FACTORS CONTRIBUTING TO ANKLE INSTABILITY

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ABSTRACT

CATHLEEN N. BROWN: Factors Contributing to Ankle Instability
(Under the direction of Dr. Kevin M. Guskiewicz)

Chronic ankle instability, repetitive giving way of the ankle, commonly develops from an initial ankle sprain. Our purpose was to identify factors contributing to ankle sprain, and whether or not kinematic, kinetic, and surface electromyography differences existed between mechanically unstable (MAI), functionally unstable (FAI), and comparison groups of subjects performing five different tasks (walking, stepping up and over, running, drop jumping, and stop jumping). There were 11 male and 10 female subjects in each of the three groups, matched by gender, age, height, mass, and limb dominance. An electromagnetic tracking system, coupled with a forceplate and telemetered surface electromyography were used to collect data. Unstable ankle subjects reported repeated episodes of spraining, and MAI subjects displayed positive anterior drawer and/or talar tilt tests. Using estimates of adjusted means, 95% confidence intervals, and effect sizes, we noted the MAI group displayed a pattern across tasks of increased dorsiflexion and eversion, increased frontal plane displacement and decreased sagittal plane displacement, with slower time to peak anterior ground reaction force in comparison with the FAI and comparison group. The FAI group demonstrated increased tibialis anterior mean amplitude as a percentage of maximum voluntary isometric contraction, but decreased lateral gastrocnemius mean amplitude. The coefficient of variation and standard deviation (SD) were obtained from an ensemble curve of each variable from the 8 test trials. The unstable groups displayed greater $\log_e$ SD in the ankle inversion-eversion motion than the comparison group. The MAI group demonstrated smaller SD values for each the tibialis anterior, peroneals, and lateral gastrocnemius in comparison to the FAI group. The altered movement pattern may be a coping mechanism designed to keep the ankle in a stable position, perhaps by relying on

bony stability and not stressing the anterior talofibular ligament. The increased variability observed in the unstable groups may predispose them to experience “risky” joint positions, closer to the limits of injury, and the FAI group may not activate their leg muscles enough to sufficiently rely on the muscles as dynamic stabilizers. These findings provide an explanation for the pathomechanics of ankle instability and need to be considered in rehabilitation programs.

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LIST OF ABBREVIATIONS AND SYMBOLS

ACL	Anterior cruciate ligament
ATFL	Anterior talofibular ligament
CAI	Chronic ankle instability
CFL	Calcaneofibular ligament
CI	Confidence Interval
CLR	Confidence Limit Ratio
cm	Centimeter
CV	Coefficient of variation
daN	Deca Newtons
^{o}	Degrees
EMG	Electromyography
FAI	Functional ankle instability
GRF	Ground reaction force
IC	Initial contact
Kp	Kiloponds or Kilograms-Force
LG	Lateral Gastrocnemius
MAI	Mechanical ankle instability
ms	Millisecond
m/s	meters per second
MVIC	Maximum voluntary isometric contraction
N	Newton
PL	Peroneals
SD	Standard deviation
SE	Standard error

SL	Soleus
TA	Tibialis Anterior
TELOS	Device used to apply standardized force to the ankle during stress x-rays

CHAPTER I

INTRODUCTION

Ankle sprains are one of the most common sports-related injuries. Chronic ankle instability (CAI), defined as subjective and repeated episodes of giving way and spraining of the ankle, is often the end-result of an initial ankle sprain.[1] CAI encompasses two possible causes of repetitive ankle sprains: mechanical instability and functional instability, and may be attributable to either independently or some combination of both.[1] Some individuals may develop CAI due to mechanical ankle instability (MAI) or physiologic laxity at the ankle joint. However some individuals with CAI have no mechanical laxity. Their CAI may be caused by functional ankle instability (FAI).[1] MAI is due to ligamentous laxity at the ankle following severe or repeated ankle sprains. FAI, first introduced by Freeman[2], is thought to be due to deafferentation or tearing of neural tissue within the ligament, causing deficits in proprioception and neuromuscular control. Deficits in postural control and strength may also contribute to FAI. Some individuals with CAI exhibit characteristics of FAI and MAI simultaneously.[1] The causes and factors that contribute to CAI after initial sprain are currently unknown. Little work has been done to differentiate between functional and mechanical instability in CAI. This dissertation project attempted to identify kinematic, kinetic, and electromyographic (EMG) factors that contribute to ankle instability. It tested for differences in those factors between three ankle stability groups: one with MAI, one with FAI, and a comparison group of individuals who sustained an initial ankle sprain at least 12 months ago but did not subsequently develop CAI. The subjects were tested using a series of daily living and athletic tasks, including walking, a step-up and over, running, a drop jump, and a stop jump, collecting data at the ankle and knee joints, due to their linkage in the kinetic chain. An equal number of subjects of each gender were matched by group. The significant contributions of this research were to distinguish CAI individuals into MAI and FAI and to examine variability, not just mean, differences between groups.

Specific Aims

The specific aims of this project were:

1) To identify differences in kinematics, kinetics, and electromyography (EMG) between three different ankle stability groups on a series of tasks.

2) To identify potential interactions between the ankle stability groups and tasks

a) To assess the degree of within- and between-subject variability in kinematics, kinetics, and EMG during the tasks

Background and Rationale

Epidemiology

Ankle sprains occur very frequently in most sports and physical activities. Data collected through the National Collegiate Athletic Association's Injury Surveillance System indicated lateral ankle sprains were the most common injury in soccer, volleyball, and basketball in all three collegiate divisions.[3] It is also a very common injury in the recreationally active population. Approximately one lateral ankle sprain occurs per 10,000 people per day.[4] The injury rate has been reported as 3.85/1000 exposures in recreational basketball[5] and as 5.7/100 participants per season in high school sports studies.[6] Of those individuals who experience a lateral ankle sprain, approximately 47-73% will suffer from recurrent sprains[7, 8] and develop CAI. Currently, there are no conclusive epidemiological data detailing the incidence or prevalence of CAI in the population, nor is there data on MAI or FAI independently.

Defining Ankle Instability

The lack of data may be partially attributed to the difficulty in defining CAI and its components, MAI and FAI. The relationship between mechanical and functional instability of the ankle is unclear.[1] A number of authors have utilized different definitions of MAI and FAI, and only recently has the term CAI been used to encapsulate both types of instability either independently or in combination.[1, 2, 9] MAI is most often defined as repeated sprains and physiologic laxity of the lateral ankle ligaments as documented by clinical orthopaedic or ligament stress tests with or without x-ray.[10-15] The amount of laxity necessary to qualify as MAI has not been standardized in the literature.[15, 16] FAI does not necessarily include any of the same indications as MAI, and only a fraction of those with CAI exhibit mechanical instability.[10, 16, 17] Thus, the majority of individuals with CAI have only FAI.[10, 16, 17] Functional instability is frequently determined by self-reported complaints of the ankle "giving way" during activity, and associated with possible deficits in one or more of the following: proprioception, neuromuscular control, postural control, and strength.[1, 2] Most of the previous research has utilized subjects with a minimum number of previous ankle sprains, or tried to quantify their complaints of instability using a questionnaire.[15, 18, 19] Other techniques to standardize FAI have included a minimum level of initial sprain severity, length of time with FAI, or type of activity that causes FAI.[20-22] Because these two factors, MAI and FAI, have either been combined or ignored in most previous research, little information exists regarding any differences they might cause in CAI.[15] Fundamental differences in the nature of the ankle pathology could influence explanations for the continued episodes of giving way. Additionally, the differences in pathology may require different rehabilitation exercises and protocols to best address the deficits. Finally, there is much contradiction in the literature in terms of whether or not CAI groups demonstrate altered joint position sense, postural stability, functional capacity, and movement in comparison to control groups. Some of that contradiction may be due to the lack of distinguishing between MAI and FAI groups. Separating these two types of pathologies may clarify some of the contradictions and offer insight into goals for future research and rehabilitation.

Causes of Ankle Instability

While lateral ankle sprains and the resultant CAI are common, little work has been done to identify the factors and causes of the phenomenon.[1, 20] There are significant gaps in the knowledge regarding incidence, causative factors, and whether or not any kinematic, kinetic, electromyographic, proprioceptive, or strength differences in CAI subjects contribute to injury. Previous research has reported that individuals with FAI have decreased proprioception as demonstrated by increased postural sway in static stance compared to uninjured control subjects.[23] A prospective cohort study reported individuals who experienced ankle sprains during a basketball season had significantly higher postural sway scores during single leg stance with eyes open and closed.[24] CAI subjects also demonstrated decreased joint position sense compared to injury free control subjects.[25, 26] When monitoring a group of individuals post-unilateral ankle sprain, the injured ankle demonstrated larger joint position sense error than the uninjured ankle at weeks 1, 3, 6, and 12 after injury.[27] However, in other reports using CAI subjects and matched controls, those joint position sense findings were not supported.[19, 28, 29] Subjects with unilateral FAI also demonstrated no differences in joint position sense when comparing involved and uninvolved ankles.[30] Differences in kinematics between CAI and control groups were revealed during single leg jump landings.[31] Kinematic differences were also found between CAI subjects and controls during gait[17, 32] and during step-up and over task.[32] Kinetic differences between CAI and control groups have been identified. Individuals with CAI demonstrated longer time to stabilization following jump landing,[19, 33] as well as faster onset of peak lateral and vertical ground reaction forces compared to control subjects.[18] Little rationale exists to explain these differences, particularly as few studies have documented a complete biomechanical picture.

Differences in EMG of the leg musculature in CAI individuals have also been demonstrated. CAI groups exhibited delayed and decreased hip muscle activation as well as increased variability compared to controls.[21] CAI subjects also displayed reduced peroneal activity compared to controls during landing from a drop jump.[9] A study of range of motion at the ankle revealed increased dorsiflexion with knee extension in the ankle sprain group,[12] while another found no differences in range of motion between CAI and control groups.[34] Measures of strength between CAI and control groups are equally contradictory. Eccentric invertor strength deficits were reported in CAI groups,[35] as were higher inversion to eversion strength ratios.[12] However, an equal number of studies found no differences in peak torque[36] or concentric strength and work in the planar directions.[34]

These contradictory results are difficult to compare and assimilate because of the wide variety of methods used, as well as the lack of standardization of groups and testing procedures. Despite the numerous publications, few studies have analyzed the factors discussed above in depth or in combination. Thus, no complete biomechanical picture of CAI has been established. One limitation of the literature is the inability to fully explain a significant finding in one area (such as kinetics) because the concurrent data in another area (such as kinematics) were not collected.[9] Lack of standardization in subject selection is also a problem: defining criteria for CAI and "control" subjects has proven difficult due to the continuum of ankle instability severity. Few studies to date have used "copers," or a comparison group of individuals with a history of previous initial sprain but no complaints of instability. Similar "coper" groups have been used successfully in the anterior cruciate ligament (ACL) injury literature. These studies compared ACL deficient individuals whom did and did not report feelings of instability at the knee.[37, 38] Using a group with a similar history of initial injury but no repeated episodes of instability may be useful in ankle injury studies. Rather than compare CAI subjects to individuals who have never suffered an ankle sprain, a more appropriate comparison may be made between CAI subjects and individuals with a similar ankle injury history, who did not subsequently develop or experience repeated episodes of giving way. These individuals' ability to "cope" and recover from the injury may highlight differences that developed following initial sprain.

Long-Term Effects of Chronic Ankle Instability

While CAI and lateral ankle sprains are common, the pathophysiology is not well understood, so the long-term effects of CAI on activity and joint health are currently unknown. The pain and repetitive nature of the injury may decrease joint function and limit participation in certain activities that perpetuate episodes of instability. Athletically active individuals with CAI may self-select out of participating in certain activities that increase the risk of giving way, such as activities that involve cutting or jump landing. If instability also occurs with less demanding activities, such as running straight ahead, walking over uneven ground, or stepping down, individuals with CAI may severely restrict their activities in order to avoid the pain and nuisance of the ankle giving way. The public health concerns of rising rates of obesity, diabetes, hypertension and other cardiovascular problems are difficult to combat with activity if individuals with CAI restrict their activity types and levels. Additionally, sedentary individuals who try new activities to overcome these health problems may develop CAI or forgo activity because of the instability.

The long-term effects of CAI on ankle joint health are not well documented.[39] Unlike knee instability, most ankle arthritis is secondary to trauma and not due to overuse or wear.[40, 41] Individuals with a history of CAI displayed increased articular lesions, degeneration, and defects in the ankle.[39] There are currently no adequate surgical procedures to correct this articular damage, so prevention is the key to avoiding ankle joint degeneration. Preventing and treating chronic ankle instability is an important step in ensuring long-term joint health, especially in later life.

Statement of the Problem

This project utilized kinematics, kinetics, and EMG at the ankle and knee in an attempt to obtain a complete biomechanical picture of ankle instability. Each component is related to and influences the other – these dynamic interactions make it difficult to explain findings in one area without the other two. Current CAI literature does not identify where deficits in neuromuscular and motor control occur, thus we assessed all three components of movement. Deficits or differences in control may be identified in one measure or in interaction among components. Previous studies typically addressed only one component and used a variety of methods, making comparisons between tasks and studies difficult.[9, 18, 21, 31] Different ankle stability groups may present with different deficits (i.e., it is unknown whether or not FAI and MAI exhibit similar kinematics, kinetics, and EMG activity during these tasks because they have not been separated in previous literature). Subjects may also use different strategies to compensate for CAI or may not be able to compensate and so have adopted a deleterious or highly variable strategy. The high degree of variability may put the subjects at risk if they are in potentially injurious positions or ranges of motion. Thus, we will strictly define the criteria to divide subjects into three different groups: those with mechanical instability only, functional instability only, and a comparison group of individuals who have a history of acute inversion ankle sprain but did not subsequently develop CAI.

Most ankle literature has focused on static balance (with conflicting results)[23, 24, 28, 29] and jump landing, a complex and highly demanding task.[19, 33, 42] While some studies reported differences between groups with these tasks, little attention has been paid to other tasks that produce injury or may illuminate deficits, such as walking, running, and step-up and over. Performance in one task is not necessarily related to performance in another. Subjects may utilize different strategies and movements, and different biomechanical demands may create different results. No study to date has combined different tasks (walking, step-up and over, running, drop jump, and stop jump) in a progression to identify if or where deficits can be observed between groups. With a progression from walking to jump landing, we can observe differences in pre-programming requirements, such as the need for increased pre-activation of ankle musculature. These changing requirements may elucidate differences that exist. Thus, the purpose of this dissertation project is to identify factors that may contribute to ankle instability and ankle injury.

Research Questions

There were three ankle stability groups of subjects: mechanical ankle instability, functional ankle instability, and a comparison group. Each group performed several trials of the 5 tasks (walking, step-up and over, running, drop jump and stop jump), and their data were averaged over the trials. The following questions were applied to each group and task.

1. Are there significant differences between the three ankle stability groups in kinematic measures?

a. Flexion, inversion/eversion, and valgus/varus angles at **initial contact** (ankle and knee)

b. **Maximum** flexion and inversion/eversion or valgus/varus angles during stance (ankle and knee)

c. Flexion and inversion/eversion or valgus/varus **displacements** (total range of motion) during stance (ankle and knee)

2. Are there significant differences between the three ankle stability groups in kinetic measures?

a. **Peak ground reaction forces** normalized to body mass (vertical, anterior-posterior, and medial-lateral)

b. **Time to peak ground reaction forces** normalized to body mass (vertical, anterior-posterior, and medial-lateral)

3. Are there significant differences between the three ankle stability groups in EMG measures?

a. **EMG mean amplitude** for tibialis anterior, peroneus longus, lateral gastrocnemius, and soleus muscles

4. Are there significant group by task interactions?

a. Using the variables as in Research Questions #1, 2, and 3, use a 3 x 5 mixed model ANOVA to test for **interactions** between groups and tasks.

b. Use the curve average standard deviation and coefficient of variation calculations for each dependent variable on each task to test **within and between subject variability** on each measure

Research Hypotheses

1. Are there significant differences between the three ankle stability groups in kinematic measures?

a. Flexion, inversion/eversion, and valgus/varus angles at **initial contact**

(1) FAI and MAI groups will demonstrate increased ankle dorsiflexion at initial contact in contrast to the comparison group

(2) FAI and MAI groups will demonstrate increased knee flexion at initial contact in contrast to the comparison group

(3) FAI and MAI groups will demonstrate increased ankle inversion at contact in contrast to the comparison group

(4) No differences will be observed between the three ankle stability groups in knee valgus/varus angle at initial contact

b. **Maximum** flexion and inversion/eversion or valgus/varus angles during stance

(1) FAI and MAI groups will demonstrate increased maximum dorsiflexion angle during stance in contrast to the comparison group

(2) FAI and MAI groups will demonstrate increased maximum knee flexion angle during stance in contrast to the comparison group

(3) FAI and MAI groups will demonstrate increased maximum ankle inversion angle during stance in contrast to the comparison group

(4) No difference will be observed between the three ankle stability groups in maximum knee valgus/varus angle during stance

c. Flexion and inversion/eversion or valgus/varus **displacements** (total range of motion) during stance

(1) FAI and MAI groups will demonstrate decreased ankle flexion displacement during stance in contrast to the comparison group

(2) FAI and MAI groups will demonstrate increased knee flexion displacement during stance in contrast to the comparison group

(3) FAI and MAI groups will demonstrate increased ankle inversion displacement during stance in contrast to the comparison group

(4) No differences will be observed between the three ankle stability groups during stance in knee valgus/varus displacement

2. Are there significant differences between the three ankle stability groups in kinetic measures?

a. **Peak ground reaction forces** normalized to body mass for each task

(1) No differences will be observed between the three ankle stability groups for peak vertical, anterior-posterior, or medial-lateral ground reaction forces for any task

b. **Time to peak ground reaction forces** normalized to body mass

(1) FAI and MAI groups will demonstrate shorter time to peak vertical ground reaction force in contrast to comparison group during all tasks

(2) No differences will be observed between the three ankle stability groups for anterior-posterior or medial-lateral ground reaction forces during all tasks

3. Are there significant differences between the three ankle stability groups in EMG measures?

a. **Mean EMG amplitude**

(1) MAI group will demonstrate increased EMG amplitude in each muscle on all tasks compared to the FAI and comparison groups

4. Are there significant group by task interactions?

a. **Interactions** between groups will be observed for the MAI and FAI groups on the more challenging tasks (running, drop jumping, and stop jumping).

b. More **within subject variability** will be evident in the FAI and MAI groups in contrast to the comparison group for each task.

Definitions

Chronic ankle instability (CAI): An ankle with functional ankle instability, mechanical ankle instability, or some combination of both that is subject to feelings of "giving way" with activity and is recurrently sprained.[1]

Functional ankle instability (FAI): An ankle without mechanical instability that is subject to feelings of "giving way" with activity and is recurrently sprained.[1, 2, 43]

Initial contact: The instantaneous moment of contact of the foot with the ground.

Landing: The process of returning to the ground, absorbing the impact and regaining a standing position after a jump.[44]

Mechanical ankle instability (MAI): An ankle exhibiting physiologic laxity in the lateral ligaments, that may or may not be functionally unstable.[1]

Pre-activation: Activation of the leg musculature during the flight time prior to initial foot contact with the ground.[45]

Proprioception: "A specialized variation of the sensory modality of touch [which] encompasses the sensation of joint movement kinesthesia and joint position sense."[46]

Operational Definitions

Anterior drawer: A clinical orthopaedic test to determine laxity of the lateral ankle ligaments, specifically the anterior talofibular ligament. The subject is seated with his/her feet in 5-10 degrees of plantar flexion. The examiner places one palm on the posterior aspect of the calcaneus and grips it, while the other hand is placed on the anterior aspect of the tibia. An anterior force is imparted on the calcaneus while a posterior force is applied to the tibia to try to separate the tibiotalar joint and ankle mortise. If laxity is present, the talus will slide anteriorly from mortise and the examiner may feel a clunk. Results of this test determine whether or not individuals have mechanical instability at the ankle.[47]

Chronic ankle instability (CAI): A clinical phenomenon secondary to acute lateral ankle sprain in which the ankle feels unstable; individuals report repeated episodes of giving way and spraining. May be due to mechanical instability, functional instability, or some combination of both.[1]

Comparison group: One ankle stability group composed of individuals with a history of acute ankle sprain requiring immobilization/non-weight bearing for at least 3 days within the past 1-5 years with one or fewer ankle sprains since then; negative anterior drawer and talar tilt; no repeated episodes of the ankle giving way or complaints of ankle instability, with no reports of pain, weakness, or decreased function as determined by questionnaire. No ankle sprains within the past 6 months and no current swelling or ecchymosis.

Drop jump: A task each ankle stability group will perform consisting of a single leg jump landing off of a 32 cm box onto a nonconductive forceplate flush with the ground. Subjects will stand on the box on the non-test leg, extend the test leg, and propel themselves off the box onto the forceplate with minimum vertical displacement, landing on only the test leg and returning to an upright single leg stance.[18, 31]

Functional ankle instability (FAI): One of the ankle stability groups consisting of individuals with a history of acute inversion ankle sprain requiring immobilization/non-weight bearing for at least 3 days within the past 5 years; negative anterior drawer sign and talar tilt; repeated episodes of giving way at the ankle and complaints of ankle instability with activity; subjective reports of weakness, pain and/or decreased function in that ankle secondary to the sprain as reported on questionnaires; at least 2 episodes of giving way in the past 12 months; no current swelling or ecchymosis.[2, 9]

Initial contact: The moment in time the foot first touches the landing surface and is indicated by the forceplate with a signal exceeding 10.0V and activating ground reaction force data collection.

Mechanical ankle instability (MAI): One of the ankle stability groups consisting of individuals with a history of acute inversion ankle sprain requiring immobilization/non-weight bearing for at least 3 days within the past 5 years; positive anterior drawer sign and talar tilt; repeated episodes of giving way at the ankle and complaints of ankle instability with activity; subjective reports of weakness, pain and/or decreased function in that ankle secondary to the sprain as determined by questionnaires;[9, 15, 18, 31] at least 2 episodes of giving way in the past 12 months;[33] no current swelling or ecchymosis.[48]

Modified anterior drawer: A test to measure anterior talofibular ligament laxity. Subjects are seated with the tibia in a vertical position and the foot in 10 degrees of plantar flexion and secured to the ground. The tester's hands are used to apply force to the tibia to separate the talocrural joint and an electromagnetic tracking system will measure that separation.

Pre-activation: Muscle activity evident in the 250 ms prior to initial contact.

Post-activation: Muscle activity in the 250 ms after initial contact.

Recreational athletes: Subjects in each ankle stability group must participate in at least 1.5 hours of cardiovascular, resistance, or other physical activity/sporting activity per week.

Running: One of the 5 tasks each subject will complete; performed on a raised walkway, with a minimum of 3 strides and a speed 2.5-3.5 m/s as determined by sacral sensor linear velocity in the anterior direction in the frame prior to initial contact.[49, 50]

Step-up and over: One of the 5 tasks each subject will complete; performed by using the non-test limb to step up onto a 32cm high box and then place the test leg on the forceplate in a continuous motion, following with 2-3 strides after initial contact.

Stop jump: One of the 5 tasks each subject will complete; performed by running along the raised walkway at a speed of 2.5-3.5m/s, taking off on the test leg just before reaching the forceplate, and landing with both feet at the same time (test leg on the forceplate, non-test leg off) then performing a maximum vertical jump and landing in approximately the same place, so as to minimize horizontal movement. It will be performed in a continuous movement, similar to stop jumps performed in basketball, volleyball, or soccer.[51]

Talar tilt: A clinical orthopedic test to determine laxity of the lateral ankle ligaments, specifically the calcaneofibular and anterior talofibular ligaments. It is performed by placing one of the examiner's hands on the anterior aspect of the tibia and the other on the posterolateral aspect of the calcaneus and imparting a rotational force. The calcaneus inverts and the examiner attempts to gap the talus and rock it in the gapping. Excessive gapping would indicate the two ligaments are damaged. Results of this test determine whether or not a subject has mechanical ankle instability.[47]

Walking: One of the 5 tasks each subject will complete; performed on a raised walkway, with a minimum of 3 strides and a speed of 1.2-1.4 m/s as determined by the sacral sensor linear velocity in the anterior direction in the frame prior to initial contact.[52-54]

<u>Assumptions</u>

The following assumptions were made in the study:

1) Subjects truthfully reported their ankle injury history and answered the questionnaires to the best of their ability.

