhesive tape will be used to secure electrodes. You could experience a mild skin reaction (mild redness or itchiness) if your skin is sensitive and have had a reaction before. If you know of any existing skin sensitivities, it is important that you inform the Investigator.

If you are pregnant, it is advised that you remove yourself from the study during your pregnancy. While there are no known risks for pregnant women taking part in this study, because of the mild risk of falling, we would advise you to consider not participating if you are pregnant.

**POSSIBLE BENEFIT TO YOU IF YOU DECIDE TO TAKE PART IN THIS RESEARCH**

We cannot and do not guarantee or promise that you will receive any benefits from this research. The benefit of participating in this study is to help further research regarding chronic ankle instability.

**COST TO YOU FOR TAKING PART IN THIS STUDY**

You are not directly responsible for making any type of payment to take part in this study.
However, you are responsible for providing your own means of transportation to and from the Health Science and Human Services Building at The University of Toledo. You will not be compensated for gas for travel or any other expenses to participate in this study. You will receive a one-day parking permit for participation in this study by the investigators if you need parking.

No compensation including money, free treatment, free medications, or free transportation will be provided for this study.

PAYMENT OR OTHER COMPENSATION TO THE RESEARCH SITE
The University of Toledo is not receiving money or other benefits from the sponsor of this research as reimbursement for conducting the research.

ALTERNATIVE(S) TO TAKING PART IN THIS RESEARCH
There is no alternative to taking part in this research. Exclusion from the study, however, will not affect the quality of care you may receive at the sports medicine/physical therapy facility, doctor's office, or other medical facilities.

CONFIDENTIALITY
The researchers will make every effort to prevent anyone who is not on the research team from knowing that you provided this information, or what that information is. The consent forms with signatures will be kept separate from responses, which will not include names and which will be presented to others only when combined with other responses. Although we will make every effort to protect your confidentiality, there is a low risk that this might be breached.

IN THE EVENT OF A RESEARCH-RELATED INJURY
In the event of injury resulting from your taking part in this study, treatment can be obtained at a health care facility of your choice. You should understand that the costs of such treatment will be your responsibility. Financial compensation is not available through The University of Toledo or The University of Toledo Medical Center. By signing this form you are not giving up any of your legal rights as a research subject.

In the event of an injury, contact Phillip Gribble, PhD, ATC (419) 530-2691

VOLUNTARY PARTICIPATION
Taking part in this study is voluntary. You may refuse to participate or discontinue participation at any time without penalty or a loss of benefits to which you are otherwise entitled. If you decide not to participate or to discontinue participation, your decision will not affect your future relations with the University of Toledo or The University of Toledo Medical Center.

NEW FINDINGS
You will be notified of new information that might change your decision to be in this study if any becomes available.
OTHER IMPORTANT INFORMATION
There is no additional information.

ADDITIONAL ELEMENTS
There are no additional elements to the study.

OFFER TO ANSWER QUESTIONS
Before you sign this form, please ask any questions on any aspect of this study that is unclear to you. You may take as much time as necessary to think it over. If you have questions regarding the research at any time before, during or after the study, you may contact Phillip Gribble, PhD, ATC (419) 530-2691.
If you have questions beyond those answered by the research team or your rights as a research subject or research-related injuries, please feel free to contact the Chairperson of the University of Toledo Biomedical Institutional Review Board at 419-383-6796.

SIGNATURE SECTION (Please read carefully)

YOU ARE MAKING A DECISION WHETHER OR NOT TO PARTICIPATE IN THIS RESEARCH STUDY. YOUR SIGNATURE INDICATES THAT YOU HAVE READ THE INFORMATION PROVIDED ABOVE, YOU HAVE HAD ALL YOUR QUESTIONS ANSWERED, AND YOU HAVE DECIDED TO TAKE PART IN THIS RESEARCH.

BY SIGNING THIS DOCUMENT YOU AUTHORIZE US TO USE OR DISCLOSE YOUR PROTECTED HEALTH INFORMATION AS DESCRIBED IN THIS FORM.