2) The ankle stability groups accurately reflected subjects' ankle injury status (all subjects met the inclusion and exclusion criteria for the group they were placed into).

3) Subjects performed the tasks to the best of their ability.

4) There were no injuries, training effects, or fatigue during testing.

5) The data collection equipment was free of noise and error and accurately recorded the data.

<u>Delimitations</u>

The following delimitations were made in the study.

1) Subjects were recreational athletes aged 18-35 who complete a total of at least 1.5 hours of activity a week.

2) Only subjects with mechanical and functional ankle instability in the test leg were included in those groups.

3) Only individuals without a history of CAI (either MAI or FAI) were included in the comparison group. Any subjects not fitting the criteria of the appropriate group or displaying acute ankle or lower extremity injury or history of fracture were excluded.

Limitations

One of the potential limitations in this project was recruiting an adequate number of subjects into each group. Approximately 42% of all individuals with ankle instability are reported to have mechanical instability.[48] This closely matches the 43% of previous subjects tested in the Sports Medicine Research Laboratory who demonstrated MAI to clinical exam. Of control subjects participating in previous work in the same Laboratory, 59% reported at least 1 previous sprain with no repetitive episodes, making a comparison population accessible. There is some error and variability associated with the instrumentation as well as human movement that cannot be excluded from analyses.

Significance

Although CAI is a common phenomenon, there is little information available regarding its causes and factors. Defining and identifying deficits that exist, whether they are in terms of neuromuscular control or some other factor, is a first step to developing logical prevention and rehabilitation programs to target those deficits. This dissertation project provides a unique contribution to the literature. I used larger, more standardized groups than in previous studies. I used a progression of tasks to assess limitations in individuals with CAI may have with respect to different lower extremity loads and functional demands. These tasks are common mechanisms of injury that have not been investigated. Forming a complete biomechanical picture of individuals with MAI, FAI and a group of comparison subjects is the first step to identifying ways to treat and prevent CAI. We also addressed variability of the subjects, not just the mean data and separated CAI into MAI and FAI groups.

CHAPTER II

REVIEW OF LITERATURE

Lateral ankle sprains are one of the most common sports related injuries.[1] A significant percentage of those individuals with an initial sprain will re-sprain the same ankle, often repetitively.[1, 8] These repetitive sprains, usually associated with episodes of the ankle "giving way" with activity, have been termed functional ankle instability (FAI)[2] or chronic ankle instability (CAI).[1] Despite the large number of individuals who suffer ankle sprains, little is known about the causes of and factors that perpetuate ankle instability.[1] The purpose of this dissertation project is to identify kinematic, kinetic, and electromyographic factors that may contribute to ankle instability and ankle injury. This literature review discusses the epidemiological evidence of how common ankle instability is, the anatomical structures involved, and etiology and definitions of chronic ankle instability and its components. The body of literature related to proposed causes of ankle instability is detailed, along with findings influencing the research hypotheses of this project. Literature establishing the methods used in this project will be reviewed and the findings interpreted to this project's expected outcomes.

Epidemiology of Lateral Ankle Sprain

Ankle sprains are reported to be the most common sports-related injury.[1] It is also considered the number one injury for loss of time of participation.[55] Injury surveillance data from the National Collegiate Athletic Association ranks it as the most common injury in mens' and womens' soccer, volleyball, and basketball.[3] The injury rate has been reported as 3.85/1000 exposures in recreational basketball,[5] while the rate in selected high school sports was reported as 5.7/100 participants per season, or roughly one ankle injury for every 17 participants.[6] Commonly cited statistics report one sprain per 10,000 people per day.[4] Despite these publications, there is little available data on the incidence and prevalence of lateral ankle sprain in recreational athletes or the general population.

Because it is not always a severe injury, and perhaps because it is so common, the number of sprains, the severity, and the treatment sought are not well documented.[20]

It is estimated that approximately 47-73% of individuals with initial sprains will re-sprain their ankle again.[7, 8] This number is widely debated, and no comprehensive study has documented the re-occurrence of lateral ankle sprain in different populations. A number of studies, however, have found that a previous sprain is the number one risk factor for suffering another sprain.[5, 8, 12, 56, 57]

Despite the frequency of lateral ankle sprain and the high percentage of re-occurrence, most research has focused on only a small number of factors, and never in combination with other biomechanical aspects. Most authors have focused on only kinematics, kinetics, electromyography (EMG), proprioception, or strength alone, not in combination. And there is little literature on the first three components in individuals who exhibit chronic ankle instability.

Ankle Anatomy

Bony Anatomy

The ankle joint consists of three articulations: the talocrural joint, the subtalar joint, and the distal tibiofibular syndesmosis. The bony anatomy of the ankle consists of the ankle mortise, composed of the tibia, the fibula and the talus. Some authors include the subtalar joint in the review of ankle anatomy, as it is unclear how much of lateral ankle instability is due to the tibiotalar joint and how much is due to the subtalar joint.[58] The three articulations work in combination to allow the multiplanar rearfoot motions of supination and pronation. In the closed kinetic chain, pronation consists of plantar flexion, eversion, and external rotation while supination consists of dorsiflexion, inversion, and internal rotation. In the open kinetic chain pronation involves dorsiflexion, eversion and external rotation, while supination involves plantar flexion, inversion, and internal rotation.[1]

Bony congruency is the primary contributor to ankle stability, but only when the ankle is weight-bearing. The remainder of the joint stability is comprised of the static strength of ligaments and the muscles and tendons that cross the joint.[1, 59] The ankle joint's neutral or close pack position is the most stable when the joint articulates congruently. In this situation, or in dorsiflexion, the tibia and fibula articulate with a larger portion of the talus because of the talus' wedge shaped anterior surface.[32]

Ligamentous anatomy

The lateral ankle ligament complex consists of the anterior talofibular (a thickening of the joint capsule), the calcaneofibular, and posterior talofibular ligaments.[4] Ligaments display a nonlinear and strain rate dependent load-deflection curve.[60] The anterior talofibular ligament's (ATFL) primary purpose is to prevent anterior translation of the talus on the fibula and ankle mortise. It is taut and parallel with the tibia when the foot is plantarflexed. It is parallel to the foot when the foot is in a neutral position.[4] Because of its anatomy and construction, the ATFL is the most commonly injured ligament. It has the highest failure rate of the lateral ligaments and the lowest maximum load to failure.[58] The calcaneofibular ligament (CFL) may be injured independently or in combination with the ATFL in severe ankle injuries.[4] The CFL only indirectly aids talofibular stability.[58] The posterior talofibular ligament is extraarticular[4] and is taut only in extreme dorsiflexion. It is not a great contributor to tibiotalar instability,[58] and is generally not included in the discussion of lateral ankle instability.

Etiology

Mechanism of Injury for Lateral Ankle Sprain

The typical mechanism of injury for a lateral ankle sprain is forced plantar flexion and inversion of the ankle during landing on an unstable or uneven surface. Lateral ankle sprains usually occur with hypersupination, resulting in sprained ligaments of the talocrural and subtalar joints.[1] During weight bearing, bony congruency establishes joint stability.[59, 61] However, prior to weight-bearing, during weight acceptance, the body must rely on ligamentous and musculotendinous sources of stability.[61] Since the ligaments and musculotendinous sources of stability are not as great as bony congruency, the common time of injury is during weight acceptance. The amount of instability due to the tibiotalar and the subtalar joint, or in some combination, is currently unknown.[1, 58]

Despite a lack of empirical information, anecdotal reports of sprains involve tripping and then spraining, so the swing phase of gait prior to heel strike may contribute to the mechanism of injury. Adults need 5mm of ground clearance for the heel/lateral foot during the swing phase, and most exhibit approximately 10 degrees of inversion during the late swing phase.[62, 63] If a large enough placement error in heel clearance or inversion occurs during late swing, a trip or injury may result.[63] Joint position sense error in a healthy adult population averages 1.7 degrees, and if that error is normally distributed, placement errors prior to heel strike of magnitude 8-10 degrees (large enough to cause an inversion injury) occur once every 100,000 steps. In individuals with ankle instability, mean joint position sense error is typically increased, so the chance of the same magnitude of position error prior to heel strike is reduced to once every 1000 steps.[62, 63] However, most individuals with lateral ankle instability are not that disabled, and the model does not include many important factors, such as muscle activation, shoe type, surface, and the fact that not every stumble results in a sprained ankle. But it does provide some explanation as to why individuals with ankle instability suffer sprains more often.[62, 63]

If the loading situation is correct and instability exists, the likelihood of a lateral ankle sprain occurring may be influenced by foot position at touch down. Increased supination at the subtalar joint is one model of lateral ankle sprain mechanism of injury.[1] If the foot is supinated before touch down, the ground reaction force moment arm around the subtalar joint may be greater, causing excessive supination and increasing the risk of lateral ankle sprain.[64] The ground reaction force moment arm about the subtalar joint axis is also increased with increased plantar flexion at touch down.[64] There is a greater supination moment from the vertical ground reaction force when the center of pressure is medial to the subtalar joint axis than in a foot where the center of pressure is lateral to the joint axis.[1] When the foot is unloaded, in an unstable talotibial joint position, and in subtalar joint inversion, any weightbearing force can cause an injury.[65] With increased supination comes inversion and internal rotation at the rearfoot when the foot is in the closed kinetic chain, and if the movement is beyond physiologic limits, injury occurs to the lateral ligaments.[1] Few studies have assessed the ankle/foot position prior to weight bearing. Using a forward dynamics simulation model, Wright et al.[64] found increased dorsiflexion at initial contact decreased the chances of an ankle sprain at larger torques and supination angles. Thus the inverse, increased plantar flexion at landing, increased the likelihood of ankle sprain in their model.[64]

The subtalar joint axis moves in a medial-lateral direction during the stance phase of gait. If the foot is everted, the axis moves medially, and when the foot is inverted, it moves laterally.[66] The line of action of the reaction force is close to the subtalar joint axis if the individual is unshod, and the ankle is not exposed to an externally imposed inverting torque. During weight bearing and inversion, an external load is produced at the ankle, forcing the foot into greater inversion. If the ankle is hyperinverted, the ankle itself creates inverting external torque, which can result in injuries. If that lever arm is longer than 3-4 cm, body weight becomes too much for the counteracting evertor/pronator muscles to overcome, and if shear force is added, torque around the ankle increases.[66] Adding shoe width onto that, the ankle is at even greater risk for hyperinversion because the lever arm length is increased due to the shoe, and shear force (horizontal force) is added from friction, increasing the torque on the subtalar joint axis.[66] This is an example of when an ankle would "give way" on an individual.

Description of Chronic Ankle Instability

Definition

Freeman first identified ankle instability in the mid 1960's.[2, 67] He identified individuals with a history of chronic incidents of lateral ankle inversion sprains who reported feelings of "giving way" at the ankle with possible pain and swelling. He attributed the clinical symptoms to deafferentation of the lateral ligaments, or tearing of the neural structures within the ligaments, resulting in decreased proprioceptive input from the joint.[2, 20]

Initially, the term functional ankle instability (FAI) was used to include those individuals who had the clinical symptoms of giving way and repetitive spraining. However, this definition did not account for or take into consideration mechanical ankle instability (MAI), or physiologic laxity of the lateral ligaments[48] that can be caused from a severe sprain or repetitive sprains. MAI is not always present in those with FAI,[10, 16, 20] and the relationship between FAI and MAI is unclear.[1] In a study of 444 soccer players, 159 ankles presented with FAI. Sixty-six of those ankles, or 42%, also had MAI as defined by a positive anterior drawer test.[48] Other authors have reported approximately 40% of individuals with FAI have no discernible MAI.[20] Pilot work in our laboratory supports that finding, as 36% of FAI subjects had MAI to clinical assessment. A study using instrumented arthrometry and stress radiographs found significantly greater anterior-posterior laxity in the functionally unstable ankle of 51 subjects compared to the uninjured (stable) contralateral ankle.[15] Another study using 115 CAI patients documented approximately 40% had FAI on radiologic exam and approximately 30% had MAI.[68] Thus, some degree of mechanical laxity may be present in all FAI subjects, but the relationship is unclear[15] and most hypothesize it is possible to have FAI in the absence of MAI.[1, 20]

The term chronic ankle instability (CAI) encompasses individuals with MAI, FAI or some degree of both.[1] Differentiating between MAI and FAI is not always easy. MAI is most often determined by stress x-ray or joint arthrometry.[15, 68, 69] The amount or degree of laxity required for diagnosis has not been established and is complicated by the range of laxity in the population.[16, 20] Establishing FAI is even more problematic. Most studies have used some form of subjective complaint of giving way with activity and feelings of instability at the ankle but may or may not have included other factors in the initial injury and subsequent development of FAI. Specifically, several studies' inclusion criteria included a history of acute sprain requiring a period of non-weight bearing, protected weight bearing, or immobilization.[9, 15, 18, 23, 28, 33, 70, 71] Only one provided a length of time (three days) for the weight bearing/immobilization requirement.[33]

Most previous studies have required CAI subjects to self-report feelings of instability, but the language varies tremendously. Phrases included feelings of instability and giving way,[70, 71] complaints of giving way at the ankle,[72] a tendency to give way,[31] and giving way and rolling with activity.[15, 19] The frequency of giving way and the associated time span varied tremendously, from 2 or more sprains total,[9, 18, 31, 72] to 2 or more episodes in the last 6 months,[71] to 2 or more episodes in the last 12 months.[19, 33, 70] Additional studies required at least 1 episode of giving way in the last 12 months.[73] to 2 or more sprains in the last 5 years.[23] Several studies have also included a causation clause: that the test limb must be weaker, more painful and have decreased function since the initial sprain in subjects with unilateral CAI.[9, 15, 18] Exclusion criteria have included no history of other lower extremity injury,[28] no acute episode of giving way for CAI subjects within the last 3 months,[33, 72] no current pain or effusion,[72] no history of fracture,[9, 15, 18] and no history of lower extremity surgery.[19, 33]

As the body of literature on CAI grows, the classification criteria for unstable ankle subjects become more stringent. The general consensus among researchers for a definition of FAI appears to be a history of acute inversion injury requiring protected weight bearing and/or immobilization. Following the initial sprain, repeated episodes of giving way at the ankle should have occurred, at least two in the past 12 months, with feelings of instability and giving way during activity. The test ankle should be subjectively looser, more painful, and less functional since the initial injury. The inclusion criteria for this dissertation project were based on these criteria.

Possible Damage Due to Chronic Ankle Instability

In the short term, CAI can cause pain, swelling and inconvenience. Some individuals with CAI may self-select out of activity after an episode of giving way or may avoid certain activities that perpetuate sprains. Many individuals never seek care for CAI, choosing to ignore or self-treat the symptoms without medical input.[5]

The effects of CAI on long term disability and joint health are unknown.[39] Unlike the knee and hip, primary ankle arthritis is rare.[40] Trauma is usually the cause, and chronic lateral ankle instability may play a role in the development of ankle arthritis. Incongruency or instability at the ankle joint over a long period of time may result in increased contact stress, which can damage articular cartilage.[40] McKinley et al.[41] proposed three causes of post-traumatic arthritis: “direct impact damage sustained by cartilage and/or bone,” chronic elevation of cartilage contact stress resulting from residular articular incongruency, and “pathologic loading resulting from articular instability.”

The relative contributions of instability and incongruity to abnormal stress are unknown, and there are many confounding factors.[41] Ankle degeneration is likely linked to instability because patients with CAI who have articular surface incongruity also have high incidences of posttraumatic arthritis. [41] Hinterman et al.[39] found increased lesions, degeneration, and defects in ankle cartilage in subjects with CAI. Of 148 patients who reported CAI for at least 6 months, 66% had cartilage damage evident during arthroscopic procedures, and 55% had talar cartilage lesions, the majority of which were medial.[39] However the talar cartilage lesions were not proportionate to the degree of lateral ligament injury.[39] Ankle ligament laxity may also create greater articular incongruency at the ankle. Talar displacement of more than 1 mm decreased the weight-bearing surface of the ankle by 42.3%, creating asymmetric loading of the articular surface. Only small amounts of articular displacement were necessary to create abnormal shearing forces.[58] The knee and ankle accommodate articular incongruities very differently. Defects in the distal tibial articular surface caused increased strain in the trabecular bone underneath the defect during static testing. This was not the same in defects of the tibial plateau. The authors attribute the differences to "joint geometry, osteoarticular stability, and/or cartilage compliance" to explain why opposite changes occur in trabecular bone strain adjacent to a cartilage defect.[41]

There are limitations in testing loading and strain on articular cartilage at the ankle, confounded by heterogeneous injuries and the difficulty in studying humans. One of the limitations is that static testing cannot capture the biphasic properties of cartilage load transmission (solid matrix and interstitial fluid).[41] Transient elevations in stress are not recorded during static testing, nor are stresses related to episodes of instability. Loading rates and loads that compound over a range of motion are difficult to determine.[41] Cartilage is very sensitive to loading rate, however, even with large incongruities, investigators usually find only small increases in articular surface contact stress.[41] Therefore, dynamic testing is necessary. McKinley et al.[41] used dynamic ankle testing of cadavers with coronal plane step-off of the distal tibia. The cadavers were axially loaded during normal plantar flexion-dorsiflexion motion, with a posterior directed force on the tibia, increasing the force until the talus subluxed anteriorly. The authors measured articular surface contact pressure using a dynamic pressure transducer. This preliminary data revealed peak pressure increases of up to 300% through most of the motion cycle, and from 100-500% during an instability event.[41]

Summary

The complex anatomy and biomechanics at the ankle, coupled with the difficulty in defining CAI, make it challenging to research. CAI has the potential to impart long-term damage to the joint and requires further study.

<u>Review of Literature Related to the Hypotheses</u>

Rationale for Study

Chronic ankle instability is most likely a multifactorial problem, with a number of potential causes and mitigating features. Identifying the factors that contribute to CAI is the first step to creating prevention and treatment plans[8] targeted to prevent osteoarthritis, surgery, degeneration, and pain and to keep people with CAI active. Since there is currently no proven effective method of treatment and no cure, this is an important step.[5] In order to achieve prevention, the injury and condition must be better described, including all the possible causes and resulting deficits.

Possible Causes of Chronic Ankle Instability

Historically, joint position sense, joint kinesthetic sense, muscle activity, and proprioception were thought to play roles in CAI.[1, 74] Other potential causes or factors include muscle weakness and subtalar instability.[17] Few researchers have investigated whether or not kinematic or kinetic factors affect, or are affected by, CAI. Previous work on establishing causes and factors has been inconclusive. One potential reason is that not all factors have been considered or studied simultaneously. Only one study has assessed ground reaction force in CAI subjects during jump landing.[18] Few have analyzed CAI subjects with EMG. Caulfield et al.[9] did find EMG differences between CAI and control subjects, but since no kinematic or kinetic data were associated in the paper, there was no confirmation that changes in muscle activation were related to changes in foot position and loading at landing. Without knowing if the previously mentioned factors play roles and what the relationships are between them, it is impossible to establish effective preventive and treatment strategies.[75]

Defining Ankle Stability Groups

Potentially, CAI studies have used confounding groups that could be masking results. Combining MAI and FAI individuals, and using controls that have never sprained an ankle or have not had a recent ankle injury, may not be the strongest method of comparison. Some ACL injury studies have used groups of "copers" or comparison individuals who are ACL deficient but do not experience knee instability as a control or comparison group to ACL deficient subjects who do experience instability. Thus, the researchers include groups with similar injury histories, but very different functional outcomes. Rudolph and Snyder-Mackler[37] found EMG differences in knee musculature between ACL deficient copers and non-copers (or unstable knee subjects) and control (ACL intact) groups. Using a comparison group of subjects with a similar initial injury history to study CAI may reveal significant results not found in previous studies.

Proprioception

Proprioception is defined as a "specialized variation of the sensory modality of touch that encompasses the sensation of joint movement (kinesthesia) and joint position sense."[46] Deficits in proprioception have been thought to play a major role in FAI since Freeman et al. introduced the term.[2, 67] When injury occurs to the lateral ligaments, the ligamentous tissue is stretched or torn. Nerve injury must also occur within or proximal to the lateral ligaments, due to its decreased elasticity compared to ligaments. This nerve injury may result in decreased skin and joint sensation, weakened peroneal muscles, and may also affect joint proprioception, balance, and postural stability. Nerve conduction time may increase after injury. All of these results, whether they occur independently or in some combination, would increase the likelihood of repetitive inversion injury whether or not mechanical instability is present after the initial injury.[20]

Postural Sway

Documenting proprioceptive deficits is very difficult and controversial. Measuring postural sway is one method of indicating proprioceptive deficits.[2, 10] Tropp et al.[76] recommended using "stabilometry" as a quantitative and objective way to measure postural stability. Maintaining an upright static stance requires feedback from peripheral sensory receptors.[77] If the feedback is slow or inaccurate, either before or after injury, sway may increase and thus increase the risk of repetitive ankle sprain. Increased postural sway in static stance was found to correlate with increased risk of ankle sprain.[24, 36] Tests of static unilateral stance and dynamic balance (a lateral step onto a foam pad followed by static stance) demonstrated the CAI group had greater center of pressure excursion in both tests compared to controls.[23] Increased sway was also found in CAI groups during single leg balance compared to healthy controls.[71]

However, a greater number of studies found no significant differences in amount of postural sway in CAI and control subjects. There were no differences in single leg stance sway or in eversion strength between limbs in a group of unilateral FAI subjects. There were also no differences between the FAI group and a group of control subjects.[28] A number of other studies reported no postural sway differences during single leg stance when comparing FAI and control groups.[29, 70, 76, 78, 79]

Joint Position and Joint Kinesthetic Sense

Two other methods of testing proprioception are to measure joint position sense (sense of a joint's position in space) and joint kinesthetic sense (sense of joint movement). Both were observed to be less accurate in CAI groups when compared to controls.[25, 80] In another study, joint position sense error doubled following ankle injury and remained 12 weeks after injury.[27] Vibration perception at the ankle was decreased in individuals with ankle sprains compared to uninjured controls.[26]

Joint position sense and joint kinesthetic sense testing do not have strong, established methods that are accurate and reliable. The error found in one joint position sense study after injury was statistically significant, but very small, calling the clinical application of the results into question.[27] An equal number of studies found no differences in joint position sense between CAI and control groups.[19, 30] The methods vary between studies, as does the subject population and characteristics, making comparisons very difficult.

Kinematics

Few studies have tested for differences in kinematic variables before or after ankle injury either as risk factors for injury or as functional deficits in individuals with CAI. Accordingly, only a few movements, such as walking, a step-up and over, and landing from a drop jump have been analyzed. Most studies involved motion analysis, however Wright et al.[64] used computer models to demonstrate that increased ankle dorsiflexion during landing from a side-step decreased the risk of ankle sprain. They also reported that increasing plantar flexion corresponded to lower torque values required to cause an inversion injury.[64] An important limitation in kinematic analysis at the ankle is that subtalar joint and talocrural joint motion are collapsed into general "ankle joint" motion. This model addresses many functional activities and related questions, but must be acknowledged as a limitation.[81] The motion analysis studies of CAI subjects are summarized below by movement task.

Gait Kinematics in Chronic Ankle Instability

During gait, CAI subjects exhibited kinematic differences at heel strike, foot flat, and in the variability of the gait pattern. If an individual exhibited more than 10 degrees of calcaneal inversion at heel strike, torque necessary to cause inversion injury was generated.[62] Because the heel clears the ground by only 5 mm during the swing phase, any small misjudgment in clearance and angle at contact may cause a stumble and subsequent sprain.[62] During the last part of the stance phase, the foot is plantarflexed, and therefore is less stable compared to the dorsiflexed position of early stance.[17] Slowing at the end of the stance phase could indicate compensation, providing more time to stabilize.[17] The authors also observed a lateral shift of the center of pressure, which if occurring during the unstable period, could result in a sprain. Subjects with unilateral CAI demonstrated bilateral differences, supporting a "central pattern" theory of controlling stance.[17] In another study on gait, CAI subjects had much more variability and more dorsiflexion at toe-off compared to controls.[32]

The CAI subjects also exhibited more plantar flexion during foot contact, increasing the ankle's instability by unlocking the mortise.[32]

Step-up and Over

Other tasks have revealed differences in individuals with CAI. During a step-up task, CAI subjects exhibited higher toe raising when placing the foot on the step compared to controls. The authors theorized subjects could be trying to avoid inadvertent contact with the step, thus avoiding a step/stumble mechanism of injury commonly seen in CAI subjects.[32]

Jump Landings

In tasks involving landing from a drop jump off a box, subjects with CAI exhibited more dorsiflexion 10 ms before initial contact, at initial contact, and 20 ms after initial contact when compared to controls. Those differences were continued up the kinetic chain, as CAI subjects exhibited significantly more knee flexion from 20 ms before initial contact to 60 ms after initial contact.[31] Caulfield and Garrett[31] assessed kinematic differences in the 100ms before and 200ms after initial contact, divided into 10ms long bins for each of the 5 trials.

These few studies indicate some inherent movement differences in individuals with CAI, but none of them have addressed other mechanisms of injury, such as running and landing from a stop jump. There was also no separation of subjects into MAI and FAI groups, so results may not apply to all individuals with CAI.

Kinetics

Kinetic analysis of individuals with CAI has been limited to time to stabilization and a small number of studies on gait and jump landing. Time to stabilization, or the amount of time required to stabilize ground reaction forces into a small range following a jump landing, was longer in the anterior-posterior direction in CAI subjects compared to controls.[19, 42, 78] CAI subjects may not be able to dissipate landing forces quickly enough, remaining in an unstable state longer, increasing the chance of injury.[19]

When FAI subjects jumped off a box and performed a single leg landing on a force plate, there were significant differences in the timing of peak forces and in the magnitudes of time-averaged forces.[18] In the 0-50 ms period after initial contact, peak lateral forces occurred 13 ms earlier in the unstable ankle group. That group also had more laterally directed forces of 5-15% body mass while the control subjects exhibited medially directed forces. Vertical ground reaction force onset was faster in the functionally unstable group (during the first 35 ms after initial contact).[18] The authors hypothesized that these differences were due to faulty pre-programming of ankle joint movement pre- and post-landing, resulting in increased stress to the ankle joint during landing and repetitive injury or damage to structures. Previous work by the same group found more knee flexion and ankle dorsiflexion during landing, but the angular velocity of knee flexion and ankle dorsiflexion was slower after initial contact. The CAI group was less able to absorb force during landing. If the CAI group was not able to successfully accept weight and control how quickly the joint was loaded, increased stress could be placed on the articular cartilage. Deficits in position sense at the ankle before impact may cause difficulties in adopting the "optimal foot position" for force absorption during landing.[18] The authors recommended motor retraining to establish safer landing characteristics because the CAI group could not predict the consequences of their motor commands in terms of anticipated sensory consequences. The goal would be to correct sensory feedback to motor commands when landing from a jump, retraining muscles to accept the weight.[18]

A gait study comparing CAI to controls reported significant delay to time of peak force under the central and lateral forefoot and toes in the CAI group.[17] The CAI subjects also demonstrated longer contact time at the heel and mid-foot areas.[17] This slower weight transfer from the heel to the forefoot meant slower transfer from heel-strike to toe-off in the CAI group, who hesitated before transferring the weight to the forefoot.[17] The slower transfer may be an adopted strategy to increase control over the talocrural joint and assist the musculotendinous and ligamentous sources of stability during gait.[17]

Electromyography

The majority of research using electromyography (EMG) to investigate CAI has centered on the dynamic defense mechanism and the peroneals' electromechanical delay or reaction to a sudden inversion force. A smaller body of work has measured activity during planned movements. Unexpected inversion forces, usually involving some type of trap-door mechanism, occur too fast for the peroneals to react and "save" the ankle.[61] The body's dynamic defense mechanism is engaged upon inversion. In this centrally mediated movement strategy, information from the peripheral receptors is used and helps modify the response for the specific situation. Ipsilateral activation occurs first, followed by contralateral. Additionally, there may be some anticipatory muscle "pre-activation," but the mechanism of injury occurs in less than 50 ms, meaning the peroneals are too slow to react and evert the ankle to avoid inversion injury.[61]

Electromechanical Delay

If that mechanism of injury time is extended at all, as when the foot slips inside the shoe or the shoe slips on the support surface, increased muscle activation over a long time period could evert the ankle and save it from injury. Increasing muscle stiffness at the joint lengthens the time and increases the force required for ankle injury, effectively protecting the joint from injury.[61] Individuals with CAI may not benefit from this added protection however, if the electromechanical delay associated with peroneal activation is increased due to nerve damage. CAI subjects have exhibited longer electromechanical delay compared to controls after perturbation.[82-84] Using a trap door causing 50 degrees of ankle supination, Vaes et al. found the CAI group had significantly shorter total supination time (109.3ms vs. 124.1ms) than the control group as well as longer muscle latency times (58.9ms vs. 47.7ms) than controls.[84] Mora et al. defined electromechanical delay as the time interval between the onset of peroneal EMG activity and the onset of ground reaction force in the medial-lateral direction during stance. Onset was defined as baseline muscle activity level plus two standard deviations. The authors reported the CAI subjects' delay was significantly longer than controls.[83]

Decreased ankle stiffness and peroneal weakness in CAI subjects might increase delay.[83] These findings support Freeman's theory of deafferentation after lateral ankle sprain.[2, 67]

Muscle Stiffness

Afferents in the ligaments help continuously control muscle activity, regulate articular stability, and contribute to the pre-programming of muscle stiffness. If a proprioceptive deficit exists, altering, slowing, or stopping afferent information, the peroneals' delay might be lengthened. This could slow the increase in muscle stiffness necessary to protect the joint.[83] One study using EMG reported the CAI group had a higher background of peroneal and soleus activity during single and double leg stance, evidence that pre-programming of muscle stiffness may be altered after injury. Motor control of ankle stability changed with CAI to adapt and compensate for lower intrinsic musculotendinous stiffness by supra-activating in the leg in order to maintain single leg stance.[83]

Other authors support the idea of neuromuscular deficit associated with CAI in which subjects have a compromised ability to maintain cocontraction joint stiffness and stability.[85] If the activity level is high enough in the motorneuron pool and/or gamma muscle spindle system, low threshold mechanosensitive ligament receptors can create significant changes in EMG activity.[86] This theory offers a potential mechanism of how individuals may develop strategies to cope with injury. Individuals with nervous tissue damage following an ankle sprain may increase the motor neuron pool activity and muscle spindle sensitivity to increase muscle activity. They increase the role of musculotendinous structures in providing stability and "clamp down" on the ankle in response to losing afferent information and possibly mechanical stability.

Muscle Activity During Planned Movements

During planned activity, such as single leg landings from a jump, differences in EMG were also found between CAI and control groups. Subjects performed single leg downward jumps and single leg jumps for distance.[9] Using integrated EMG, the FAI group demonstrated reduced peroneal activity compared to controls during the pre-impact period for both types of jumps. No differences were observed in the post-impact period in the peroneals or any other muscle tested.[9] The authors found that pre-activity, or feed-forward muscle activity, was important for ensuring dynamic stability.[9] Unfortunately, the sample size was small for this study and neither a-priori nor post-hoc power and effect sizes were reported.

Alterations in EMG activity after injury have also been found in proximal muscles. Subjects with a history of severe ankle sprain exhibited delayed and decreased hip muscle activation during hip extension, as well as increased variability in muscle onset order.[21] Additionally, a study using a group with history of ankle injury and talocrural hypermobility found the injured group recruited hip muscles earlier following perturbation. These subjects exhibited a hip dominant balance strategy compared to controls.[87] Limited research has analyzed muscle activity's contributions to stability during dynamic, functional tasks that are also inversion mechanisms of injury. If deficits do exist, this may be one area to focus on treatment of CAI and prevention of CAI after acute ankle sprain.

Other Possible Factors in Ankle Instability

Range of Motion

Testing for range of motion differences that may predispose or perpetuate CAI is stymied by the different methods in each study. McKnight and Armstrong[34] found no differences between FAI and control groups in range of motion at the ankle using a goniometer. However, in a prospective study, the uninjured group had less dorsiflexion with knee extension than the injured group.[12] A study using instrumented arthrometry and stress x-ray found no difference in inversion rotation, talar tilt, or total inversion-eversion rotation between the injured and uninjured ankle in a group with unilateral FAI.[15] The limitations of the literature include the method to measure range of motion (goniometer or other instrument), motion measured (direction and passive vs. active), position of measure (supine, seated, or while moving).

Strength

Many of the same limitations from range of motion apply to the strength literature as well. Differences in mode and position of testing, as well as the variable measured, make comparisons between studies difficult. Whether or not strength differences are actually present in individuals with

CAI is contested in the literature. No differences were found in peak torque in the planar directions,[36] or in concentric strength and work in plantar flexion, dorsiflexion, inversion, or eversion between control and FAI groups.[34] There were no differences in peak torque between the injured and uninjured limb in a group with FAI or between the FAI group and controls.[28] Controls and unilateral FAI subjects were tested on concentric and eccentric eversion at 0, 30, 60, 90, 120, 150 and 180 degrees per second with an isokinetic dynamometer and no differences were found.[88] When ratios of strength were tested, however, the ankle injury group had higher inversion to eversion ratios, higher plantar flexion peak torque, and a lower ratio of dorsoflextion to plantar flexion peak torque.[12] A CAI group also exhibited lower relative eversion strength as a percentage of body mass.[25]

Most early literature tested only concentric strength, and focused on the evertors as the mechanism to overcome inversion torque occurring during ankle hypersupination.[55] More current research is focusing on eccentric invertor deficits in CAI subjects. The invertors act eccentrically to assist in controlling lateral postural sway and thus limit closed kinetic chain eversion.[35, 55] If the lateral displacement of the shank is limited, an individual can prevent the medial border of the foot lifting off the ground, thus preventing the foot and ankle from going into rapid inversion.[35] If eccentric weakness exists in the invertors, they may not be able to stabilize the ankle. Munn et al.[35] found eccentric inversion strength deficits in a CAI group but no evertor weakness. Deafferentation may be one mechanism for invertor weakness.[35]

Review of Literature Related to Methods

Groups

For inclusion into the CAI or FAI group, most previous studies have used some form of self-report data. Subjects had to have a history of one or more traumatic ankle sprains that required protected weight bearing or immobilization.[9, 15, 18, 23, 28, 70, 71] Subjects also had to have a history of repeated episodes of the ankle spraining or giving way with activity;[15, 28, 71] typically the number of episodes was two or more.[9, 18, 31, 72] Several studies included a time component in which the episodes of instability had to occur. Most often it was two or more in the past 12 months,[19, 33, 70] although other studies required two episodes in the last 6 months,[71] one episode in the last 12 months,[73] or two or more episodes in the last five years.[23] Subjects were also required to report weakness, pain, and decreased function in that ankle[9, 18] secondary to the initial sprain.[15] Subjects had to be able to walk or perform other athletic activity without limping,[15, 73] and demonstrate basic functional capabilities, such as 42 or more degrees of plantar flexion[72] and no pain or effusion.[19, 33, 72] Subjects in certain studies were excluded if they had a recent ankle sprain or episode of giving way that might confound the existing injury, such as an acute episode within the last three months[72] or a history of ankle fracture.[15]

The consensus among previous studies appears to be individuals with CAI must have a history of a traumatic ankle sprain requiring protected weight bearing that developed into repeated episodes of giving way. At least two episodes of instability in the last 12 months is evidence of that instability, coupled with pain, weakness, and loss of function secondary to the initial sprain. Excluding subjects with those factors should control for confounding factors such as ankle fracture, severe limitation in range of motion, or current swelling at the ankle. Thus, these common criteria were followed for this project.

Determining Ankle Instability

Although there is no gold standard for measuring or classifying CAI, most of the studies above used some type of self-report instrument. Some authors designed their own questionnaires, requiring either yes/no responses[15] or offering a Likert-type scale with a response score range to determine inclusion or exclusion.[22, 33] The Ankle Assessment Questionnaire asks subjects to rate their ankles' ability to perform different daily living and sport tasks.[33] CAI groups scored significantly lower on the questionnaire in a time to stabilization study[33] and in other preliminary work done in the lab indicating decreased ankle function. The Foot and Ankle Disability Index and its Sports subscale have also been used. In preliminary work, it was reliable in detecting functional deficits in CAI subjects over 6 weeks and sensitive to differences between CAI subjects and controls. The CAI group scored significantly lower than the control group, and the index demonstrated moderate to high sensitivity to changes in function after rehabilitation.[89] Though none of these instruments have been proven valid or reliable in large, diverse populations, they have separated subjects into groups that demonstrate significant differences on the dependent variables studied, so they appear to be crudely effective.

Alternate "Control" Groups

Most of the literature reviewed has compared CAI groups to controls with no previous ankle injury or no history of repetitive injury.[9, 18, 19, 31, 33] Some studies compared the contralateral uninjured side to the injured side in subjects with unilateral CAI.[15, 28] Limitations in using a control group include matching on a number of confounding factors, including age, height, weight, gender, limb dominance, injury history, history of physical activity, and type of activity. When testing the contralateral side, centralized changes in motor patterns may mask any differences in variables between limbs.[17]

Some authors have tried to circumvent these difficulties by comparing the CAI group to a group of individuals with a similar initial ankle injury history but no complaints of instability. Comparison subjects have a similar history of traumatic ankle sprain requiring protected weight-bearing and/or immobilization but did not develop CAI or experience repetitive ankle injury after the initial sprain. Researchers studying anterior cruciate ligament (ACL) injury have used similar methods to study neuromuscular control differences among those with ACL deficiencies. These researchers separated subjects with ACL deficiencies into those with functional deficits after the injury and those who had no functional deficits, or "copers."[37, 38, 90] Similar methods have been employed successfully in CAI research. A group of comparison subjects who had one to three ankle sprains within the past two years but did not develop instability were assessed and compared to a group with CAI.[25] Strength and joint position sense were measured in both groups. A history of previous ankle sprain was the number one risk factor for CAI. The authors found no differences in strength or joint position sense between the comparison group and a control group with no history of ankle sprain.[25] Using a comparison group presents a method to control injury history and investigate different functional outcomes.

Tasks

This project used a series of tasks involving daily living activities as well as more sport-related physical activities. Most studies of CAI have assessed primarily jump landing, the most common mechanism of injury. However, there are many other mechanisms, including walking, stair climbing, and running that have not received much attention. The following summarizes the CAI literature related to each task.

Walking

Few studies have used walking as a task to test for differences in a CAI population. CAI subjects demonstrated different walking patterns, with some "hesitation" during the end of the stance phase.[17] The subjects bore greater loads on the lateral forefoot, creating a lateral shift in the center of pressure. There were no differences between the injured and uninjured side in the CAI group, therefore the authors attributed the differences to changes in central control.[17] Another study on CAI subjects' gait revealed increased plantar flexion during foot contact and increased dorsiflexion during toe-off compared to controls. However, there was no change in knee angle to compensate for the altered foot kinematics. The CAI subjects also displayed a longer stance time than controls and more variability in gait characteristics.[32]

In general studies on gait, subjects walked at self-selected or set speeds.[53, 91] Vertical ground reaction forces demonstrated a two-peak pattern, with the first peak at heel strike averaging 650N and the second at toe-off about 600N.[91] The time to the first peak vertical ground reaction force (normalized to 100% of the stance phase) was 21.43 ± 2.7%. Time to the second peak was 49.23±2.81%.[53] Subjects in this study walked for 30 minutes and the authors used coefficient of variation to test for the percent variance that occurred in different portions of the stance phase. During the 30 minute test period, 5.4% was the highest variability in gait ground reaction force recorded.[53]

Step-Up and Over

Only one study to date has investigated CAI populations performing step-ups. The author found CAI subjects exhibited a higher toe raise during the task, possibly trying to avoid inadvertent contact and a step/stumble mechanism of injury.[32] CAI subjects also exhibited a decreased braking force at the foot on the step-up compared to controls and decreased plantar flexion at toe-off.[32] Alterations in gait may be compensations for deafferentation at the ankle.

Stepping is a more common task in ACL studies to measure functional deficits, but the requirements of the step task vary widely between publications. In a study of EMG during stair climbing, subjects performed 10 trials, 5 ascents with each foot, starting 40-50 cm away from the step of height 26cm. After stepping up and over the subjects continued straight ahead walking for four steps. Muscle onset, time of peak activity, termination of activity, and cocontraction were measured.[37] Other studies on control subjects have used different stair stepping specifications. Recreational athletes performed two approach steps, with the step 50% of the subject's stride length away from the forceplate. The subjects landed with heel strike to get full foot contact. The walking speed was standardized to 1.34 m/s using laser timing, with forceplate collection frequency at 480Hz. Using 11 females and 4 males, average peak 1 force was 15.96± 2.78 N/kg and peak 2 was 16.26±1.98 N/kg.[92] Standardizing gait speed and step height and length should decrease some of the variability in these tasks.

Running

No studies to date have used running as a test task for CAI subjects. A previous running study used 11 control recreational female runners who demonstrated heel-strike gait.[93] The forceplate was set to collect at 500Hz with a lowpass 4th order Butterworth filter and a cutoff frequency of 100Hz. The runners demonstrated peak impact forces of 1.66 times body mass and a push-off peak force of 2.35 times body mass.[93] A fine wire study on running EMG had an N of 15 subjects.[94] The authors used a bandpass filter of 100-1000Hz and a sampling frequency of 2500Hz. The data was normalized to a 1-second peak manual muscle test. The run was divided into the stance phase, early swing, midswing, and late swing phases with 20ms expressed as a percentage of the normalized base.[94]

Jump Landing

Landing from a jump has been used extensively in the CAI literature and those findings are detailed in the previous *Kinematics* and *Kinetics* sections. The following is a summary of the methods most often employed to study jump landing. There are several types of jump landings; the ones we will focus on include a drop jump, or jumping off a box to land from a specific height, and the stop jump consisting of an approach run, two-footed landing, and immediate take-off into a vertical jump.

Drop jumps have been used often because they easily standardize height of the jump and subject technique. Caulfield and colleagues have used this technique in their publications.[9, 18, 31] Subjects included soccer and gaelic football athletes with FAI but no MAI who drop jumped from a box 40 cm high to compare ground reaction forces to control groups.[18] The sampling frequency was 500Hz. Five trials of single leg landings were performed, analyzing the 150ms after initial contact. No instructions were given to standardize the jump height off the box. Ground reaction force was normalized to body mass, and the dependent variables were the magnitude and timing of peak medial-lateral, anterior-posterior, and vertical of the ground reaction forces. Individual and group means were calculated and no significant differences in the magnitudes of peak vertical ground reaction forces normalized to body mass were found between groups. The FAI group had earlier peak forces than the controls on average, and there were no differences in the timing of peak medial, vertical, or posterior forces after impact. The authors did observe significant differences in medial-lateral forces at 30-40ms after initial contact amounting to 5-20% of subjects' body mass. The FAI group demonstrated more lateral force. In the anterior-posterior direction, there were significant differences at 44-50ms after initial contact with similar percentage differences. The FAI group demonstrated more posterior ground reaction forces. In the vertical direction, differences were found at 24-36 and 85-150ms after initial contact up to 100% body mass with the FAI group exhibiting larger forces. Not all FAI subjects exhibited differences, but the group average was larger than the control subjects. Analyzing the ground reaction force in bins allowed these authors to identify differences they might have missed had they collapsed the time period after initial contact for analysis. The authors attributed the differences to faulty pre-programming of ankle joint movement pre- and post-landing. The increased forces result in increased stress on the ankle joint during landing, thus repetitively injuring and damaging structures.[18]

In a similar study using EMG measures, subjects performed drop landing from a 0.6m height.[95] The authors observed soleus activity began 150ms before landing with the medial gastrocnemius initially bursting at 160ms before impact and the tibialis anterior at 170ms before.[95] Pre-activation time seems to vary between muscles and subjects, so a large enough time window is necessary to capture all the pre-activation activity.

The vertical ground reaction force reported varies by type of jump, but it is at least more than one multiple of body weight and has been reported up to 4.5 times body weight.[96] No CAI literature has used the stop jump as a task, but it has been used in ACL injury research. In the stop jump, subjects perform an approach run up to 5 steps at maximum velocity, take off of one leg, land with two legs (one on the forceplate and one lateral). This landing is immediately followed by a 2-foot takeoff for maximum vertical height and minimum anterior-posterior displacmenet.[51, 97] The horizontal velocity, anterior braking force directed at the ankle, and similarity to mechanisms of lateral ankle sprains make the stop-jump a good task likely to elicit deficits in a CAI population.

A combination of the drop jump and stop jump maneuvers, in which the subject jumps down and some distance anteriorly, has been used to investigate landing techniques. Seegmiller and McCaw[98] tested 10 recreational female athletes and had them jump off a 30cm high box onto a forceplate 21cm away. Subjects landed with two feet but only the right side was assessed and on the forceplate. The sampling frequency was 960Hz and 10 trials were performed, for an average peak force of 9.46 ± 2.13 N/kg. The second peak force at heel contact was 21.51 ± 4.88N/kg.[98] The subjects then jumped off 60 and 90 cm high boxes, demonstrating increasing vertical ground reaction forces at the first and second peaks. In comparing the recreational athletes with gymnasts, the authors concluded that any box height below 40 cm resulted in “careless” landing techniques.[98] Thus a box height of at least 40 cm was recommended to elicit more challenging landings.