The date you sign this document to enroll in this study, that is, today's date, MUST fall between the dates indicated on the approval stamp affixed to the bottom of each page. These dates indicate that this form is valid when you enroll in the study but do not reflect how long you may participate in the study. Each page of this Consent/Authorization Form is stamped to indicate the form's validity as approved by the UT Biomedical institutional Review Board (IRB).

Name of Subject (please print)

________________________

Signature of Subject or Person Authorized to Consent

________________________

Date

________________________

Relationship to the Subject (Healthcare Power of Attorney authority or Legal Guardian)
Name of Person Obtaining Consent  
(please print)

______________________________
Signature of Person Obtaining Consent Date

______________________________
Name of Witness to Consent Process  
(when required by ICH Guidelines) (please print)

______________________________
Signature of Witness to Consent Process  
(when required by ICH Guidelines)

______________________________
Date

YOU WILL BE GIVEN A SIGNED COPY OF THIS FORM TO KEEP.
Appendix B

Health History Questionnaire

Participant #:  
Name:  
Age:  Height:  Weight:  
Sex:  M  F

1. How many hours and days do you participate in physical activities?: 

2. Which foot do you kick a ball with:  Right  Left

3. Have you sprained your ankle?:  Yes  No  
   If Yes, which have you sprained, RIGHT or LEFT ankle?  
   How many times have you sprained your ankle?  
   When was the most recent?

4. Have you ever experienced more than 2 repeated episodes of your ankle "giving way" in the past 12 months?:  Yes  No  
   a. When was the last time your ankle "gave way"?  
      <1 month  1-6 months ago  6-12 months ago  1-2 years ago  >2 years

5. Have you had a concussion in the past twelve months?:  Yes  No  
   If yes, explain:

6. Have you ever experienced a head injury beside concussion?:  Yes  No  
   If Yes, what was the injury?  
   When was the most recent?

7. Have you ever suffered from a significant back injury causing you to interrupt your sports activity?:  Yes  No  
   If Yes, when was the most recent incident?  
   What was the cause of the back injury/pain?

8. Have you ever suffered from a fracture to any part of your leg, knee, ankle, hip, back, thigh, or foot?:  Yes  No
If Yes, when did the fracture occur?
Which bone(s) was fractured?

9. Have you ever suffered from a significant hip/thigh injury causing you to interrupt your sports activity?
   a) If Yes, when was the most recent incident?
      What injuries have you experienced?
   b) Did the injury require surgery?
      If yes, when was the surgery?

10. Have you ever suffered from a significant knee injury causing you to interrupt your sports activity?
    a) If Yes, when was the most recent incident?
       What injuries have you experienced?
    b) Did the injury require surgery?
       If yes, when was the surgery?

11. Have you ever suffered from a significant lower leg injury causing you to interrupt your sports activity?
    c) If Yes, when was the most recent incident?
       What injuries have you experienced?
    d) Did the injury require surgery?
       If yes, when was the surgery?

12. Have you ever suffered from a significant ankle/foot injury (other than ankle sprains) causing you to interrupt your sports activity?
    a) If Yes, when was the most recent incident?
       What injuries have you experienced?
    b) Did the injury require surgery?
       If yes, when was the surgery?

13. Do you suffer from vertigo, or any other neurological disorders?:
    If Yes, explain:

14. Are you currently suffering from the effects of a cold or flu? Yes No
Appendix C

Functional Ankle Disability Index and Functional Ankle Disability Index Sport Scale

<table>
<thead>
<tr>
<th>Activity</th>
<th>No difficulty at all</th>
<th>Slight difficulty</th>
<th>Moderate difficulty</th>
<th>Extreme difficulty</th>
<th>Unable to do</th>
<th>N/A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standing</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Walking on even ground</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Walking on even ground without shoes</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Walking up hills</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Walking down hills</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Going up stairs</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Going down stairs</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Walking on uneven ground</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Stepping up and down curbs</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Squatting</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Sleeping</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Coming up on your toes</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Walking initially</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Walking 5 minutes or less</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Walking approximately 10 minutes</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Walking 15 minutes or greater</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
</tbody>
</table>

Foot and Ankle Disability Index (FADI)

Please answer every question with one response that most closely describes your condition within the past week.