Electromagnetic Tracking System

Electromagnetic tracking systems have been used previously to quantify joint and limb segment motion of the lower extremity while performing a number of tasks. Woodburn et al.[99] used an electromagnetic tracking system to assess ankle motion in controls and those with Rheumatoid arthritis. Ten healthy subjects were tested with sensors placed on the tibia and calcaneus. This preliminary work demonstrated face validity and sensitivity in measuring ankle kinematics with the tracking system. This dissertation project followed a similar axes system and set up as established in this paper.[99] Calcaneal inversion/eversion was measured with a sensor placed on the posterior inferior portion of the calcaneus in an open space cut out from a shoe, since placing sensors on the shoe was not thought to accurately capture foot motion. Subjects took one step per trial and performed 5 trials, for a CMC value of greater than 0.8 for all three planes, which was accepted by the authors.[99]

Innovative Sports Training, the manufacturer of the Motion Monitor software running the tracking system, provides guidelines for sensor placement when testing lower extremity kinematics. The sensors on the sacrum, lateral thigh, anterior tibia, and dorsum of the foot followed these guidelines.[100] No study to date has published data on CAI subjects using a sensor placed on the calcaneus. The manufacturer gives no specifics about what types of ankle joint motion may be captured. The ankle joint is composed of the talocrural and subtalar joints, and an ideal instrument would be able to separate and quantify those movements. However, due to marker size and technological limitations, only gross "ankle joint movement" were recorded and analyzed.[81]

Determining Joint Laxity

The electromagnetic tracking system will also be used to quantify joint laxity or mechanical instability at the ankle. There are no studies using electromagnetic tracking systems to quantify ankle joint laxity, but previous literature has used motion capture devices to measure laxity in the shoulder.[101, 102] Without instrumented measurement of laxity, clinicians and researchers have relied on "feel" of laxity at the joint and radiological assessment. Because of the subjective nature of "feel," and the two-dimensional nature of radiographs, three-dimensional translation of joints may not be captured accurately during exam.[101, 102] As at the ankle, data regarding normal variability and magnitude of shoulder laxity is not well defined, thus one study attempted to quantify that laxity using clinical tests.[101] Sensors were pinned to the scapula and humerus in several volunteers' healthy shoulders, then different clinical tests of glenohumeral laxity were performed while measuring the magnitude and direction of glenohumeral joint movement.[101] Means and standard deviations of movement for those tests were 8±4 mm for anterior drawer, 8±6 mm for the posterior drawer, and 11±4 mm for the sulcus sign.[101] Variability between subjects was quite high and varied between tests, however intersubject reliability was reported as "high." No statistical analysis of reliability was performed, instead the assertions were made based on visual inspection.[101] The authors documented the largest translations when the shoulder capsular restraints were in the laxest positons.[101] Shoulders that were lax on one clinical test, tended to be lax on all the others as well.[101] The authors also noted the variability in laxity between healthy subjects, and recommended more studies detailing the distribution of laxity in the normal population.[101]

A similar study used 20 unimpaired control subjects to measure glenohumeral translation.[102] Applied forces of 181-203 N were required to reach capsular end-point, and force-displacement curves were generated.[102] Intertrial intraexaminer intraclass correlation coefficients (ICC) (2,1) were reported as 0.98 for anterior translation and 0.96 for posterior translation.[102] In this study, translations were 14.5±2.3mm anteriorly and 14.0±2.8mm posteriorly.[102] Applications for this measure included developing a consistent clinical evaluation in force imparted, understanding the force required to reach capsular endpoint, and more reliable clinical evaluation.[102] Limitations included measurement error, changes in the rate of force application, and muscular tension that limited translation.[102]

While no publications to date have used the Flock of Birds to test ankle laxity, it has been used in the shoulder and may be applicable to the CAI population.[101-103] Stress x-ray is the gold standard for testing ligamentous laxity, but that procedure is costly and may be invasive. After ankle sprain, the ligaments involved and amount of damage present may be determined by using magnetic resonance imaging (MRI), but the imaging is not correlated to the degree of instability present and cannot replace exam and x-ray at this time.[69] Using the electromagnetic tracking system may be a faster and less invasive alternative.

Grading scales for laxity have ranged from clinical observations[10, 12] to instrumented arthrometry and stress x-ray.[20] There is no consensus, however, as to what values determine mechanical instability instead of functional instability.[16, 20] Hubbard et al.[15] used an instrumented ankle arthrometer coupled with a Telos device to provide constant force on the joint. Measuring ankle subtalar joint displacement for anterior-posterior displacement required 125 N and inversion/eversion rotation required a 4 Nm load. The Telos was set to 15 kiloponds (kp or kilograms-Force) to provide anterior or lateral stress. The total anterior-posterior displacement in the injured ankle was 19.8±5.1mm while the uninjured ankle displacement was significantly smaller at 18.3±4.4mm. For just anterior displacement, the injured side was also significantly greater than the uninjured side: 12.1±3.1mm vs. 11.1±3.2mm. In this study stress radiographs exhibited significant differences as well. The injured side's anterior displacement was 6.9±2.5mm in the injured side vs. 6.2±2.2mm in controls. There were no differences in inversion-eversion range of motion, inversion rotation, or talar tilt between the injured and uninjured side in the FAI subjects. The stress x-ray also did not reveal significant differences in inversion talar tilt angle.

Other work involving the Telos included laxity measurements pre- and post-surgery to repair lateral ankle instability. Colombet et al.[13] used 120N of force to measure lateral ligament laxity. The surgical candidates exhibited 17mm of displacement before surgery and only 4mm after surgery, thought he authors do not detail in which direction. The Telos provided a supinating force of 15kp in another study on the reliability of ultrasonography to measure fibular ligament rupture.[14] Of 115 patients with CAI who had a stress x-ray with the Telos, researchers demonstrated 4 degrees of lateral tilt in the uninjured leg and 7.6 degrees in the injured leg, which was significantly different.[68] The posterior opening to modified anterior drawer test at the tibiotalar joint was 4.7mm in the uninjured leg and 5.6mm in the injured side.[68] Nyska et al.[20] recommended a minimum five degree side-to-side difference in talar tilt and a 4 mm difference in anterior drawer as the upper limit of normal. Normative data on male and female athletes reported talar tilt values of 1.07±3.20 and 1.48±3.25 degrees respectively with 15 daN of force.[104] There is a large variation in normal and abnormal measures of ankle laxity. Due to this range, defining a cut-off point for MAI is difficult.[16] Taking the range of observed values and the literature into account, cut-off values of 5 mm of anterior displacement and 7 degrees of talar tilt seem to match the most recommendations.[20, 105]

Using electromagnetic tracking systems to measure ankle ligamentous laxity offers biomechanical researchers an opportunity for a non-invasive, on site alternative to stress x-ray. Initial data for the shoulder indicates it is possible and that the measure has face validity and good reliability.[101, 102] The range of movement measured in the laxity testing is within the accuracy and sensitivity limits of the hardware and software and is more than skin artifact.[100, 106] Initial data in the shoulder also appears to be clinically significant.[101, 102] Initial data collected for this study will be a start in establishing face validity and intertribal reliability. Comparing electromagnetic tracking system measurements of ankle joint laxity to the gold standard stress x-ray is beyond the scope of this project. Establishing normative data in a large population of MAI, FAI, and healthy controls is also beyond the scope of this project. However, the subject pool that will be tested in this study can serve as a start in determining the feasibility of using the Flock and Motion Monitor software to measure joint laxity.

Electromyography

Electrode Placement

A number of techniques and recommendations have been used to standardize electrode placement.[107] For the tibialis anterior, Basmajian and Blumenstein[108] recommend centering the electrodes over the muscle belly 1-2 finger breadths from the tibial tuberosity. However, they state the electrodes can also be placed more distally, down to the mid-shaft of the tibia.[108] Others recommend 4 fingerbreadths distal to the tibial tuberosity and one fingerbreadth lateral to the tibial crest.[109] More objective measures include placing the electrodes 1/3 the distance of the lower margin of the patella to the lateral ankle, or 75% of the distance between the lateral popliteal fossa and the lateral malleolus.[110] Other authors have placed the electrodes over the muscle belly approximately 12 cm below the fibular head.[95]

Electrode placement on the peroneals was recommended to be 3 fingerbreadths below the fibular head toward the lateral aspect of the fibula.[109] Alternatively, the electrodes may be placed at the 25% mark of a line drawn between the fibular head and the lateral malleolus.[108]

For the gastrocnemius, the electrodes are to be placed “almost anywhere” over the muscle belly of either head of the muscle[108] or over the most prominent part of the muscle head.[95] Delagi et al.[109] recommend one handbreadth distal to the popliteal crease over the lateral gastrocnemius. Placing the electrodes 1/3 of the distance from the head of the fibula to the heel has also been recommended, as well as 30% of the distance from the lateral popliteal fossa and the calcaneal tuberosity.[110]

To measure soleus activity, the electrode placement would be just medial to the Achilles’ tendon, at the mid-point in the length of the leg, although sensors may also be placed laterally to the tendon.[108] Delagi et al.[109] provided similar guidelines, with placement distal to the gastrocnemius belly and medial and anterior to the Achilles' tendon. Additional recommendations include 50% of the distance between the head of the fibula and the calcaneal tuberosity.[110] More specific recommendations include the distal 1/3 of the muscle, approximately 16 cm proximal to the calcaneus.[95]

Period of Measurement

The period of time necessary to capture relevant EMG data depends on the task performed. When landing from a height, leg muscle activation increases in amplitude prior to landing, and that amplitude is related to the drop height and is timed for initial contact.[44] The muscle activity is not reflexive, but pre-programmed.[44] In a comparison of jump landings between skilled and unskilled jumpers, 3 total seconds of data were collected around initial ground contact.[45] The tibialis anterior, lateral gastrocnemius, and soleus all pre-activated within 200ms of initial contact and continued activation after landing.[45] A similar study collected EMG for 80ms before initial contact and 100ms after.[111] Most soleus activity occurred after initial contact and before the termination of ankle joint rotation, but the tibialis anterior remained active even after joint rotation ended. EMG activity also began 200ms before initial contact in this study.[111]

For a drop jump landing, data was collected for 100ms before and 300ms after landing.[112] A similar task required data collection from 300ms before to 300ms after initial contact.[9] Using a false-floor landing surface, post-landing EMG occurred 35-80ms after initial contact.[44] The tibialis anterior was active in the first 50 ms after initial contact, with peak activity occurring around 26ms. These authors also observed EMG activity in the 200ms before initial contact and recorded for 200ms after initial contact.[44]

In activities such as downhill walking and running on a treadmill, pre-activation of the quadriceps, hamstrings, and gastrocnemius was assessed in the 150ms period prior to foot strike.[113] Downhill walking speed was 0.92m/s and running was 2.08 m/s.[113]

The methods for measuring EMG of lower extremity muscles during planned and reactionary movements vary considerably between authors and tasks. Most authors have utilized the tibialis anterior and soleus muscles,[9, 45, 111, 112, 114-116] however the gastrocnemius has also been utilized frequently.[45, 112-115] The peroneals have rarely been included.[9, 19] The period of measurement also varies by task and author. Most authors have used some range of time before and after initial ground contact. Several studies analyzed the period 100 to 150ms before and/or after initial contact,[9, 112-116] while others have extended that time period to 200 to 250ms before and/or after initial contact.[45, 96, 111, 112] Still other authors have extended that time period further, to 500ms before [111] and even up to 900ms after initial contact.[115] Considering this range in the literature, a representative data collection period for EMG would be 250ms before and after initial contact in order to capture pre- and post-activation muscle activity without collecting data that is not relevant to the kinematic and kinetic data of interest. Visual inspections and pilot testing can also be used to truncate the EMG data analysis period following collection if it appears the activities of interest are occurring closer to initial contact within that time frame.

Processing the Data

In order to compare EMG between subjects it must be normalized to some value. A study assessing gender effects on the preactivation levels of hamstrings and the gastrocnemius used a maximum voluntary isometric contraction (MVIC) to normalize data.[113] Other processing and filtering techniques vary widely between researchers and are not standardized. Caulfield et al.[9] used a sampling frequency of 2000Hz, a bandpass filter of 20-500Hz, rectified, and averaged the data over a 15ms moving window. The 5 test trial data files were then normalized to the average maximum amplitude found in those 5 trials. Integrated EMG was found during a 150ms linear envelope on either side of initial contact.

Variability

Background

Accomplishing human movement requires complex systems and constraints that interact and coordinate the degrees of freedom of movement to create variability. Individual variability is a result of the structure or function of the biological system in that individual that interacts with the task and its constraints, the environment, and the individual's psychological state. All of these factors, independently and in combination, contribute to individual variability in movement. In order to control variability, the degrees of freedom in the task and the system must be controlled, and as systems get larger (eg cellular to organism level) the number of degrees of freedom increase.[117, 118]

Movement errors can originate from a number of sources, including program selection, scaling errors, and random noise or peripheral error.[117] Variability may arise from anatomical, neural, or mechanical sources. The different types and sources of variability are not well documented in the motor control literature.[118] Historically, movement variability has been treated as a source of error in movement measurement and is therefore undesirable for prediction or differentiation of groups.[117, 118] This view is held in a number of motor control fields, including kinetics, kinematics, motor programs, and feedback.[118] However, error and variability are not necessarily the same quantity, and variability may not be detrimental. Dynamical systems studies hold a different view of variability. In system control issues, noise (within certain ranges) may have positive factors. The dynamical systems definition of variability is "an index of movement fluctuations" and not a reflection of movement error.[118] When the neuromotor system self organizes its nonlinear dynamical properties, variability is thought to emerge.

Two major sources of variability are thought to be stochastic or random fluctuations (noise) and chaotic fluctuations that are mathematically predictable if the initial conditions are known.[117] There are some benefits thought to be associated with variability. Variability determines stability around an attractor and offers flexibility in order to learn new motor patterns. Variability also allows flexibility to select or change previously learned motor patterns by rescaling the parameters to access new attractors.[117, 118] Stochastic perturbations also allow exploration in movement to allow the selection of the best motor pattern.[117] However, it is difficult to establish the positive aspects of variability in human movement research, and recent studies in a number of biological fields indicate variability may be either positive or negative.[117]

Biological rhythms are affected by variability. Increased variability may be positive or it may be negative and indicative of disease. Disease may be inferred by changes in amplitude of variability, new rhythms or periodicities, or a loss of variability and more constant dynamics.[117] Biological fields that have observed and measured variability in healthy and diseased states include cardiac physiology, brain pathology, neurological impairments, and the movement sciences.[117, 118] Examples from these fields include using standard deviation to measure variability in timing of finger tapping. Individuals with cerebellum and frontal cerebral cortex damage demonstrated greater variation in the timing compared to healthy controls and Parkinson's patients.[117] However, greater variability was observed in center of pressure movement during quiet stance in healthy young adults compared elderly subjects categorized as at-risk for falls.[117] Thus, increased or decreased variability may indicate disease or deficits in motor control.

In the movement sciences, variability has been used to investigate overuse injuries through a musculoskeletal loading hypothesis.[117, 119] Types of variability include spatial, temporal, and force variables, as well as impulse or integrals and rates or derivatives of the variables with respect to time.[119] Variability in biomechanical kinetic measures such as forces, moments, and temporal characteristics of forces and moments may be related to musculoskeletal injury.[119] No direct connection currently exists between movement variability in total and musculoskeletal injury.[117, 119] Joint or tissue loading and injury potential seem linked to kinetic characteristics in terms of severity, magnitude, or application. Injury location and severity might be caused by these factors and could be influenced by load magnitude, rate or site of application from variations in motor patterns.[119] It is hypothesized that musculoskeletal health is maintained by submaximal loading conditions that repeat over time by creating variation above some level of the characteristics of loading. Too little variability may cause accumulation of trauma by not allowing adaptation of tissue or by loading one tissue area and not spreading forces over an area.[117, 119]

Variability may be the task criterion (such as in riflery or archery), but for most movements it is only one component of the reliability of a successful completion of a task for an individual.[117]

Variability may be studied as the differences in individual performance of skills. It may be used to characterize population differences, to see if performance is affected compared to a designated "control" group, as is the goal in this project. With technological advances, motor skill and movement control variability can now both be analyzed.[117]

Measuring Variability

In measuring human movement, variability may be both the "subject of interest and a factor that constrains the effectiveness of the methodological process."[117] Using traditional analyses, the sources of experimental error cannot be partitioned to assess how much is attributable to movement variation. Increases in movement variability "increase the magnitude of unsystematic experimental error within the general linear model."[117] If the investigator is not studying variability, it cannot be separated from true experimental error, such as motion artifact. Thus, one must account for individual variability to differentiate between groups.[117] The structure of the variability must be analyzed, and to truly assess its complex nature, traditional measures of variability, such as the standard deviation and the coefficient of variation, should not be used alone. As the variability of the movement changes, the neuromotor organization may be changing as well, which will not be documented with traditional measures of variability.[117]

Using traditional methods of quantifying variability from descriptive statistics is acceptable as one component of the analysis for both traditional and nontraditional variables. Total variability within the system can be quantified and discrete and continuous variables can be analyzed. Nontraditional methods of variability analysis from nonlinear dynamics may also be used.[117] Variability in discrete variables such as joint angle in time, timing of an event, or peak magnitude can be assessed through traditional descriptive statistical measures. Range, variance and standard deviation (SD), coefficient of variation (CV), and interquartile range (IQR) are each acceptable. The CV and SD are most commonly used and have been used previously in human movement science on both discrete and continuous data. They may be used to describe point by point and curve averaged data that is either temporally aligned (such as vertical GRF) or data that were normalized to 100 points.[117]

In movement science, the SD of a system is usually measured with a repeated trials task. One must remember, however, that SD is a single statistic representing many measures or trials. If the data are normally distributed, the mean and SD are adequate descriptors. Variability and SD are therefore closely associated with the mean. But if the distribution of data is not normal and is skewed, more complex analyses must occur. Standard deviation provides only the degree of variability and no the "index of the structure of the … variability."[118]

The CV is the SD normalized to the mean of the score distribution. It represents relative or normalized variability and is variability (SD) converted to a percentage of the mean value. The CV is useful for quantifying the amount of variability compared to the magnitude of the mean.[117, 118] Thus, one can compare performances with very different mean scores.[117] Using adjusted comparisons of variability values, one can investigate if variability is due to the inherent properties of the movement or if it is due to the magnitude of movement within each performance. The CV however, is strongly influenced by outlying or extreme data points, and previous research has indicated that small CV values s may occur during the portion of movement with the most complex variability. Thus, CV in itself may not be an adequate representation of variability.[117]

The IQR, alternatively, shows the length of data where 50% of the observations lie, allowing investigators to observe if the data is grouped closely or more spread apart. The IQR is more immune to outliers than the CV. Other methods for analyzing variability include angle-angle diagrams for continuous motion or trials and ensemble curves with a variability band. This variability, however, is only one-dimensional and does not capture the true variability of the joint.[117] To understand the nature and complexity of the system, a number of variability measures should be used, including the traditional SD and CV, as well as the power frequency structure, approximate entropy values, and dimensionality, which come from nonlinear dynamics.[117]

Other methods of dealing with variability in movement include filtering and collecting an adequate number of trials. Low pass filters are used to eliminate high frequency components of signal that are not biological movements but random noise. Noise and actual movement signal usually overlap, though, and the filter either allows noise through, loses biological signal, or both. A power spectrum analysis with a Fast Fourier Transformation may be used to identify the best signal cut-off point.[117] The number of trials collected in movement science varies by the discipline and the task and ranges from one to an infinite number. For cyclic movements, more than one trial is needed. Greater movement variability demonstrated by individuals necessitates greater number of trials collected because of the increased chance of sampling an outlying performance. Usually a number of samples should be collected, similar to using a number of different subjects. Ideally, a random sample of those trials would be analyzed much like a random selection of subjects is sampled.[117] Stability in movement variability was defined as successive mean deviations that were ¼ or less of the SD of mean value for each variable. Ground reaction force data indicated that 8 trials were necessary to achieve stability, and computer models suggested 8-10 trials were acceptable.[117]

Using Variability in Movement Analysis

Consistency is crucial in many activities, including sports. If the demands of accuracy are high, the performer typically completes several trials. Consistency is also important in gait and other motion activities.[120] Because a number of systems coordinate to produce motion, characteristics of variability may be in systems outside of the movement goal. For example, joint movement is due to muscular contraction, and variability in performance could be related to variability in muscle force. Muscle force then has variability on several levels, including muscle state, activity of the neurons, and the higher nervous centers.[120]

Early researchers wanted to test if variability increased proportionally with isometric force production. They found the relationship was not proportional. Later research demonstrated that as force production levels increased, so did force variability, but at a less than proportional rate in peak force or a static force level.[120] Additional research highlighted that maximum peak forces achieved had much lower variability associated than did increases at low force levels. Variability increased proportionately with force generated up to about 65% of maximum, then decreased as force generated exceeded that percentage. However, the finding is not consistent in the literature.[120] Most of the literature produced so far focused on single degree of freedom movements with only one muscle agonist-antagonist group. Researchers do not know if these variability principles hold within different motor actions, especially multi-joint movements, if they hold across movements, or if they hold across variables, such as kinematics or EMG.[119, 120]

Different joints may exhibit different variability characteristics. A previous study increased walking cadence and noted increased variability at the hip and the knee and the total support movement as evidenced by increased SD. However, the ankle variability decreased.[119] Joint kinetic parameters have complex relationships with variability in movement, and moment variability may be different than force variability.[119] In a study assessing the connection between joint kinetic variability and proneness to lower extremity overuse injury, the authors hypothesized the injury prone group of recreational athletes would exhibit greater joint kinetic variability than a control group.[119] Using 10 recreational athletes of each gender, the subjects performed 10 trials of drop landing from 50, 100, and 200% of their maximum jump heights. Half of those subjects were injury prone and the other half were control subjects. The dependent variables were peak, time to peak, and impulse joint moment variables. Variability was calculated as the mean absolute difference of the individual trials within a condition from the condition mean.[119] The formula to calculate variability was[119]:

Equation 1: $V = \left[\Sigma_{i=1-n} \left| \overline{X} - Xi \right| \right] / N$ where X_i is the individual dependent variable, $\overline{X}$ is the condition mean for that variable, i is the trial number, and N is the total number of trials for that condition.

First, checks of normality were performed, and skewed data was transformed using a log 10 transformation. Checks for learning and fatigue were performed with 1-Way Analyses of Variance (ANOVA), followed by correlations. Variables with Pearson-R correlation coefficients greater than

0.90 or less than –0.90 were discarded. Any coefficients greater than 0.707 or less than –0.707 were considered correlated and were noted. Differences in magnitude of each variable were evaluated for differences among group and condition. A mixed model 2x3 Multiple ANOVA was used with an alpha level of 0.02 to test for differences between groups and conditions, and follow-up tests were conducted on significant results (ANOVA with alpha level 0.05). Increased landing height resulted in greater joint moment peak and impulse magnitude and faster time to peak.[119] The variability, however, was dependent on the group and the height. Healthy subjects exhibited greater variability at 50% jump height compared to the injury prone group. In this instance, variability appears to be a healthy quality. But at the 100% height, the injury prone group exhibited greater variability.[119] The authors hypothesized that at 50% jump height, the control group did not think an injury would happen and were not concerned with controlling their motor pattern. But at the 100% jump height, the control group was more concerned with the possibility of injury and changed the landing variability to prevent a one-time injury and risk overuse injury. Not all the variables' variability changed significantly with jump height, but they did all change in the same direction (either increase or decrease). The 200% jump height could have strained the neuromuscular control system and made it decrease the possible degrees of freedom to decrease variability and the chance of acute injury.[119]

A previous study on gender differences on the biomechanics of side-step cutting reported the variability within subjects was much greater than the variability between subjects.[121] The authors found the intertrial variability in kinematic and kinetic parameters across conditions for each subject. The trials were normalized to 100 points or time-steps during the stance phase. The authors calculated the SD for each of the 10 trials at each time step in two conditions (with and without a defensive opponent). The mean SD was then calculated for all the trials. The authors compared the mean SD between groups (men and women) and within subjects using an ANOVA. Using this method, males were reported to have more variability in hip rotation during the stance phase and females more variability in peak knee flexion and peak knee valgus.[121] In this example, a traditional method of calculating variability (SD) was used on discrete variables.

The CV has also been used on discrete and continuous variables. In discrete variables, CV is defined as the (SD/Mean) x 100. In continuous variables, the CV has been computed using both point-by-point and curve-average methods. For the point-by-point method, the formula is

Equation 2: $CV_i = (SD_i/M_i) \times 100$

where i indicates the specific value for the ith sample, and

$$\text{Equation 3: } SD_i = \left[\frac{\sum_{j=1}^{n} (x_{ij} - M_i)^2}{n-1} \right]^{1/2} \text{ and Equation 4: } M_i = \frac{\sum_{j=1}^{n} x_{ij}}{n}$$

where M_i is the mean for the ith sample, x_{ij} is the data value for the ith sample and jth trial, and n is the number of trials.[117]

For the curve average method,

$$\text{Equation 5: } CV_{avg} = \frac{SD_{avg}}{\frac{\sum_{i=1}^{k} |M_i|}{k}} \bullet 100 \text{ where Equation 6: } SD_{avg} = \left[\frac{\sum_{i=1}^{k} SD_i^2}{k} \right]^{1/2}$$

SD_{avg} is the average of individual point-by-point SD values across all k samples composing the continuous curve. SD_i is the SD value for the ith sample.[117] Due to the ease of calculation, common usage in human movement science, and ease of understanding for clinical application, SD and CV for curve-average methods were used to assess variability in this dissertation project. The SD and CV can be considered discrete variables that are measures of central tendency. Thus, they may be tested with ANOVA models. It is unlikely this mean SD will violate the assumptions necessary to perform the ANOVA, but if there are violations, a z-transformation can be used on the data before running an ANOVA. Though neither the SD nor CV is a complete description of variability, it is a start for the literature.

Variability has rarely been assessed in the movement sciences, especially in complex multi-joint movement tasks. Additionally, variability in CAI kinematics, kinetics, and EMG has not been sufficiently addressed in the literature, but it may be an important component in perpetuating the injury. Initial studies of variability between injured and control subjects need to occur to determine what joint measures display variability, whether it is positive or negative variability, and how best to pick a measure of variability. If variability in movement is a factor in the CAI population, rehabilitation programs may be designed to target those deficits.

Summary

Although lateral ankle sprain is a common injury and has been investigated numerous times, there are still gaps in knowledge regarding causes and factors that influence the progression and perpetuation of the injury. CAI is likely a multifactorial problem that must be addressed on several fronts to resolve functional deficits. Identifying functional deficits is the first step in designing effective prevention and rehabilitation programs to return individuals to activity and avoid long-term joint degeneration and damage.

CHAPTER III

METHODS

This study used a quasi-experimental design, with an enrollment of 21 subjects in each of the three groups, for a total N of 63. A-priori power calculations were performed to determine necessary sample size using the conservative t-test model. Based on estimated means from graphic data from a similar study, an n of 10 provided power of 0.60-0.99 in kinematic variables at the ankle and knee. The effect sizes were 0.93-1.15.[31] Additionally, pilot data from 4 chronically unstable ankle subjects and 4 comparison subjects indicated the ankle variables for plantar flexion at initial contact, inversion-eversion at initial contact, maximum plantar flexion and maximum eversion all required 20 subjects or fewer to achieve a power of 0.80. Using published and pilot data, power calculations for kinetic and electromyography variables indicated a larger sample size would be necessary for a power of 0.80 in some variables, but a sample size of 20 would be appropriate in others.[19, 31]

Data collection occurred from August through December of 2005, with data reduction occurring from September through February 2006. All testing, reduction, and analysis occurred in the Sports Medicine Research Laboratory on the University of North Carolina at Chapel Hill (UNC-CH) campus.

Subjects

Subjects were 18-35 year old recreationally active individuals who performed at least 1.5 total hours of cardiovascular, resistance, sport-related, or other physical activity per week. Subjects were members of the UNC-CH campus community and reflective of the races therein, with equal numbers of subjects of each gender. Only subjects aged 18 years and older were included because developmental changes in biomechanical factors such as weight, height, muscle development, and limb segment length are still occurring in minors and may affect kinematic and kinetic results. Therefore the subject population will include only developmentally mature adults.

Inclusion Criteria

Each subject had a history of acute inversion ankle sprain that required immobilization or non-weight bearing for at least 3 days within the past 5 years. All subjects were recreationally active as defined above with 5/5 strength in four planar directions at the ankle as determined by clinical manual muscle testing.[122] The strength requirement was to ensure subjects could safely perform the tasks. Inclusion criteria for each group was as follows:

Mechanical Ankle Instability (MAI) Group

1) Positive anterior drawer sign and/or positive talar tilt sign to clinical orthopedic exam (4/5 "loose" or 5/5 "very loose" on the laxity scale).[10]
2) Repeated episodes of "giving way" and complaints of ankle instability with activity secondary to the initial sprain, with a minimum of 2 episodes of giving way or spraining in the past 12 months. A sprain was defined as an episode of "giving way" or "turning over" during activity with possible pain and/or swelling.
3) Subjective reports of weakness, pain, and less function than before the injury or compared to the other ankle. A score of 77 or less on the Ankle Assessment Questionnaire.[33]
4) No current swelling or ecchymosis.

Functional Ankle Instability (FAI) Group

1) Negative anterior drawer sign and negative talar tilt sign to clinical orthopedic exam (2/5 "hypomobile" or 3/5 "normal" on the laxity scale).[10]
2) Repeated episodes of "giving way" and complaints of ankle instability with activity secondary to the initial sprain, with a minimum of 2 episodes of giving way or spraining in the past 12 months. A sprain was defined as an episode of "giving way" or "turning over" during activity with possible pain and/or swelling.

3) Subjective reports of weakness, pain, and less function than before the injury or compared to the other ankle. A score of 77 or less on the Ankle Assessment Questionnaire.[33]

4) No current swelling or ecchymosis.

Comparison Group

1) Negative anterior drawer sign and negative talar tilt sign to clinical orthopedic exam (2/5 "hypomobile" or 3/5 "normal" on the laxity scale).[10]

2) No repeated episodes of "giving way" or complaints of ankle instability with activity secondary to the initial sprain, with one or fewer episodes of giving way or spraining in the past 12 months and no sprain within the past 3 months. A sprain was defined as an episode of "giving way" or "turning over" during activity with possible pain and/or swelling.

3) No subjective reports of weakness, pain, or less function than before the injury or compared to the other ankle. A score of 85 or more on the Ankle Assessment Questionnaire.[78]

4) No current swelling or ecchymosis.

5) The initial sprain must have occurred at least 1 year ago, to provide 12 months (or a full sport season) of activity since the sprain.

Exclusion criteria

Exclusion criteria for all groups included:

1) A history of surgery in either leg.

2) Previous ankle fracture in either leg.

3) A lower extremity injury in the last three months, other than an episode of ankle sprain or giving way in the MAI and FAI groups. An injury was defined as an episode of pain and/or swelling requiring limitations in activity for at least three days.

4) Ankle pain with the test tasks reported as a “yes” response to the question, “Does this task cause you ankle pain?” The question will be asked during each task.
5) Obvious ankle swelling or ecchymosis.
6) Gross limitations in ankle range of motion (zero degrees or less dorsiflexion and/or less than 20 degrees of plantar flexion).
7) Any self-reported instability in the knee or hip.
8) Current enrollment in a formal rehabilitation program.
9) Diagnosis of a vestibular or balance disorder or Charcot-Marie-Tooth or other hereditary nerve disorder.

If subjects reported bilateral ankle instability, the most unstable ankle was tested as determined by self-report data and laxity testing. If both sides were determined to be equally unstable, the side with the greater number of previous sprains was tested. If equally unstable ankles had the same number of previous sprains, the dominant limb was tested.

Recruitment and Incentives

Recruitment occurred via flyers posted in and around Woollen and Fetzer Gymnasiums on the UNC campus. Verbal announcements were also provided to various Physical Activity courses in the Department of Exercise and Sport Science for recruitment purposes. Subjects received $10 upon completion of testing as incentive to participate and compensation for their time.

<u>Research Protocol</u>

Overview

The single testing session consisted of an initial screening portion to determine group eligibility, followed by the actual testing session.

Initial Screening

Once subjects were recruited, a brief telephone or email interview ensured they matched the global inclusion criteria of age (18-35 years), recreational activity level, history of previous ankle sprain as well as the exclusion criteria. If they matched these criteria, an initial screening 15 minutes in length occurred to place the subjects into the appropriate ankle stability group. During this initial screening, subjects read and signed the consent form and completed the questionnaires regarding their activity type and level, ankle injury history, and ankle pain and function level. Demographic data and anthropometric measurements such as range of motion and limb dominance[123] were also performed. They a brief orthopedic exam was performed by a Certified Athletic Trainer (ATC), licensed in the state of North Carolina, to ensure they matched the inclusion criteria for strength and range of motion and that subjects could safely perform the tasks. This clinical orthopedic exam determined laxity using the anterior drawer and talar tilt tests[47] for assignment to one of the three ankle stability groups. Pilot testing using an intraclass correlation coefficient (ICC 2,1) determined interrater reliability, which was greater than 0.80 on both tests. The standard error of the measurement (SEM) was less than 0.25 for both tests. Subjects in each group were matched for gender and limb dominance between groups, as gender differences have been shown for some kinematic variables during the stop jump and other tasks[51] and limb dominance may confound results. Subjects were also matched across groups for age (±2 years) and height and weight (±10%).

Test Session

Immediately following the screening, the testing session took approximately one hour. Subjects were set up for recording electromyographic (EMG) system on four leg muscles (tibialis anterior, peroneals, lateral gastrocnemius, and soleus) and for recording limb kinematics using the electromagnetic tracking system. Instructions for the 5 tasks (walking, step-up an over, running, drop jump, and stop jump) were provided, then subjects performed practice trials prior to the five test trials. Maximum voluntary isometric contraction tests for each muscle using a hand held dynamometer were used to normalize the EMG data during each task. The mean and peak force measured by hand-held dynamometry were recorded for each trial. At the end of the test session, the electromagnetic tracking system was used to quantify ankle joint laxity for secondary analysis.

Equipment

Instrumentation

Clinical measures

Active ankle range of motion was measured using a standard universal goniometer. Intratester reliability was previously reported as ICC = 0.92-0.96.[124] The same researcher measured range of motion every time. Limb dominance testing did not need any instrumentation and used the platform for the electromagnetic tracking system as a standard step of approximately 31cm in height. Ankle joint laxity tests (anterior drawer and talar tilt)[10, 47] and strength using manual muscle tests,[122] were performed by an ATC licensed to practice sports medicine in the state of North Carolina. Each subject also completed three questionnaires, the Ankle Assessment Questionnaire[33] (AAQ) regarding ankle function, the Foot and Ankle Disability Index and its Sport subscale (FADI-S)[89] regarding ankle function in sporting activity, and a demographic form detailing ankle injury history and type and frequency of physical activity. The AAQ was the primary outcome questionnaire to determine subjects' functional deficits at the ankle and was used to categorize subjects into groups. The FADI-S was also administered, but the data were not used in determining group membership. Instead, a post-hoc analysis comparing agreement between the AAQ and the FADI-S was conducted. Neither questionnaire has established validity and reliability in large healthy and CAI populations. The AAQ has been used previously in this laboratory to differentiate between CAI and control groups.[78] Preliminary data suggest it is capable of differentiating between those with and without symptoms of CAI as demonstrated by significantly different mean scores between groups. Additionally, individuals with more repeated sprains and episodes of giving way score lower.

Forceplate

A piezoelectric non-conductive forceplate (Model #4060-NC Bertec Co., Columbus, OH) with a frequency response of 400 Hz in the vertical direction and 300 Hz in both horizontal directions measured the subject's mass (in kg) and the kinetic variables for the walking, step-up and over, running, drop jump, and stop jump trials. The forceplate was synchronized with the Flock of Birds electromagnetic tracking device through an A/D board using a manual trigger switch for each trial.

Ground reaction forces were measured using the forceplate, with the Motion Monitor software controlling the tracking device and collecting the ground reaction forces during the trials.

Flock of Birds and Motion Monitor

The Flock of Birds (Ascension Technologies, Burlington, VT) with 6 sensor "birds" and the Motion Monitor software (Version 6, Innovative Sports Training, Chicago, IL) controlling it collected kinematic variables, including ankle laxity data during the final test procedure. The position and orientation of the sensor "birds" was tracked through a pulsed DC magnetic field. The Fast Bird Bus measured each receiver site and was hard wired to the computer. The electromagnetic field was generated through 3 orthogonal coils.[100] We used the standard range transmitter (72 inches), with 6 birds, one of which was moveable and attached to a stylus for digitization of joints. An A/D board in the Flock input and synchronized kinematic, forceplate, and EMG data through the Motion Monitor software. The static accuracy of sensor position is 0.5 mm root mean square (RMS) and orientation is 0.1 degrees RMS. Accuracy is defined as the RMS deviation of a true measurement of the magnetic center of a single sensor with respect to the magnetic center of single transmitter measured over the translation range.[100] Resolution is 0.25 mm positional and 0.01 degrees rotational.[106] The standard range transmitter emits a spherical field approximately 1 m in diameter. The Motion Monitor software controls the mass assigned to each body segment and each segment's center of mass and radius of gyration.[100] The default parameters for each segment are published data,[125, 126] or the user may select and enter specific segment data. The Motion Monitor software can be used to record joint angle at foot contact, as well as maximum joint angles and joint displacements during a task. These measures were recorded for each walking, stepping, running, and jumping trial. The software can also be used to measures position data and linear and angular distances between sensors. These measures were recorded during the laxity test trials. A static neutral stance trial was used to demean joint angles and avoid offsets due to sensor position and axes alignment. Interobserver and intraobserver reliability measures were reported to be good for position and orientation using the tracking device.[127]

Electromyography

A telemetry EMG system (Model #T42-L8T0, Konigsberg, Pasadena, CA; differential amplification; input impedance = 200kΩ; CMRR >70dB; SNR >40 dB) with an 8-channel amplifier/encoder transmitter and receiver/demodulater was synchronized through the A/D board in the electromagnetic tracking system. Self-adhesive Ag/AgCl surface electrodes (Medicotest Inc., Olstykke, Denmark) with circular contact areas were used. The electrode contacts were 6 mm in diameter with 20 mm interelectrode distance were used on the tibialis anterior, peroneals, lateral gastrocnemius, and soleus muscles in the test leg. EMG was collected through the Motion Monitor software and was filtered there as well. The EMG identified the muscle activity during the tests and ensured no muscle activity was present during the laxity testing using the tracking system. The reliability of EMG is low – it is rarely reported in the literature. We attempted to minimize variability by standardizing electrode placement and maximum voluntary isometric contraction (MVIC) testing.

Hand held dynamometer

A Chatillon CSD 300 strength dynamometer (Ametek, Largo, FL) was used to complete maximum voluntary isometric contractions (MVIC) of each of the muscles to normalize the EMG data. Intrarater reliability was pilot tested and Intraclass Correlation Coefficients (ICCs; 2,1) were 0.57-0.86 with Standard Error of Measurement (SEM) from 0.119-0.442 Volts. Subject positioning was standardized for each muscle to isolate it and the subjects performed the contraction with minimal movement. Mean and peak force in Newtons was recorded for each trial to ensure consistent effort.

Data analysis software

The Motion Monitor software provided anthropometric data such as height and mass as measured by the sensor location in the field and the forceplate. The software normalized ground reaction force to that mass. Custom DataPac 2K2 programs (Version 3.11, RUN Technologies, Mission Viejo, CA) identified peak ground reaction forces, time to peak ground reaction forces, and muscle activity reported as mean amplitude during the stance phase (initial contact to toe off as defined by vertical ground reaction force) in the walking, step-up and over, running, and stop jump trials. During the drop jump trials, those variables were located in the 250ms after landing. DataPac also identified joint angles at initial contact, maximum joint angles, and joint displacements during the trials. An Excel spreadsheet (Microsoft Corporation, Redmond, WA) was used to find EMG mean amplitude as a percentage of the MVIC.

Dependent Variables and Definitions

Each of the variables of interest and a brief description and definition are included in Table 1. Further descriptions of each dependent variable and the testing procedures are in the following sections.

Data Collection

Introduction

Subjects reported to the Sports Medicine Research Laboratory wearing shorts and were tested in bare feet. In the screening portion of the test session, after completing the approved consent form, subjects completed the demographic and ankle function questionnaires. They were assessed on the clinical measures, including range of motion, limb dominance, and ankle laxity. The screening process took approximately 15 minutes. Subjects warmed up on a stationary bike for 5 minutes, then were set up on EMG and the electromagnetic tracking system for testing. Sensors were attached, then subjects completed the walking, step-up and over, running, drop jump, and stop jump trials in a modified counterbalanced order. Finally, subjects underwent laxity and MVIC testing at the end of the session. These data will undergo secondary analysis and were not a dependent variable in this project.

Initial Screening

Questionnaires

The Ankle Assessment Questionnaire has been used previously to separate subjects into CAI and control groups.[33] The AAQ is a 100-point questionnaire assessing ankle function during daily activities and sport-related activities that may elicit feelings of instability. It is based on a 100-point scale, with a score of 100 representing full function and no feelings of instability at the ankle. Lower scores represent decreased ankle function and confidence in ankle function. CAI subjects reported significantly lower scores indicating decreased ankle function in a previous dissertation (control subjects' mean 96.35 ± SD 0.67 and CAI subjects 61.08 ± 2.23)[33] and pilot work (control: 95.67±5.46 range 81-100 and CAI: 63.72 ±13.45 range 43-89). Based on this data, the mean score plus one standard deviation for the CAI subjects was calculated and that number (77) was used as the cutoff point for subjects entering the FAI or MAI groups. For the comparison group, the cutoff score was set at 85 to ensure subjects are functioning at a high level and had no deficits at the ankle.

The Foot and Ankle Disability Index and its Sport subscale have also been used previously, with the CAI group scoring significantly lower than the control group.[89] The FADI-S was reliable in detecting CAI functional deficits over a 6-week period and sensitive to differences between a CAI and a control group.[89] The FADI ICC (2,1) and SEM for the CAI groups' involved ankles over one week was 0.89 (2.61). Over six weeks it was 0.93 (1.31). For the FADI-S the ICC and SEM on the CAI groups' involved ankle 0.84(5.32) over one week and 0.92 (4.43) over six. The FADI and FADI-S also demonstrated significantly different scores between CAI and control groups. The control group scores for both ankles and the CAI group's uninvolved ankle scores were all 98% or better for the FADI and the FADI-S. The CAI group's involved ankle mean score was 89.6±9.1% for the FADI and 79.5±12.7% for the FADI-S. Thus, the questions addressing more challenging activities on the FADI-S may have been more sensitive to the deficits caused by CAI. The questions on the FADI-S are very similar to those on the AAQ. The AAQ was the primary questionnaire to determine whether or not subjects reported a decrease in function in the test ankle and to separate the subjects into ankle stability groups. The FADI-S was collected simultaneously, but those responses were not used to determine group membership. Instead, the FADI-S and AAQ scores will be compared with secondary post-hoc testing to assess agreement.

Range of motion

Subjects were seated on an exam table with their knees in 90 degrees of flexion. Subjects were asked to actively dorsiflex and then plantarflex their ankles as far as possible. Dorsiflexion and plantar flexion were measured by aligning the goniometer axis at the lateral malleolus, with the stationary arm along the fibula and the moveable arm parallel to the 5th metatarsal.[124] Subjects were then asked to lay prone with their knees extended and feet off the end of the exam table. Subjects were instructed to actively invert and then evert their hindfoot (subtalar joint) as far as possible while maintaining their foot at 90 degrees to the tibia (neutral plantar flexion-dorsiflexion). The goniometer axis was aligned midway between the malleoli with the stationary arm along the midline of the Achilles and the moveable arm along the midline of the calcaneus.[124] Measurements were recorded for each leg. Subjects had to actively perform at least 1 degree of dorsiflexion and 20 degrees of plantar flexion to meet inclusion criteria.

Strength

Subjects performed resisted manual muscle tests for the tibialis anterior, peroneals, lateral gastrocnemius, and soleus muscles as previously described.[122] An ATC performed the manual muscle tests to make sure subjects were able to safely complete the test tasks. Subjects must score 5/5 in order to participate, representing strong resistance to manual forces.[122]

Limb dominance

Subjects performed 3 tests to determine limb dominance. Subjects stood in front of the platform containing the forceplate and electromagnetic tracking system and were asked to step up on it (approximately 31 cm). Subjects were asked their preferred leg with which to kick a ball. Finally, the subjects stood in front of the investigator in a comfortable stance. The investigator applied a force between the scapulae strong enough to cause the subject to step forward to recover their balance. Whichever leg the subject uses in the majority of the three tests was considered the dominant leg.[123]

Warm up

Subjects were allowed a 5 minute warm up period on a stationary bike at a self-selected speed, followed by any stretching they wish for 2-3 minutes.

Test Session

Electromyography

Electrode placement: During the test session, subjects were set up on this equipment first, following the warm up. The electrode placement sites were shaved, abraded, and then cleansed with alcohol. Subjects stood in a comfortable position and measurements, manual muscle tests, and palpation were used to find for electrode placement over previously established guidelines.[108] The tibialis anterior electrodes were placed at 25% of the distance from the lateral popliteal fossa to the lateral malleolus over the muscle belly.[110] The peroneal electrodes were placed at 25% of the distance between the fibular head and the lateral malleolus, also over the muscle belly.[108] The lateral gastrocnemius electrodes were placed on the lateral head of the gastroc, approximately 1 cm medial from the muscle border. The soleus electrodes were placed on the midline of the leg, approximately 10 cm distal to the inferior gastroc border but proximal to the attachment of the Achilles, or 2 cm distal to the insertion of the gastroc on the Achilles depending on leg length.[83] The reference electrode was placed on the tibial tuberosity. Electrode placement and cross-talk were checked by manual muscle test using an oscilloscope, and electrodes were moved as necessary. The electrodes were self-adhesive and secured to the skin with underwrap. The telemetry pack was secured in a holster around the subject's waist. The leads were secured together with ties and to the subject's legs using underwrap to minimize noise from the wires.

Electromyography normalization: Following motion tracking system set up and testing as detailed below, MVIC testing was performed on each muscle while collecting EMG through the Motion Monitor software using the A/D board. A hand-held dynamometer and strap provided resistance for the isometric tests. Peak and mean force in N was recorded to ensure consistent subject effort during each trial. The process was used to normalize EMG between subjects as a percentage of

MVIC.[113] The following testing positions were used to isolate each muscle and minimize subject movement to maximize consistency between and within subjects. The tibialis anterior and soleus were tested with the knee at 20-30 degrees of flexion and the ankle in neutral inversion and zero degrees dorsiflexion. A bolster was placed under subjects' knees to standardize flexion and a strap over the quadriceps minimized leg and thigh movement. For the tibialis anterior the researcher was positioned facing the subject pulling the foot into plantar flexion while the subject resisted. For the soleus, the researcher was positioned behind the subject pulling the foot into dorsiflexion while the subject resisted. The lateral gastrocnemius was tested with the knee extended as much as comfortable and the foot in neutral inversion and zero degrees dorsiflexion. The researcher was positioned behind the subject as in soleus testing. The peroneals were tested with the knee extended and the foot in neutral plantar flexion-dorsiflexion and inversion-eversion with a padded bolster between the legs to stabilize them. The researcher was positioned medially to the subjects' test leg pulling the foot into inversion while the subject resisted. Subjects received a warm-up period of 3 non-maximal repetitions to familiarize them with the procedure. For each test trial the subjects contracted for 5 seconds, and the middle 1-second of the data was used as "maximum" contraction. Subjects received 15 seconds of rest between trials and at least one minute of rest between each muscle while the strap and dynamometer position was changed. The order of muscle testing (tibialis anterior, peroneals, soleus, and lateral gastrocnemius) was counterbalanced. The rest time between trials and the fact each muscle was tested in isolation should have been sufficient to avoid fatigue. The EMG test data was presented as a percentage of the average amplitude of the middle 1-second of the MVIC tests for each respective muscle.

Kinematic Data

Axes system and set up: Prior to data collection, the electromagnetic field for the tracking system was established, along with the stylus, forceplate, and global axis system. The standard range transmitter was mounted on a non-metal stand 32 cm from the forceplate. The axes system had +x in the direction the subject faces, +y to the right and +z in the upward vertical direction. All digitization occurred with a 15.4cm long wooden stylus, whose length was established by a 20-point digitization around a stationary point. Root mean square (RMS) error of the stylus will be less than 0.003 and was recorded. Once the stylus was set up, the global axes were established, then the stylus was turned off and the moveable sensor was removed to establish the plane and location of the forceplate. After forceplate set up, the sensor was replaced on the stylus, which was set up again, recording the RMS. Once EMG set up was finished, sensor set up on the subject began.

Sensor placement and digitization: The sacral sensor was placed inside the sacral belt which was secured to the subject's sacrum on the midline between the posterior superior iliac spines using double sided tape. The lateral femur attachment site was over the iliotibial band midway between the hip joint and the knee joint. The tibial sensor was placed on the antero-medial portion of the tibia, 3-5 cm distal to the tibial tuberosity. The calcaneus sensor was placed on the most inferior portion of the bone on the midline of the shank. The foot sensor was placed between the 2nd-3rd metatarsals, midway between the metatarsals and the metatarsophalangeal joints. Sensors were placed over areas with minimal muscle mass to decrease potential skin movement. The sensors were positioned so the cords were oriented cephally and cords were looped and secured to subjects' legs and feet to avoid tension and movement artifact.