If the activity in question is limited by something other than your foot or ankle mark not applicable (N/A).
Because of your foot and ankle, how much difficulty do you have with:

<table>
<thead>
<tr>
<th>Activity</th>
<th>No difficulty at all</th>
<th>Slight difficulty</th>
<th>Moderate difficulty</th>
<th>Extreme difficulty</th>
<th>Unable to do</th>
<th>N/A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Home responsibilities</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Activities of daily living</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Personal care</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Light to moderate work</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Heavy work (push/pulling, climbing, carrying)</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Recreational Activities</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
</tbody>
</table>

Please rate your pain level as it relates to your foot and ankle:

<table>
<thead>
<tr>
<th>Activity</th>
<th>None</th>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
<th>Unbearable</th>
</tr>
</thead>
<tbody>
<tr>
<td>General level of pain</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>At rest</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>During your normal activity</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>First thing in the morning</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
</tbody>
</table>

**FADI Sports Scale**

Because of your foot and ankle, how much difficulty do you have with:

<table>
<thead>
<tr>
<th>Activity</th>
<th>No difficulty at all</th>
<th>Slight difficulty</th>
<th>Moderate difficulty</th>
<th>Extreme difficulty</th>
<th>Unable to do</th>
<th>N/A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Running</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Jumping</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Landing</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Starting and stopping quickly</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Cutting/lateral movements</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Low impact activities</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Ability to perform activity with your normal technique</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td></td>
</tr>
<tr>
<td>Ability to participate in your desired sport as long as you would like</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td></td>
</tr>
</tbody>
</table>
Appendix D

The Foot Posture Index (FPI-6) Scoring Table

<table>
<thead>
<tr>
<th>Rearfoot Score</th>
<th>-2</th>
<th>-1</th>
<th>0</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Talar head palpation</td>
<td>Talar head palpable on lateral side/but not on medial side</td>
<td>Talar head palpable on lateral side/slightly palpable on medial side</td>
<td>Talar head equally palpable on lateral and medial side</td>
<td>Talar head slightly palpable on lateral side/palpable on medial side</td>
<td>Talar head not palpable on lateral side/ but palpable on medial side</td>
</tr>
<tr>
<td>Curves above and below the malleoli</td>
<td>Curve below the malleolus either straight or convex</td>
<td>Curve below the malleolus concave, but flatter/more shallow than the curve above the malleolus</td>
<td>Both infra and supra malleolar curves roughly equal</td>
<td>Curve below malleolus more concave than curve above malleolus</td>
<td>Curve below malleolus markedly more concave than curve above malleolus</td>
</tr>
<tr>
<td>Calcaneal inversion/eversion</td>
<td>More than an estimated 5° inverted (varus)</td>
<td>Between vertical and an estimated 5° inverted (varus)</td>
<td>Vertical</td>
<td>Between vertical and an estimated 5° everted (valgus)</td>
<td>More than an estimated 5° everted (valgus)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Forefoot Score</th>
<th>-2</th>
<th>-1</th>
<th>0</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Talo-navicular congruence</td>
<td>Area of TNJ markedly concave</td>
<td>Area of TNJ slightly, but definitely concave</td>
<td>Area of TNJ flat</td>
<td>Area of TNJ bulging slightly</td>
<td>Area of TNJ bulging markedly</td>
</tr>
<tr>
<td>Medial arch height</td>
<td>Arch high and acutely angled towards the posterior end of the medial arch</td>
<td>Arch moderately high and slightly acute posteriorly</td>
<td>Arch height normal and concentrically curved</td>
<td>Arch lowered with some flattening in the central portion</td>
<td>Arch very low with severe flattening in the central portion – arch making ground contact</td>
</tr>
<tr>
<td>Forefoot abd/adduction</td>
<td>No lateral toes visible. Medial toes clearly visible</td>
<td>Medial toes clearly more visible than lateral</td>
<td>Medial and lateral toes equally visible</td>
<td>Lateral toes clearly more visible than medial</td>
<td>No medial toes visible. Lateral toes clearly visible</td>
</tr>
</tbody>
</table>