Before digitization, the following bony landmarks were palpated and marked with a felt-tip pen: the most medial and lateral points knee joint line, the most prominent portions of the medial and lateral malleoli, the most prominent portions of the 1st and 5th metatarsal heads, and the most inferior portion of the calcaneus on either side of the calcaneal sensor just above where the heel contacts the ground. Initial digitization included the medial and lateral knee joint line points, the medial and lateral malleoli points, and the tip of the second phalanx. A visual representation was posted to check for accuracy. The hip joint was digitized using the Leardini method option in Motion Monitor with 7 positions (neutral stance, anterior, antero-lateral, lateral, postero-lateral, posterior, and neutral stance again). The subject supported his/her body weight with the non-test leg, positioning the test leg as detailed above, with the knee and ankle extended and the toes touching the floor. The subject was instructed to keep the pelvis facing anteriorly and not allow it to rotate during movement to the various positions. Another visual check for accuracy was required. Following initial set up, anthropometric data such as distances from the sacrum sensor to the hip and the thigh sensor to the hip was available. The Motion Monitor software used tabled data to calculate segment mass, center of mass, and radius of gyration.[126] The RMS error of the hip joint was also reported and recorded.

Following initial digitization, a similar process was undertaken for each of the segments and joints of interest. The proximal and distal ends of the longitudinal axis, a 3rd point on the plane, a 4th point above and on the positive side, and the origin were digitized for each joint/segment. Each origin was a centroid, or calculated midpoint, between two bony landmarks around a joint. The sacrum's proximal end of its longitudinal axis was two points on either side of the sacral sensor, and the distal end was one point at the tip of the coccyx. The 3rd point on the sacral plane was established with one point on the left side of the sacral sensor. A 4th point above and on the positive side of the sacrum was digitized around the subject's sternum. The sacral origin was established as the centroid of two points on either side of the sacral sensor. The proximal end of the longitudinal axis of the thigh was one point on the most prominent portion of the greater trochanter, as palpated. The distal end was the centroid of the marked points on the medial and lateral knee joint lines. The 3rd point on the plane was the lateral joint line point, and the 4th point was digitized around the subject's abdomen. The origin of the thigh was the centroid between the medial and lateral knee joint line points. The proximal end of the longitudinal axis of the shank was the centroid of the medial and lateral knee joint line marks. The distal end was the centroid of the marked points on the medial and lateral malleoli. The 3rd point on the plane was the lateral malleolus, and the 4th point was digitized above the subjects' knee on the anterior side of the body. The origin of the shank was the centroid of the medial and lateral malleoli points. The proximal end of the longitudinal axis of the foot for the metatarsal sensor was the centroid between the medial and lateral malleoli points. The distal end was the centroid between the 1st and 5th metatarsal heads. The 3rd point on the plane was the 1st metatarsal head and the 4th point was digitized at the midline of the shank, superior and anterior to the foot. The origin of the metatarsal sensor was the centroid of the 1st and 5th metatarsal heads. The proximal end of the longitudinal axis of the foot for the calcaneal sensor was the centroid of the two marks on either side of the calcaneal sensor. The distal end was the centroid of the marks on the 1st and 5th metatarsal heads. The 3rd point on the plane was the mark on the medial side of the calcaneal sensor, and the 4th point was at the midline of the foot, anterior to the tibia. The origin of the foot for the calcaneal sensor was the centroid of the two marks on either side of the calcaneal sensor. A final set up visual check and then a real-time view check ensured the joints and segments were digitized correctly.

Because of the size and nature of the sensors and software, motion at the ankle was considered gross ankle joint movement in the directions of plantar flexion/dorsiflexion and calcaneal inversion/eversion. Ankle joint internal/external rotation was not be considered, nor was subtalar joint motion, due to the constraints of the system.[81] According to International Society of Biomechanics recommendations, the frontal plane was the centroid of the malleoli and the medial and lateral knee joint line points. The sagittal plane was perpendicular to the frontal and contained the long axis of the tibia/fibular line connecting the centroids of the malleoli and the knee joint line points. The transverse plane was perpendicular to the frontal and sagittal planes.[81]

Segment axes were aligned with the world axes. Cords were bound in an elastic waistband out of the subject's way. See Figure 1 for sensor set up. A neutral static stance trial was recorded prior to testing for use during data reduction to demean joint position data and avoid offsets along with the software's neutral stance file obtained during digitization.

Test Tasks

During the testing session, the subjects performed five different tasks. Each task was practiced a minimum of 3 times, followed by 8 test trials.[117] The tasks were walking at a speed of 1.2-1.4 m/s,[52, 53] step-up and over on a 32 cm high box, running at 2.5-3.5 m/s,[49, 50] performing a single leg drop jump from a box of height 32 cm, and performing a stop jump with the same velocity as the running task. These speeds reflect typical daily living and game speed for the respective tasks. For the drop jump trials, subjects were instructed not to jump "up" off the box to minimize upward vertical movement but instead to "step off" the box to standardize vertical distance traveled. Single leg drop jump trials were completed without any touch-downs or stepping or stumbling with the other leg. The subject balanced for approximately 3 seconds at the end of each drop jump trial. For the walking, running, and stop jump trials, sacral sensor anterior linear velocity was used to measure the speed of movement during the trial. Real time data was presented following the trial, and subjects had to stay within the stated ranges for walking and running speed on each trial in order for that trial to be considered "good." Sacral speed was measured just before the subject contacted the forceplate. Subjects will be given feedback to speed up, slow down, or remain the same based on the real-time sacral sensor data. Trials not meeting these criteria were not counted. Subjects received at least 30 seconds rest in between all trials. The test tasks were performed in the order stated, however each subject began the testing session with a different task. This modified counterbalancing helped avoid confounding due to fatigue or learning or practice effects.

Electromyographic data

Data on muscle activity were collected and synchronized through the Motion Monitor software. Data were collected for the 250 ms before and after initial contact. This period was chosen based on previous methods.[9, 45, 96, 111, 113, 128] It is a common length of measurement for planned activity and may easily be decreased following visual inspection and pilot testing if the activity of interest is deemed to have began later or ended prior to the 250 ms window.

Kinetic data

The forceplate coupled with the electromagnetic tracking system was used to measure kinetic data (ground reaction forces). The peak ground reaction forces (vertical, anterior, posterior, medial, and lateral) were collected during every test trial for each of the 5 tasks. The Motion Monitor software collected the data and exported it through a custom program. Time to peak ground reaction force was calculated during data reduction.

Electromagnetic tracking system testing ankle joint laxity

Only three sensors were used to measure laxity. Axes set-up and sensor placement, fixation, and digitization remained the same from the *Kinematic Data* section above. Talar tilt testing occurred first. Subjects were seated on a stool with their test foot in 5-10 degrees of plantar flexion. A clinical talar tilt test was performed[47] with the examiner stabilizing the tibia with one hand and inverting the calcaneus with the other. The talar tilt test was repeated three times to calculate the maximum rotation in degrees of the calcaneal sensor relative to the tibial sensor.

A modified anterior drawer test was performed next. The calcaneal sensor was removed. The subject's foot was fixated to the floor using a custom device (see Figure 2).

The foot was placed on an immovable wooden wedge in 10 degrees of plantar flexion and restricted posteriorly by a rigid heel cup and anteriorly by adjustable velcro straps. The straps were positioned so as not to interfere with the metatarsal sensor. The wedge was secured to a 2 x 3 foot piece of wood that the subjects' stool will be placed on top of, so that no movement of the wedge or foot will occur. The subject was seated with the tibial shank perpendicular (90 degrees) to the floor. The shank angle was verified with a digital inclinometer (Saunders Group Inc., Chaska, MN). The tester positioned her hands approximately 5 cm superior to the malleoli over the midline of the tibia. An anterior-posterior directed force was manually imparted on the tibia to separate the talocrural joint. Sensors on the metatarsals and tibia recorded any anterior-posterior displacement, measuring anterior talofibular ligament laxity. The maximum anterior-posterior linear separation in mm of the metatarsal and tibial sensors was a secondary analysis to determine whether or not mechanical laxity was present. This post-hoc testing will attempt to establish face validity in the use of an electromagnetic tracking system to measure ankle joint laxity as well as the sensitivity to match measured laxity to clinical impressions of laxity and functional questionnaire scores. Figure 3 represents a flow chart of the testing procedure.

Data processing

Kinematic data

The Flock of Birds sampling rate was 144 Hz. For the test tasks and laxity data, kinematic data was "zeroed" or demeaned to the neutral standing values recorded by the Motion Monitor. The axes system was established as a left-handed system (origin starting in the left corner of the forceplate). Using the left hand screw rule, the following motions were positive: ankle plantar flexion, external rotation, and eversion,[81] and knee flexion, external rotation, and valgus. The following motions were negative: ankle dorsiflexion, internal rotation, and inversion,[81] and knee extension, internal rotation, and varus. Data was aligned to this configuration, regardless of side. When exporting data in the Motion Monitor software, the order of rotations of Euler angles at the ankle was Y, X', Z'' or plantar flexion/dorsiflexion, calcaneal inversion/eversion, and ankle internal/external rotation. At the knee, the same order was used, representing the flexion/extension, valgus/varus, and internal/external rotation movements. The last rotation was not analyzed in either joint because it was not a variable of interest, it was the 3rd rotation with the most offset error, and it had the smallest range of motion.

For laxity data, displacement of the shank to the foot (anterior drawer excursion in mm) and rearfoot tilt (talar tilt in degrees) was provided by Motion Monitor software and values were extracted from DataPac reduction. For the test tasks, a custom DataPac program was used to find joint angles at contact, maximum joint angles, and joint displacements at the ankle and knee. For the drop jump trials, data will be analyzed in the 250 ms after initial contact. For all other trials, data was analyzed during the stance period, as defined by the time period between initial contact and toe-off, or the time when the forceplate reading returns to less than 10 V. The walking, step-up and over, running, and stop jump trials all had an easily defined stance period. Because subjects will remain on the forceplate following the drop jump, an artificial end to data collection must be instituted.

A low-pass Butterworth filter with cut-off frequency of 15 Hz was applied to the kinematic data. This cut-off frequency was calculated using previously established methods.[129] We estimated the mean optimum cut-off frequency given our sampling frequency of 144Hz using Equation 9 as provided in the reference. We used a 4th order recursive low-pass Butterworth filter at that estimated frequency and then calculated the relative mean residual using equation 7 as provided. This procedure was performed on both the walking and stop jump task data for ankle plantar flexion/dorsiflexion.[129]

Kinetic data

Kinetic data were collected at 1440 Hz. Peak ground reaction forces for walking, step-up and over, running, drop jump, and stop jump trials were normalized to body mass. Kinetic data were not filtered.

Electromyography data

EMG data was collected at 1440Hz, and amplified by 10,000. It was passively demeaned, notch filtered from 59.5-60.5 Hz and bandpass filtered from 10-400 Hz[130] then full wave rectified. A 10ms moving root mean square (RMS) window was used. This processing was done by DataPac software during reduction of each trial. A Excel spreadsheet was used to find average amplitude during the 250 ms after contact in the drop jump and during the stance phase of all the other tasks. It was reported as percentage of MVIC of each respective muscle. The 250 ms window was based on previous studies performing similar tasks.[9, 45, 96, 111, 113, 128] It is long enough to capture all activity of interest and may be truncated if necessary. Data was transferred from the Motion Monitor software into ASCII files and then into DataPac for reduction.

Variability

Once the kinematic, kinetic, and EMG data were reduced, additional data processing was performed for the variability measures. For each trial, the data for each dependent variable were normalized to 100 points for the stance phase in each of the tasks, except the drop jump. For the drop jump, all data from initial contact to 250ms after initial contact were normalized to 100 points. Since there was no clear end to the stance phase in the drop jump, an artificial end was instituted. After normalization, the 8 trials were averaged for an ensemble curve 100 points long. The standard deviation (SD) of the mean for each data point was found by the software, and a grand mean SD, using the SD_{avg} and coefficient of variation (CV_{avg}) equations (equations 4-6 in Chapter 2) were found using Excel spreadsheets. This grand mean SD was used to calculate the CV for the trial. The SD was used as a discrete variable. If it violated the assumptions required to perform an ANOVA, a log_e-transformation will be performed. The SD was utilized primarily, to assess within subject variability, but the CV may be assessed to compare different variables as it is a value normalized to the mean.

Diagnostic Procedures and Data Cleaning

Impact artifacts were observed on some variables and trials on each subject. A custom Mat Lab (The Mathworks, Natick, RI) program was used to identify artifacts visually on position-time graphs. The frames immediately before and after the artifact were identified on the graph and a linear interpolation was used to connect those values. There were no more than two artifacts in each trial, thus this procedure was performed no more than two times in each trial. In the majority of cases, the artifact was 1-3 frames long.

Out of 2520 total movement trials for all subjects in all tasks, there were a total of 9 single trials missing (or less than 1% of trials). No subject had more than 1 missing trial. For subjects missing a trial, the average of the 7 remaining trials was used for analysis. For all other subjects, the average of the 8 trials was used. Following reduction, data were initially explored for descriptive qualities. Data that were extreme outliers (> 3 standard deviations from the mean) in each group in each task were noted and checked for validity. Data that were not valid were re-exported and reduced. This occurred with 11 subjects on whose initial export, the axes systems were not aligned. Following correct axes alignment and re-exporting, the data were re-reduced and the exploratory analysis was run again. The majority of the data then fell within 3 standard deviations of the mean for each respective group on each task. On each of the following tasks, the following number of subjects were more than 3SD away from their respective group means in one or more dependent variables: drop jump: 3; run 5; stop jump: 7; step up: 7; walk: 5. No trials were excluded from analysis based on values.

Data Reduction, Analysis, and Interpretation

Reduced data from DataPac was placed into Microsoft Excel spreadsheet form and then into the Statistical Program for the Social Sciences (Version 13.0, SPSS Inc., Chicago, IL) program for analysis.

Preliminary analysis

Histograms of each variable for each task grouping all subjects together were checked for normality. The majority of variables appeared sufficiently normal to meet the ANOVA assumptions. Some variables did appear skewed, particularly the EMG and GRF data. Scatterplots of the Observed vs. Standardized Residuals were assessed. If a data point appeared to be separated from the group, that data point was identified using histograms and box plots and assessed for how much it skewed the distribution of data from normal. If there was skewness, the analysis was re-run excluding the data point(s) in question, which caused some p-values to change level. However, the changes in p-values were very small and no subjects were excluded in the final analysis. The CV and SD values calculated were heavily skewed, and a natural logarithmic ($\log_e$) transformation was performed on all of the calculated CV and SD scores to meet the assumptions for an ANOVA. Histograms of each variable were re-assessed, the skewness was almost entirely eliminated, and the few extreme values were identified. Each extreme value was checked for influence, and the analysis was re-run without it to see if the results changed. There were limited changes after excluding the extreme values, so all values were retained for analysis.

Analysis

Estimates of adjusted means and 95% confidence intervals (CI) from 3x5 mixed model Analyses of Variance (ANOVAs) were used to determine if selected interactions or main effects for group were present. For interactions, an overall, within-subjects p-value was identified from the ANOVA for the interaction and assessed if it was less than 0.05. In that interaction, if a group adjusted mean for that task fell outside the 95% CI for another group, that mean was considered different from the other group. Traditional Tukey-post hoc tests were also performed and reported.

Selected interactions were also assessed using solely the 95% CI in the same manner. If no interaction was noted, main effects for group were assessed, using 95% CI as described above, but for estimates of adjusted means collapsed across tasks. Effect sizes were reported to indicate the magnitude of the differences. Additionally, the ratio of upper to lower 95% confidence level (CLR) was presented to indicate precision of the confidence interval.[131] This method was modified from the published description, taking the absolute values of the CI limits, and finding the ratio of the larger to the smaller.[131]

A preliminary 1-Way ANOVA was used to ensure the groups were statistically equivalent in age, height, and mass and statistically different in ankle function as reported in the questionnaires. A 3x5 mixed model ANOVA (3 ankle stability groups x 5 tasks) was used to determine 95% CI for interactions and group main effects for each kinematic variable (*Research Questions #1 and #4a*). A 3x5 mixed model ANOVA was used to determine 95% CI for interactions and group main effects for each kinetic variable (*Research Question #2 and #4a*). For *Research Question #3 and 4a*, the same type of ANOVA was used for EMG variables. For *Research Question #4a and #4b*, the mean standard deviation (SD) coefficient of variation (CV) were calculated for each dependent variable in each task (see equations 4-6 in Chapter 2). A 3x5 mixed model ANOVA was used to determine 95% CI for interactions and group main effects on the SD and CV of each variable. Because of their long-standing use in statistical analyses and interpretation, we also reported traditional F-values and p-values. This was as a supplement to the CI and to aid in interpreting the relatively new use of CI. A summary of the research question, dependent variable, and statistical procedure used to test the question is in Table 2.

Levene's test for equality of variances were checked for each variable. Because Mauchly's test of sphericity was significant on all the repeated measures ANOVAs, the Greenhouse-Geiser adjustment was used during analysis. Post-hoc testing of significant interactions were done by hand using the Tukey HSD procedure. For the post-hoc, d-critical was found using

Equation 7: $d_{critical} = q_a, df_{error}\sqrt{\frac{MS_{error}}{n}}$ with $d_{critical}$ being the critical value, q_a the number of ordered means (cells) being compared, df_{error} from the within subjects ANOVA table, MS_{error} from the within subjects ANOVA table, n the number of subjects in each group (or the number making up each mean being compared or the number in each cell), and the $\alpha = 0.05$. Thus, for interactions in Research Question 4, q_a was 15, n was 21, and the df_{error} and MS_{error} were obtained from the appropriate ANOVA table. Differences between 95% CI for interactions and group differences were also assessed as described above. The analysis was later re-run using a ranked transformed ANOVA as a parametric test.

Pilot Studies

Reliability

Using 4 CAI and 4 control subjects, a brief reliability study was performed on the kinematic and kinetic data. I used the same methods as detailed in this chapter for subject set up and had subjects perform the drop ump tasks. The subjects were matched for gender (two females and two males per group), age, height, weight, activity type and level, and limb dominance. The age range was 18-21 years old. Using a repeated measures analysis of variance (ANOVA), I tested for differences between the CAI and control groups. Only the peak vertical ground reaction force variable was different between the groups. I then collapsed the groups for analysis of all the variables except peak vertical ground reaction force. Using an intraclass correlation coefficient (ICC 2,1) and standard error of the measurement (SEM), with 5 trials and an n of 8, I calculated the reliability for each of the kinematic and kinetic variables of interest on the drop jump. See Table 3. The peak vertical ground reaction force is reported with an n of 4 because the CAI and control groups were analyzed separately.

In summary, the kinematic ankle variables had ICC values of 0.67-0.88 (SEM = 1-5 degrees) and the knee variables had values of 0.68-0.97 (SEM = 1-5 degrees). In the control subjects peak vertical GRF ICC was much higher and the SEM much smaller than in the CAI group. Time to peak vertical GRF ICC was low. It appears CAI subjects are least reliable in terms of kinetics, but variability is a question of interest, so those levels are acceptable. Because the calcaneal sensor placement is not well reported in the literature, special attention was given to that variable's reliability. It appears acceptable with moderate ICC values and SEMs that are within clinically relevant ranges.

I also performed a laxity testing pilot study on 4 MAI subjects with gross ankle ligamentous laxity using the methods described in this chapter. A metallic hand held dynamometer, however, was used in the trials to impart anterior-posterior forces instead of manually. A metal offset of approximately 0.110m was noted using the dynamometer, so it was decided that only the hands would be used to impart forces. There will be no difference in magnitude of forces imparted, since the dynamometer force was also applied manually, but the magnitude of the force will not be recorded. With the hand held dynamometer, the reliability of the modified anterior drawer laxity test with an anterior to posterior force was measured using an ICC (2,1) with an SEM. Values for that test were 0.70 (0.006m) and the modified anterior drawer with a posterior pulling mechanism was 0.61 (0.001m). For the clinical orthopedic tests that were performed without foot fixation, the talar tilt test ICC and SEM were 0.79 (2.71 degrees) and the anterior drawer was 0.50 (0.008 m). It appears the best tests are the talar tilt and the anterior drawer with fixated foot and pushing posteriorly. Increasing the number of trials and removing the metal will likely improve the reliability. For initial data collection in this secondary objective measure, the reliability and SEM appear acceptable. This data will not be used to separate groups or as a dependent variable but as initial data for secondary analysis.

Power

The following power calculations are based on the t-test model, which is very conservative with respect to effect size. Caulfield and Garrett[31] reported differences in kinematic variables such as ankle and knee flexion angles before and after contact during a single leg drop landing with an n of 10 per group. Power calculated from estimated means in graphic data was 0.60-0.99 with an effect size of 0.93-1.15. The authors did not report means and standard deviations in table format. For kinematic data, it appears a sample size of 10 is adequate.

I used pilot data from 4 CAI and 4 control subjects performing the drop jump task to perform an a-priori power analysis using the conservative t-test model. See Table 4. In summary, the ankle variables for plantar flexion at initial contact, inversion-eversion at initial contact, maximum plantar flexion and maximum eversion all required 20 subjects or fewer to achieve a power of 0.80. The ankle variables maximum dorsiflexion and maximum inversion would require 25-30 to 50 subjects, respectively for the same power. This increase in sample size may be due in part to the small range of motion available at the ankle in those directions. Because the other variables had a smaller sample size necessary, that is the sample size I will use in this study. The knee kinematic variables all required much larger sample size to reach a power of 0.80. See Table 4. All of the variables required at least 40 subjects and several were into the hundreds of subjects. The effect sizes for these variables were all much smaller, ranging from 0.09 to 0.61 with associated low power of 0.25 or less. It is not feasible to test several hundred subjects for this project. Since the ankle is the primary joint of interest, I will use the proposed n of 20 per group and if the knee variables effect sizes and power are too low, the data will not be included. It is also possible the two groups are simply not different in terms of knee motion and that the small differences in means will be clinically relevant.

Caulfield and Garrett[18] observed no differences in kinetic variables such as peak ground reaction forces (vertical, anterior-posterior, or medial-lateral) between CAI subjects and controls when the forces were normalized to body mass in the 150ms post-impact from a single leg drop jump. Calculated power was 0.08-0.19 with effect sizes of 0.001-0.30. The authors also tested a time to peak force variable and found significant differences in lateral and anterior forces, with a power of 0.57-0.70, and effect sizes of 0.78-0.89. The other ground reaction forces were not significantly different. In those variables, power was <0.27, with effect sizes of 0.08-0.47. This same project found significant differences in the medial-lateral force (at 30-40ms after impact), anterior-posterior force (at 50ms after impact), and vertical force (at 25-35 and 85-150ms after impact) as a percentage of body mass. The authors did not provide tabled means and standard errors, so means and standard deviations were estimated from graphs. The sample size was 10 control and 14 CAI subjects. Increasing the sample size is likely necessary to increase the statistical power available.

With my pilot data, the sample size required to reach a power of 0.80 on the kinetic variables would be 75-300. See Table 4. The effect sizes were also small. It appears a sample size of 20 would not be adequate to detect differences between groups. Again, it is not feasible to test several hundred subjects. Caulfield did find significant differences in some GRF variables with a smaller sample size.[18] Variability may also play a role in the low power and effect size. In my pilot work, the initial ANOVA comparing groups prior to the ICC indicated they were significantly different and the reliability in the CAI group was much lower. Because variability is of interest, this may be able to explain the lack of difference and low power between groups.

In a separate publication, Caulfield et al.[9] reported significant differences in integrated EMG (IEMG) with groups of 12 CAI and 10 control subjects. The authors calculated IEMG during 150ms linear envelopes on either side of impact, which was then expressed as a percentage of peak activity in the linear envelope, comparing between groups. There were no significant differences in the tibialis anterior or soleus IEMG pre or post-impact. There was a trend toward increased tibialis anterior activity pre-impact in the CAI group during the drop jump, but it was not statistically significant. The CAI group had reduced peroneal IEMG compared to controls during pre-impact periods in the drop jump, but no post-impact differences. Power was calculated from tabled data and was less than 0.08 to 0.48 with effect sizes of 0.06-0.64. Previous work in our laboratory found significant differences between CAI and controls in terms of soleus activity post-impact in a jump landing with a sample size of 10 per group.[19] EMG is marked by variability both between and within subjects. We will standardize electrode placement and MVICs as much as possible, reporting EMG values as percentages of MVIC to normalize between subjects. However, high variability and low power is still possible.

Previous pilot work using the Ankle Assessment Questionnaire demonstrated significant differences in scores between the CAI and control groups. Each group had a n of 10, for an effect size of 4.0 and a power greater than 0.99. Another study with 24 CAI and 24 control subjects used the same questionnaire and had an effect size of 15 and power greater than 0.99. In a study of 30 CAI subjects and 19 healthy subjects, the FADI and FADI-S demonstrated significantly different scores between groups. The FADI and FADI-S had effect sizes of 1.31 and 1.59 respectively and powers greater than 0.98. Other than the above examples, there are few articles to date that provide data with which to calculate power and effect size, and virtually none report the a priori or post-hoc power calculations. A sample size of 20 per group appears to generate adequate statistical power.

Limitations

There are several potential challenges with this dissertation, however I have designed the study taking all of these into consideration. The first was the ability to recruit and test an adequate sample of recreational athletes between the ages of 18-35 who fit into each ankle stability group: functional instability, mechanical instability, and comparison group. Previous work in our lab has demonstrated an adequate CAI subject pool from which to draw, and, supported by literature values, we believe over the 4-month data collection period, subjects will be found to fit the criteria. Adequate numbers of comparison subjects also appear to be in the general recreational population through secondary analysis of previous and ongoing projects.

The second limitation was ensuring that subjects are accurately placed into the ankle stability groups. Using self-report data for recall of injury date and severity is not always accurate. Previous work with the Ankle Assessment Questionnaire found significant differences in functional levels between CAI subjects and controls in a dissertation[33] and pilot work in the laboratory. Orthopedic tests are most commonly used to identify those with and without mechanical instability in the clinic. Using a clinical tool, coupled with the surveys, is intended to provide results with clinical applications.

The third limitation is the unknown accuracy of some of the equipment used for the proposed tasks. The forceplate has been proven valid and reliable, as have flexion-extension of the ankle and knee using the Flock of Birds coupled with the Motion Monitor software. However, the sensor placement on the calcaneus for these tasks is unique to CAI subjects, although it has been previously reported in the literature.[99] Although valgus-varus at the knee is also accepted, inversion-eversion at the ankle has less support, if any, in the literature.[99] My pilot data indicate the calcaneal sensor is reliable and has face validity (see Tables 3 and 4). EMG measures are extremely variable, but with a single testing session, we hope to decrease some of the potential error. Validity has not yet been established in either questionnaire in large populations. However, preliminary work has established that the groups score differently on the AAQ and that individuals with a history of more sprains score worse. Despite some difficulty with certain measures, it appears an n of 20 per group for a total of 60 subjects will provide adequate statistical power for most of the variables of interest.

The coefficient of variation is only one measure of variability and does not capture the entire variability of the system. I am using discrete and continuous calculations of CV. This is only a preliminary assessment of variability in a CAI population, but it is a start.

Summary

Very few investigators have utilized kinematic, kinetic, and EMG analysis in a CAI population. This is the first step in assessing whether alterations in movement patterns may influence the development and perpetuation of CAI. By using established methods in combination with new, a complete biomechanical picture of movement performance across several tasks can be captured. With this information, negative movement strategies can be identified and used to design rehabilitation programs and or prevention programs to decrease the incidence of CAI and avoid joint degeneration with aging.

Table 1: Dependent Variable Name, Definition, Measurement Time, and Instrument

Variable Name	Definition	Measurement Time & Instrument
Clinical		
Demographic Questionnaire	Years of experience with sport activity Type/frequency of activity; injury history	Initial screening
Ankle Assessment Questionnaire	Self-report assessment of ankle function with various activities	Initial screening
Ankle Range of Motion	Maximum active plantar flexion, dorsiflexion, inversion, and eversion	Initial screening Universal goniometer
Limb Dominance	Preferred limb to step-up, kick a ball, and recover balance	Initial screening Ask subject to perform
Kinematics		
Joint angle at initial contact	Ankle and knee flexion, ankle inversion/ eversion, and knee valgus/varus at initial contact (defined as >10Volts on the forceplate)	Test session Electromagnetic tracking system
Maximum joint angle	Joint angles (above) at maximum angle during stance	During walk, step-up, run, drop jump,
Joint displacement	Total joint motion during stance, defined as foot contact with the forceplate	and stop jump
Kinetics		
Peak ground reaction forces	Peak force during impact Vertical, medial-lateral, and anterior-posterior	Test session Non-conductive forceplate during 5 tasks
Time to peak ground reaction force	Time from initial contact to peak force Vertical, medial-lateral, and anterior-posterior	Test session Non-conductive forceplate during 5 tasks
Electromyography		
Muscle activity mean amplitude	EMG activity of the tibialis anterior, peroneals, lateral gastrocnemius, and soleus of the test leg normalized to MVIC	Test session EMG system and Motion Monitor software during 5 tasks
Variability		
Mean standard deviation Of trials (curve-average) Coefficient of variation	Within subject variability on each task	Test session Each dependent variable above See equations 4-6

Table 2: Research Question Summary

Research Question	Objective	Variables	Statistical Method
1	Test for differences in kinematics Functional ankle instability group Mechanical ankle instability group Comparison group	Ankle/Knee Flexion Inversion/eversion Valgus/varus At Initial contact Maximum angle Displacement	3x5 mixed model ANOVA Tukey HSD post-hoc if necessary
2	Test for differences in kinetics Functional ankle instability group Mechanical ankle instability group Comparison group	Ground reaction forces Vertical Anterior-posterior Medial-lateral Peak normalized to body mass Time to peak	3x5 mixed model ANOVA Tukey HSD post-hoc if necessary
3	Test for differences in muscle activity Functional ankle instability group Mechanical ankle instability group Comparison group	EMG mean amplitude Tibialis anterior Peroneals Lateral gastroc-nemius Soleus	3x5 mixed model ANOVA Tukey HSD post-hoc if necessary
4a	Group x task interaction for each Research Question #1-3	Dependent variables from Research Questions #1-3	3x5 mixed model ANOVA
4b	Assess within and between subject variability on each dependent variable	Mean SD and CV From Research Questions #1-3	3x5 mixed model ANOVA SD and CV from each dependent variable on each task

Table 3: Summary of Reliability Tests in Pilot Study

Variable	ICC (2, 1)	SEM (in degrees unless otherwise stated)
Ankle plantar flexion at initial contact	0.86	4.73
Ankle inversion-eversion at initial contact	0.74	2.16
Knee flexion-extension at initial contact	0.97	1.66
Knee valgus-varus at initial contact	0.96	1.22
Maximum ankle plantar flexion angle	0.88	4.11
Maximum ankle dorsiflexion angle	0.81	5.13
Maximum ankle inversion angle	0.78	2.14
Maximum ankle eversion angle	0.67	4.39
Maximum knee flexion angle	0.88	4.38
Maximum knee extension angle	0.93	2.45
Maximum knee valgus angle	0.68	4.90
Maximum knee varus angle	0.95	2.19
Time to peak vertical ground reaction force	0.47	0.20
Normalized peak vertical ground reaction force		
CAI group	0.44	0.77 x body mass
Control group	0.93	0.50 x body mass

Table 4: A-priori Power Calculations using Pilot Data

Variable	Control mean	CAI mean	Largest SD	d	n	Power	n for power of 80
Ankle plantarflexion at initial contact	39.53	26.70	8.81	1.46	8	85	--
Ankle inversion-eversion at initial contact	9.24	6.19	3.60	0.85	8	46	20
Knee Flexion-extension at initial contact	6.86	7.80	8.98	-0.10	8	7	>1000
Knee valgus-varus at initial contact	-6.21	-2.68	6.72	-0.53	8	25	40-50
Time to peak vertical ground reaction force	0.06	0.06	0.02	-0.22	8	10	300
Normalized peak vertical ground reaction force	-4.34	-3.88	1.35	-0.34	8	13	75-80
Maximum ankle plantarflexion	47.12	36.74	10.71	0.97	8	61	13
Maximum ankle dorsiflexion	-28.10	-22.16	8.99	-0.66	8	38	25-30
Maximum ankle inversion	11.96	9.70	4.21	0.54	8	25	50
Maximum ankle eversion	-8.29	3.20	6.58	-1.75	8	99	8
Maximum knee flexion	54.52	49.26	10.23	0.51	8	25	50
Maximum knee extension	4.07	4.85	8.53	-0.09	8	7	>1000
Maximum knee valgus	-8.90	-6.58	8.64	-0.27	8	13	180-200
Maximum knee varus	4.44	6.57	10.44	-0.20	8	10	300

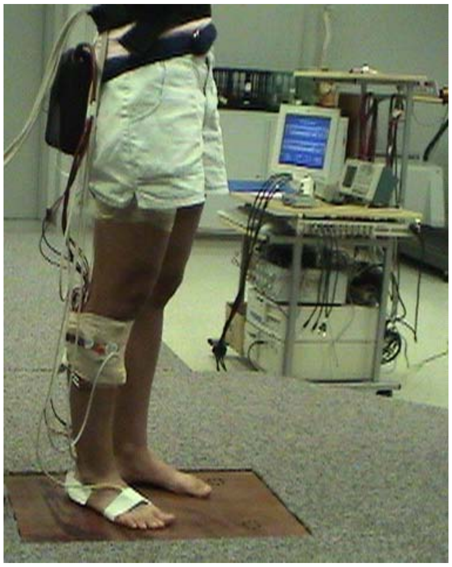

Figure 1. Subject set-up for electromyography and electromagnetic tracking system sensors.

Figure 2. Subject positioning and device for anterior drawer laxity testing.

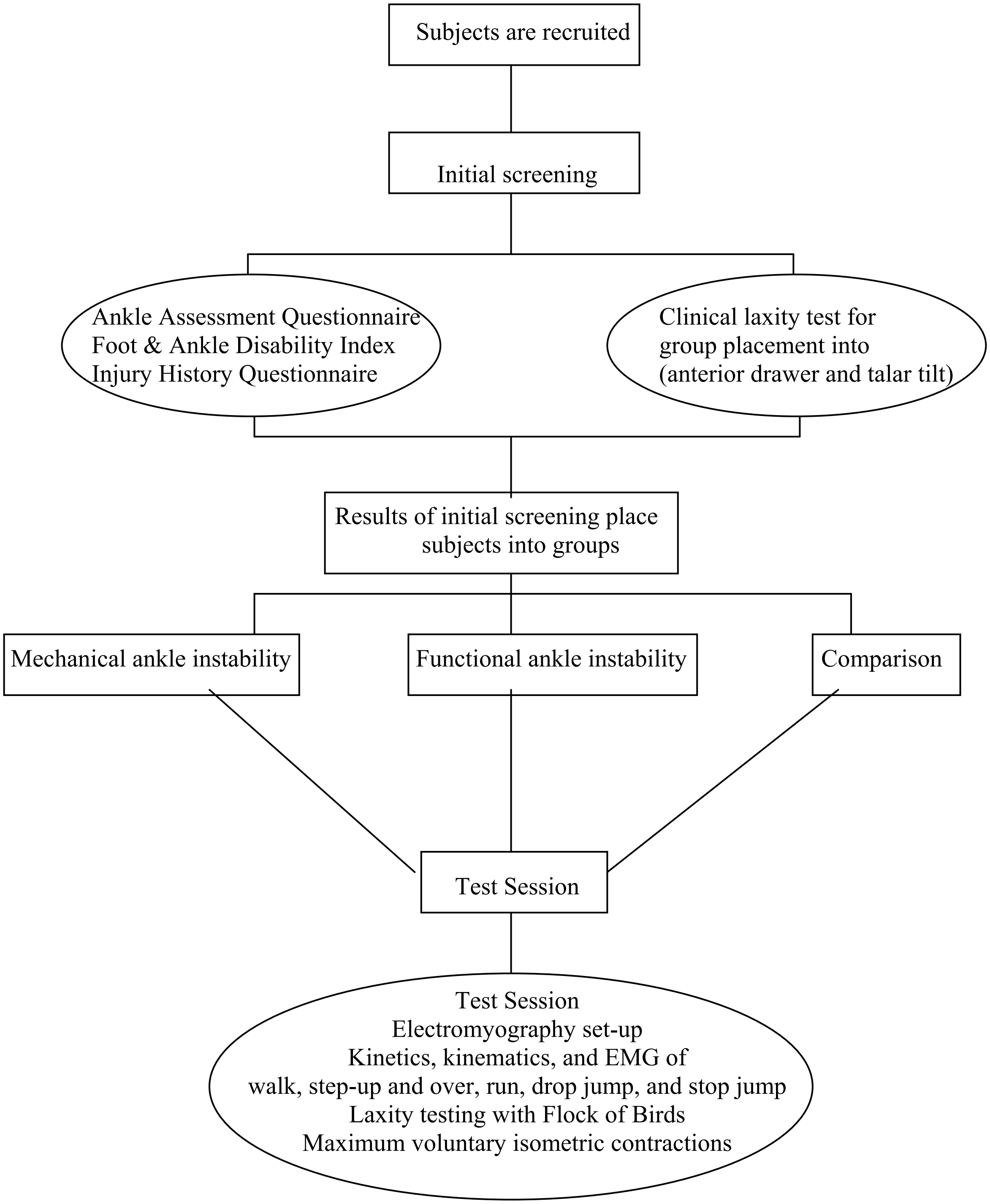

Figure 3. Testing procedures

CHAPTER IV

SUMMARY OF FINDINGS

This chapter serves as a brief summary of the results of each research question. Some interpretation of results was included, however the majority of the discussion of the results and their implications is in the attached manuscripts. For variables not included in the manuscript, more discussion was included in this chapter. The results are organized by Research Question. To determine differences between groups, estimated adjusted means, 95% confidence intervals (CI), and effect sizes were used. Additionally, the ratio of upper to lower 95% confidence level (CLR) was presented to indicate precision of the confidence interval.[131] This method was modified from the published description, taking the absolute values of the CI limits, and finding the ratio of the larger to the smaller.[131] Traditional measures of significance, including p-values, were reported as well.

The most important finding of this study was that individuals with chronic ankle instability (CAI) exhibited altered movement patterns than the comparison group across and within tasks. This is most evident in individuals with mechanical ankle instability (MAI). The implications of this finding have repercussions on treatment and rehabilitation programs, as well as the long-term joint health of the ankle and possibly the knee in individuals with MAI and functional ankle instability (FAI). The research questions address interactions between groups and tasks, as well as main effects for group. The main effects of task were ignored, because tasks are expected to yield different results, and this comparison was therefore not of interest in this investigation.

Demographics

There were 11 male and 10 female subjects in each of the three groups. Subject demographics are reported in Table 5. Subjects' scores on the 3 ankle stability questionnaires are reported in Table

6. The initial 1-Way ANOVA (Table 7) demonstrated the groups were equivalent in age, height, and mass ($p > 0.05$). The MAI and FAI groups reported significantly lower scores than the comparison group in both the Ankle Assessment Questionnaire (AAQ) and Foot and Ankle Disability Index Sport Subscale (FADI-S) ($p < 0.05$). On the FADI, the MAI group scored significantly lower than the FAI, which scored significantly lower than the comparison group ($p < 0.05$). Less than 1/3 of subjects (20 out of 63) reported bilateral instability. Additionally, the MAI group reported more sprains averaged over the course of their lives (8 right, 5 left) than the FAI (4 right, 4 left) or the comparison (3 right, 3 left). Thus, it appears the groups were appropriately matched by gender, age, height, mass and limb dominance. The two ankle stability groups also reported decreased function in the test ankle compared to the comparison group.

Research Question 1

Are there significant differences between the three ankle stability groups in kinematic measures?

Part A: Flexion, inversion/eversion, and valgus/varus angles at initial contact (ankle and knee)

A main effect for group was observed in the ankle plantar flexion/dorsiflexion angle at initial contact ($F_{(2, 60)}=3.482$, $p=0.037$) (Table 8). Post-hoc testing revealed the MAI group demonstrated significantly less ankle plantar flexion (or more dorsiflexion) than the comparison group ($p= 0.030$). Additionally, using 95% CI, the MAI group's estimated marginal mean fell outside the 95% CI for both the FAI and comparison groups. The effect sizes of those comparisons were 0.23 and 0.37, respectively. Thus, the MAI group demonstrated less plantar flexion than both other groups. No other main effects for group were noted at initial contact in either joint (Tables 8 and 9).

Part B: Maximum flexion and inversion/eversion or valgus/varus angles during stance (ankle and knee)

A main effect for group was noted on maximum ankle plantar flexion angle ($F_{(2, 60)}=3.317$, $p=0.043$) (Table 8). Tukey post-hoc testing revealed no significant differences at the $p<0.05$ level. The MAI estimated marginal mean was outside the 95% CI for both the FAI and comparison groups, with effect sizes of 0.31 and 0.32, respectively. The MAI group demonstrated smaller maximum plantar flexion angles (more dorsiflexion) than the FAI and comparison groups.

No main effect for group was found in maximum ankle dorsiflexion using the alpha level of 0.05 criterion, however, the comparison group estimated marginal mean was outside the 95% CI for the MAI group, with an effect size of 0.25. The MAI group demonstrated smaller maximum ankle dorsiflexion angles than the comparison group (Table 8).

A main effect for group was also present for maximum ankle eversion during the stance phase ($F_{(2, 60)}$=3.922, p=0.025). Post-hoc testing revealed the MAI group exhibited more eversion than the FAI group during foot contact (p= 0.042). (Table 8). We observed the estimated marginal mean for the MAI group was outside the 95% CI for both the FAI and comparison groups. The effect sizes were 0.34 and 0.35. The MAI group demonstrated greater maximum eversion angles than the FAI and comparison groups (Table 8). No other main effects for group were noted at maximum angles in either joint (Table 8 and 9).

Part C: Flexion and inversion/eversion or valgus/varus displacements (total range of motion) during stance (ankle and knee)

A main effect for group was observed on ankle sagittal plane (plantar flexion-dorsiflexion) displacement ($F_{(2, 60)}$=5.402, p=0.007) (Table 8). Post-hoc testing revealed the MAI group demonstrated significantly less plantar flexion-dorsiflexion displacement than both the FAI and comparison groups (p=0.022 and p=0.013, respectively). The estimated marginal MAI mean was outside the 95% CI for both the FAI and comparison groups, with effect sizes of 0.39 and 0.42.

A group main effect was also present for ankle frontal plane (inversion-eversion) displacement ($F_{(2, 60)}$=5.860, p=0.005) (Table 8). Post-hoc testing indicated the MAI group demonstrated more inversion-eversion displacement than both the FAI and comparison groups during the stance phase (p=0.034 and p=0.005, respectively). The estimated marginal MAI mean fell outside the 95% CI for both the FAI and comparison groups, with effect sizes of 0.36 and 0.46, respectively. No group main effects for displacement were noted at the knee (Table 9).

Interpretation

Comparing across the five tasks, the MAI group demonstrated more dorsiflexion (less plantar flexion) and more eversion, as well as less sagittal plane and more frontal plane displacement. In combination, these findings may be interpreted as a coping mechanism designed to avoid lateral ankle sprain. The most common mechanism for lateral ankle sprain is plantar flexion and inversion.[1] By avoiding excessive plantar flexion and keeping the ankle more everted, the MAI group may be able to avoid a position of injury and decrease the number of sprains experienced. Clinically, this seems logical, as this close pack position of maximized joint congruency is the most stable for the joint and may be effective at avoiding risky positions. An increase in plantar flexion angle was found to correlate with increased sprains using a forward dynamics model of the lower extremity.[64] Although this movement pattern appears to try to avoid a “risky position,” it is not completely effective, as participants still reported episodes of spraining and giving way at the ankle in similar tasks to those in the study.

The increased dorsiflexion pattern we observed is consistent with previous studies. One used single leg jump landings[31] and another used walking and a step-up task.[32] However, neither of these studies distinguished whether the participants had mechanically or functionally unstable ankles. We do not know if the motion pattern we observed was exhibited before the injury or adopted after the initial sprain to avoid additional or repeat injuries.

The MAI group reported similar scores to the FAI group in both the AAQ and the FADI-S, with the comparison group scoring significantly higher. Only in the FADI questionnaire did the MAI group report decreased function compared to the FAI group, while the comparison group still scored higher than both other groups. Despite reporting similar functional abilities in sports-related tasks (such as those participants performed during testing), the unstable ankle groups demonstrated different ankle motion patterns from each other. This may be due to the altered arthrokinematics of the MAI group compared to the FAI group. If the mechanical laxity of the lateral ligaments was great enough, the MAI subjects may have been relying on bony stability instead of ligaments to support the ankle joint.[1, 59]

Ankle ligament laxity may also create greater articular incongruency at the ankle. Ankle arthritis is secondary to trauma, and instability at the ankle increases contact stress and can damage articular cartilage.[40] For example, talar displacement of more than 1 mm decreased the weight-bearing surface of the ankle by 42.3%, creating asymmetric loading of the articular surface.[58] Asymmetric loading may help explain why individuals with CAI have more medial talar articular cartilage lesions than individuals without CAI.[39] Only small amounts of articular displacement were necessary to create abnormal shearing forces.[58] By remaining in a more closed-pack position, MAI subjects may have been trying to increase the stability of the ankle joint and avoid destabilizing forces.

Interestingly, there appear to be no differences in ankle and knee movement patterns between the FAI and comparison groups, despite differences in reported function. Without mechanical laxity, the FAI group may lack the impetus to adopt an altered movement pattern at the ankle, despite repeated sprains. The differences observed between the MAI and comparison groups, and the lack of differences between the FAI and comparison groups, may elucidate some of the conflicting results in previous CAI literature. Most previous studies have not separated CAI subjects by mechanical or functional instability. A number of studies reported no differences when comparing CAI to controls in multiple variables, and our results may help account for that lack of difference.[19, 28-30, 70, 76, 78, 79] Based on our results, it appears to be important to separate out individuals with CAI into MAI and FAI groups. By differentiating between the two pathologies, clearer differences between individuals with ankle instability and controls may become evident in the literature. The different movement patterns identified here indicate that fundamental differences exist between the two groups, and collapsing them may blur the distinction and make the results confusing and inaccurate.

There were also no differences in knee pattern movements between any of the groups. This result is not consistent with a previous study which reported increased knee flexion in the CAI group during jump landing.[31] Differences in jump landing height may account for the inconsistency. Our results indicate that differences between groups due to instability are centered at the ankle, and do not manifest further up the kinetic chain at the knee. This may occur because the knee does not have any instability and has no need to adapt to differences observed at the ankle. Alternatively, we may not have observed differences at the knee because the hip joint was altered. A previous study reported individuals with CAI used a hip strategy to recover balance following perturbation.[87] The subjects with hypermobile ankles displayed earlier hip muscle recruitment,[87] which is consistent with another study that reported a change in the motor program at the hip following severe ankle injury.[21] Changes may occur proximally at the hip, though we did not test for them in this project. Use of a hip strategy, or changes in proximal joint motor control, may be why we did not observe differences in the knee joint between groups. Future research should focus on whether or not changes occur up the kinetic chain at the knee and hip. An a-priori power calculation was performed using ankle data, and indicated a sample size of approximately 20 would yield a power of 0.80. The relatively low power we observed for each of the knee variables may also account for the lack of statistically significant differences. Additionally, the effect sizes were small and there simply may have been no differences between groups.

The majority of CLR for the kinematic variables are precise and less than 2.0. However, our main effect with maximum ankle eversion had much larger CLR, up to 23.87. This lack of precision and large differences in CLR between groups calls the results regarding maximum ankle eversion into question. This value is likely unstable and heavily influenced by outliers.

<u>Research Question 2</u>

Are there significant differences between the three ankle stability groups in kinetic measures?

Part A: Peak ground reaction forces normalized to body mass (vertical, anterior, posterior, medial, and lateral)

No main effects for group were noted in any of the maximum ground reaction forces (GRF) in any direction using an alpha level of 0.05, and none of the means had overlapping 95% CI (Table 10).

Part B: Time to peak ground reaction forces normalized to body mass (vertical, anterior, posterior, medial, and lateral)

There were no differences observed in the time to peak GRF variables in any direction at an alpha level of 0.05. The MAI group's estimated marginal mean for time to peak anterior GRF (63.06 ms) was outside the comparison group 95% CI upper limit (Table 10). The effect size was 0.22, with an approximately 11% difference between means. It appears the MAI group had a slower time to peak GRF in the anterior direction than the comparison group. All other time to peak variables had overlapping 95% CI.

Interpretation

The kinetic variables were close to equivalent between groups. Only in the time to peak normalized anterior GRF did we observe differences between the MAI and comparison groups, with the MAI taking longer to reach the peak anterior GRF. This may be due to the damage in the anterior talofibular ligament, the most commonly injured ligament in lateral ankle sprains.[1] In a closed kinetic chain with the foot planted (such as in the tasks used in this study), the role of the anterior talofibular ligament is to limit anterior translation of the tibia on the fixed foot.[60] Because of its low load to failure, it is often stretched or completely ruptured following ankle sprain,[60] as was likely the case in our MAI group. Because this group demonstrated laxity in the ligament, this may be a compensatory pattern designed to limit load on the ligament and avoid stressing it during landing. Alternatively, because the ligament was stretched or ruptured, increased anterior translation of the tibia on the fixed foot might have increased the time to peak force. Our results disagree with previous findings that reported faster time to peak anterior GRF in the unstable ankle group.[18] The contradiction may be due to differences in sample: the previous study did not separate individuals with ankle instability into mechanical and functional groups. Another study reported a CAI group displayed significantly delayed time to peak force under the central-lateral forefoot and toes.[17] The authors attributed the delay to hesitation in transferring weight from heel contact to toe-off, possibly to avoid unstable situations.[17]

The comparison estimated marginal mean for peak normalized vertical GRF (-2.36 body mass) was close to the upper limit of the FAI 95% CI, but the effect size was very small at 0.21 (Table 10). This difference was only 0.12-0.14 times body mass in the unstable ankle groups (approximately 5%), but over months and years, this increase in vertical GRF experience may contribute to the long-term degeneration. We did observe differences in ankle sagittal plane displacement between the MAI and the other two groups. Given less angular displacement over which to apply the normalized vertical GRF, and with no changes in knee motion, one might expect increases in the peak vertical GRF. Perhaps changes in kinematics at the hip were able to compensate for the decreased ankle sagittal plane displacement at the ankle in the MAI group, thus making GRF equivalent, despite less time over which to apply forces.

A study comparing FAI to controls in a v-cut found the FAI group had significantly increased first peak vertical GRF on the involved leg compared to the uninvolved leg.[132] Vertical GRF was 0.79 body weight greater on the affected versus unaffected leg in the unstable group.[132] Though not statistically significant, the authors argued it was physiologically relevant, as an 80 kg athlete with a 0.79 body weight difference between sides experiences an increased load of 63.2 kg or 620 N of force for every cut performed.[132] Our results were not of similar magnitude, however, the type of task performed was different.

In the peak normalized medial GRF, the FAI group's estimated marginal mean (-0.16) was the smallest medial force, and was close to the upper limit of the MAI group's 95% CI. The effect size between the FAI and MAI groups was very small at 0.21. The difference between the FAI and other groups was approximately 5-16%. In the peak normalized lateral GRF, the FAI group's estimated marginal mean (0.18) was close to the 95% CI upper limit in the comparison group. The effect size was 0.36, with a 17-27% difference between the comparison group and the unstable ankle groups' means. A previous study reported an FAI group demonstrated more lateral GRF of 5-15% body mass compared to the control group, who exhibited more medial GRF.[18] These results match our findings, in that the unstable ankle groups had larger lateral GRF and the difference was of similar magnitude. While both the unstable ankle groups had faster time to peak medial and lateral GRF than the comparison group, the differences were minimal and less than 10% between groups.

The time to peak vertical GRF was faster in the unstable ankle groups by 13-16 ms. This difference was not great enough to cause the means to be outside the 95% CI. This was a small difference (8-10%), but, over the long term, the faster loading may contribute to ankle joint degeneration. A previous study, reporting similar results to ours, found no significant differences between the groups in peak vertical GRF, or time to peak vertical force. The authors reported the FAI group experienced peak vertical GRF 10-13ms earlier in than the controls, which matches our findings.[18] Another study, however, reported the unstable ankle group demonstrated faster time to first peak vertical GRF in comparison to controls when performing a v-cut.[132] The nature of the task may explain the difference in results.

The CLR values for kinetic variables are fairly precise. Only peak normalized lateral GRF had a CLR greater than 2.0. This most likely represents a fairly stale number not influenced heavily by outliers.

<u>Research Question 3</u>

Are there significant differences between the three ankle stability groups in surface electromyography measures?

Part A: EMG mean amplitude for tibialis anterior, peroneus longus, lateral gastrocnemius, and soleus muscles

There were no significant group main effects on any muscle's electromyography (EMG) mean amplitude as a percentage of maximum voluntary isometric contraction (MVIC) using an alpha level of 0.05 (Table 11). The FAI group's tibialis anterior mean amplitude (46.90%MVIC) was greater than the comparison's group 95% CI upper limit, with an effect size of 0.25. This difference in group means was approximately 19%. Thus, the FAI tibialis anterior mean amplitude appears to be greater compared to the comparison group across the tasks. The FAI group's lateral gastrocnemius mean amplitude (114.94%MVIC) was smaller than the 95% CI lower limit for both the MAI and comparison groups. The effect size was 0.27 and 0.21, respectively, for a mean difference of 23-27%. The FAI group demonstrated less lateral gastrocnemius mean amplitude over the five tasks in comparison to the MAI and comparison groups. There were no other group differences in the peroneals and soleus muscles.

Interpretation

It appears that across tasks, the FAI group displayed greater tibialis anterior mean amplitude than the comparison group and less lateral gastrocnemius mean amplitude than the comparison and MAI group. Few studies have utilized surface EMG on CAI subjects during voluntary movements. In those that have, the differences were observed in the peroneal muscles. Peroneal surface EMG activity was significantly lower on the injured side of FAI subjects when compared to their uninjured side during walking.[133] During two different types of jump landing, subjects with FAI demonstrated significantly decreased peroneal integrated EMG pre-impact when compared to control subjects, with no differences post-impact.[9] This same study reported no differences in the soleus or tibialis anterior before or after impact.[9] Our results do not agree with these findings, and instead indicate differences in the FAI group in the muscles moving the ankle in the sagittal plane. Clinically, differences in peroneal muscle activity would be expected, as it is the muscle that controls eversion and is active to keep subjects from inverting toward injury. The differences we observed may be attributed to the differences in sagittal plane kinematics reported earlier. However, only the FAI group was different, and most kinematic differences involved the MAI group. Instead, we may be observing a lack of adequate activity or co-contraction that could play a role in the repeated sprains in the FAI group. Without adequate active stabilizers working on the ankle joint, the FAI group may be more at risk for sprains. The high degree of within and between subject variability in EMG may confound these results.

The CLR values for EMG variables appear to be fairly precise. All of them are less than 2.

<u>Research Question 4</u>

Are there significant group by task interactions?

Part A: Using the variables as in Research Questions #1, 2, and 3, use a 3 x 5 mixed model ANOVA to test for interactions between groups and tasks.

Selected group x task interactions were evaluated based on the most pertinent and appropriate comparisons for the aims of this study. An interaction was observed for the ankle plantar flexion angle at initial contact, with $p<0.05$. The estimated marginal means for the groups on each task were compared, and the MAI group means fell outside the comparison group's 95% CI on each task, with effect sizes ranging from 0.44-1.19 (Figure 4). The MAI means were outside the FAI's 95% CI on the step up, run, and drop jump tasks, with effect sizes ranging from 0.54-0.91. The FAI group demonstrated less plantar flexion at initial contact (more dorsiflexion) than the comparison group in the walk and stop jump tasks, with means beyond the comparison group's 95% CIs and effect sizes of o.39 and 1.04 respectively.

Using $p<0.05$ and 95% CI, a group x task interaction was observed in the maximum ankle inversion variable. The MAI group mean was below the 95% CI lower limit for the comparison group in the step up and over task (effect size 0.52), and below the FAI 95% CI lower limit in the stop jump task (effect size 0.61). The FAI group mean was below the 95% CI lower limit for the comparison group in the walk task (effect size 0.75) (Figure 5).

A group x task interaction was observed for ankle frontal plane displacement using $p<0.05$, with Tukey post-hoc testing revealing significant differences between the MAI and FAI/comparison groups on the step up and over, drop jump, and stop jump tasks (Figure 6). Using Equation 7 in Chapter 3, the $d_{critical}$ value was calculated as $q_a = 15$, $df_{error} = 175$ for value of 4.80, and $(\sqrt{16.227/21}) = 0.879$. Multiplying $4.80 * (0.879) = 4.22$.[134] Using the $d_{critical}$ value, the MAI group demonstrated greater frontal plane displacement than the FAI and comparison groups in the drop jump, step up, and stop jump tasks using the $\alpha = 0.05$ criteria. Using the 95% CI criteria, the MAI group's mean displacement for each task was greater than the comparison group's upper limit on each task and the FAI group's upper limit on the step up, run, drop jump, and stop jump tasks (effect sizes 0.86-1.44). The FAI group displacement was also greater than the comparison group, but only on the walk task.

A group x task interaction with p-value <0.05 was also observed in lateral gastrocnemius EMG mean amplitude (Figure 7). In this case, the q_a=15, df_{error}=121.7 for a value of 4.90 and √(5629.39/21)=16.37. Multiplying 4.90* 16.37 resulted in a $d_{critical}$ of 80.23.[134] Specifically, the MAI group demonstrated greater EMG mean amplitude expressed as a percentage of MVIC than the FAI group in the run task, and the comparison group demonstrated greater mean amplitude than the FAI group in the stop jump task using the alpha level of 0.05 criterion. Using 95% CI, the MAI mean was beyond the upper limit of the FAI group on the run, drop jump, and stop jump tasks (effect sizes 0.29-1.17). The FAI mean was below the comparison group's 95% CI lower limit on the stop jump task.

Additional interactions were observed using only the 95% CI, with p-values >0.05. For maximum ankle plantar flexion angle, the FAI group demonstrated greater plantar flexion than the MAI group on the step up, run, drop jump, and stop jump tasks. The comparison group demonstrated greater maximum plantar flexion than the MAI group on all the tasks except running (Figure 8). The MAI group demonstrated less maximum dorsiflexion than the FAI group on the walk and step up tasks and than the comparison group on the run and drop jump tasks (Figure 9). The FAI exhibited less maximum dorsiflexion than the comparison group only on the stop jump (Figure 9). In maximum ankle eversion, the MAI group demonstrated larger means than the FAI and comparison groups in the walk, step up and over, run, and drop jump tasks (Figure 10). The MAI group also demonstrated less sagittal plane displacement than the FAI and comparison groups on each task (Figure 11).

In GRF variables, interactions were noted using 95% CI. In the time to peak vertical GRF, the MAI group had faster time to peak than the comparison group in the step up and drop jump tasks. The FAI group was faster than the comparison in the drop jump task as well (Figure 12). The MAI group was slower in time to peak anterior GRF than the comparison group in the drop jump task, and the FAI group in the stop jump. Additionally, the FAI group was slower than the comparison group in the drop jump (Figure 13). In EMG, the MAI group TA mean amplitude was greater than the comparison mean amplitude in the step up and run tasks, but less than the FAI group in the drop jump.

Additionally, the FAI group exhibited greater TA mean amplitude than the comparison group in the walk, run, and drop jump tasks (Figure 14).

Interpretation

At initial contact, the MAI group displayed less plantar flexion (more dorsiflexion) than the comparison group on all the tasks and the FAI group on 3 of the tasks. It appears that no matter what type of task is being performed, whether the performance demand is great or not, the MAI group contacts the ground in a more dorsiflexed position. This matches our previous results regarding main effects for group. Because the lateral ligaments exhibit laxity in the MAI group, landing in a more dorsiflexed position may offer protection against feelings of instability. The fact the MAI group was more dorsiflexed than the FAI group (who did not display laxity in the lateral ligaments) in a number of tasks, lends credence to this interpretation. To an extent, the FAI group demonstrated a similar strategy, landing in less plantar flexion (more dorsiflexion) than the comparison group in the stop jump and walk. Since the FAI ligaments are more intact, there may not be a similar impetus to adopt this landing strategy. There does not appear to be a pattern between the demands of the task and whether or not the FAI group displayed decreased plantarflexion.

Two different reasons may account for the ankle maximum inversion and frontal plane displacement interactions. Individuals who suffer an ankle sprain most often injure the anterior talofibular ligament with the calcaneofibular ligament being the second-most injured.[1, 59] The role of the calcaneofibular ligament is to limit inversion and help control frontal plane motion at the ankle.[1, 59] It is very likely the calcaneofibular ligament was excessively stretched or torn in the MAI group because they demonstrated greater joint laxity to the talar tilt test, designed to detect deficiency in that ligament.[47] Thus, because of their mechanical laxity, this group may demonstrate greater motion in this plane. We observed earlier in Research Question 1B that the MAI group was oriented more towards eversion and had a greater maximum eversion angle. Although excessive frontal plane motion may be detrimental in terms of joint stability, if the MAI group was oriented toward more eversion, it may represent an adaptive movement pattern designed to avoid lateral ankle sprain. With greater maximum eversion, it seems logical the group would also undergo more frontal plane (inversion-eversion) displacement during foot contact. Thus, this finding may be attributed to joint instability in that plane following injury or to a movement pattern designed to avoid injury. There were no differences between the FAI and comparison groups, which makes the mechanical laxity seem the factor involved with the group differences. See additional analyses at the end of this chapter for discussion regarding active range of motion value differences between groups.

In the lateral gastrocnemius interaction, the FAI group demonstrated less mean EMG amplitude in that muscle during the run task when compared to the MAI group. The FAI group also demonstrated less mean amplitude than the CAI group during the stop jump. The MAI group landed with less plantar flexion (increased dorsiflexion) and less sagittal plane displacement, therefore they may use the lateral gastrocnemius to contract and control the limited motion in that plane. The comparison group also demonstrated greater lateral gastrocnemius mean amplitude compared to the FAI group, but only on the stop jump task. This is the most challenging task, and the FAI group may not be relying on dynamic stabilizers at the ankle as much as the other groups. Failure to adequately co-contract during landing and foot contact may account for the repeated episodes of spraining and giving way. A previous study supports this finding as it reported decreased cocontraction in a CAI group,[85] however, another study hypothesized that motor control changes occurred following injury, and unstable subjects “supraactivated” leg muscles in order to control ankle stability.[83] This latter hypothesis is supported by other authors, who wrote that changes in ligaments following injury create EMG differences, thus supporting the idea of coping strategies.[86]

Why only the lateral gastrocnemius demonstrated differences is unclear. Differences in the peroneals would make sense clinically. There is limited EMG analysis of CAI subjects during voluntary movement, but one previous study reported no differences in peroneal EMG activity in CAI subjects following landing, but did find the CAI group demonstrated decreased peroneal activity pre-impact.[9] This does not fit our findings of differences after landing, but we did not study pre-activity, and the groups were not separated into MAI and FAI. Interpreting the EMG interaction is difficult with limited literature for comparison and the high variability. Overall, FAI subjects displayed lower mean EMG amplitude as a percentage of MVIC, although the differences were not large. See additional analyses at the end of the Chapter for discussion regarding MVIC values.

Other interactions not significant at the 0.05 level reveal similar findings. The MAI group exhibited less maximum plantar flexion, less maximum dorsiflexion, less sagittal plane displacement, and greater maximum eversion than either the FAI and/or comparison group on all the tasks. The MAI group had less active dorsiflexion range of motion available (see Additional Analyses), which may indicate a lack of available closed-kinetic chain dorsiflexion that influenced motion patterns. The MAI group also demonstrated greater eversion available in active range of motion. The lack of sagittal plane motion and increased eversion range of motion during stance may be a result of the differences between groups in available active range of motion, or be attributable to coping mechanisms to keep the ankle in its most stable position during landing. The MAI group may be restricting its sagittal plane motion across all the tasks and using more eversion to remain in the most stable and "locked" position (joint close-packed position) during stance phase to try to prevent lateral ankle sprains. Interestingly, the FAI group is more similar in these measures to the comparison group, which may indicate a basic difference in the pathology and arthrokinematics between the FAI and MAI groups.

Other interactions observed using only 95% CI indicated the MAI group reached peak vertical GRF faster than the comparison group in the step up and drop jump task. These two tasks require landing from a height, and may be good indicators of deficits in shock attenuation in MAI groups during landing. Even though the differences between group means were small (Figure 12), the clinical relevance of the difference may impact joint health over years of use. Loading the joint at a faster rate, with decreased joint displacement to absorb the force, may lead to higher incidence of articular cartilage degeneration and osteoarthritis. The MAI group demonstrated slower time to peak than the FAI and comparison groups on the stop jump and drop jump tasks, respectively. These were the two most challenging tasks, requiring force attenuation during landing and stopping of anterior motion. If the MAI group had a stretched or damaged anterior talofibular ligament, the tibia may have moved more anteriorly during stance or the MAI group may have been avoiding stressing the ligament. In either case, it appears the ligament was deficient in its ability to stop anterior motion of the tibia on the fixed foot. This may have implications for ankle joint stability if the talus is not stable in the mortise and microtrauma can occur to the articular cartilage during episodes of instability. Increased episodes of instability have been associated with ankle joint degeneration.[39]

The tibialis anterior also had greater %MVIC mean amplitude in the FAI group compared to the MAI group in the drop jump and the comparison group in the walk, run, and drop jump. The MAI group was more active than the comparison group in the step up and run tasks. The comparison group appeared to activate the tibialis anterior less than either of the unstable groups, which may be attributable to the changes in dorsiflexion and plantar flexion between these groups as reported earlier. It is likely that the EMG is affecting the kinematic patterns observed, however, the comparison group may not be relying on dynamic stability or co-contraction as much as the FAI and MAI groups to keep the talocrural joint stable.

Part B: Use the curve average standard deviation and coefficient of variation calculations for each dependent variable on each task to test within and between subject variability on each measure

The coefficient of variation and standard deviation values for each ensemble curve were treated as discrete values, and each subject had a separate curve for each variable in each task. Because they were heavily skewed, a $\log_e$ transformation was performed, making the reported values unitless. We report the original values in Tables 12-14 and the $\log_e$ transformed values and statistical analyses in Tables 15-17. For kinematic variables, only the $\log_e$ SD of ankle inversion demonstrated a main effect for group ($F_{(2,60)}=5.17$, $p=0.008$) (Table 15) using the alpha level of 0.05 criterion. Tukey post-hoc testing revealed the MAI and FAI groups had a significantly higher SD than the comparison group ($p<0.05$). The mean $\log_e$ SD ankle inversion for the comparison group was smaller than the 95% CI lower limit of the MAI and FAI groups, with an effect size of 0.4. The comparison group's mean CV of vertical GRF fell beyond the lower limit of the 95% CI for the MAI and FAI groups, with an effect size of 0.20-0.25 (Table 16). In the CV of peroneal muscle mean amplitude, the MAI estimated marginal mean was less than the lower limit of the 95% CI for the FAI group, with an effect size of 0.31. For the SD of the tibialis anterior muscle, the MAI group mean fell below the 95% CI lower limit in the comparison group, with an effect size of 0.32. On the SD of the peroneal and lateral gastrocnemius mean amplitude, the MAI mean fell above the FAI group 95% CI upper limit, with effect sizes of 0.31 and 0.30, respectively (Table 17). There were no differences between groups in any of the ground reaction force directions or the % MVIC EMG variables (Tables 16 and 17).

The repeated measures ANOVAs were also used to investigate whether selected group x task interactions occurred. Of those interactions that had overall within-subjects p-values<0.05, none had significant Tukey post-hoc tests. But there were differences between groups in tasks noted using estimated marginal means and 95% CI. The first occurred in the $\log_e$ CV ankle inversion, with the FAI group means falling outside the upper limits of the 95% CI for the comparison group (Figure 15). The FAI group was more variable in contrast to the comparison group on the walk, step up and over, and drop jump tasks, with effect sizes from 0.78-1.20. Another interaction was noted on the $\log_e$ CV vertical GRF variable, with the MAI group falling beyond the 95% CI upper limit of the FAI group on the step up and over task and the comparison group on the stop jump task (effect sizes 0.61 and 0.48 respectively) (Figure 16). Additionally, the FAI group mean was greater than the upper limit of the 95% CI for the comparison group on the running task, with an effect size of 1.37. In the $\log_e$ SD of peroneal activity, the FAI estimated marginal mean was greater than the 95% CI upper limit in the MAI group on the drop jump and walk tasks (effect sizes 0.63 and 0.53 respectively). The FAI estimated marginal mean was greater than the 95% CI upper limit in the comparison group on the drop jump task (effect size 0.53). The MAI group mean on the run and the walk task was less than the 95% CI lower limit for the comparison group (effect sizes 0.56 and 0.54 respectively) (Figure 17).

Additional interactions were noted using only 95% CI to test for differences. In the $\log_e$ SD of ankle plantar flexion, the MAI and FAI groups demonstrated less variability than the comparison group in the drop jump and stop jump (Figure 18). In the $\log_e$ SD of ankle inversion, the MAI group demonstrated more variability than the FAI group in the step up, but less in the stop jump, and more variability than the comparison group in the step up, run and drop jump (Figure 19). Additionally, the comparison group had less variability than the FAI group in the walk, run, and stop jump (Figure 19).

Other interactions in EMG included the MAI group exhibiting less variability than the FAI group in the $\log_e$ SD of tibialis anterior mean amplitude in the step up and stop jump, and the comparison group in the walk, step up, run, and stop jump (Figure 20). In the $\log_e$ SD of lateral gastrocnemius mean amplitude, the MAI group demonstrated less variability than the FAI group in the step up, run, and stop jump, while the FAI group was less variable than the comparison group in the run and stop jump tasks (Figure 21). Finally, the MAI group was less variable than the FAI and comparison groups in the $\log_e$ SD of soleus mean amplitude in the stop jump, and the FAI group was less variable than the comparison group in the drop jump (Figure 22).

Interpretation

Main effects: The mean $\log_e$ SD of ankle inversion was greater in the unstable groups versus the comparison group across all tasks. It appears the unstable ankle groups were more variable in ankle inversion-eversion movement during the stance phase. The unstable groups had a harder time replicating the same movement across the 8 trials. This high degree of within subject variability may be detrimental, placing the unstable ankle groups at risk and closer to the “point of no return” for inversion sprains. That much variability in the frontal plane may put the FAI group at risk to contact the ground in a risky or potentially injurious joint position, and makes safe replication of movement more challenging.

We know that CAI individuals demonstrate sensorimotor deficits in joint position sense and postural stability, but we do not know what the pathogentic mechanisms are that connect these deficits with sustaining an inversion injury when the comparison group is uninjured[62]. During transition from an unloaded to a loaded lower extremity (as during weight acceptance in each of the tasks) a situation in which inversion torques could create a lateral ligament injury is endured. If the unloaded ankle goes past a certain point of rotational mal-alignment, moving to the loaded condition results in subtalar inversion torque.[62] Konradsen and Voigt (2002) demonstrated that a 10^o miscalculation in inversion during the swing phase follow through, with a collision between the between the lateral border of the foot and the ground, resulted in maximal inversion, plantar flexion, an internal rotation of the foot and ankle. Using joint position sense data, they calculated a $7\text{-}8^o$ error in inversion foot position could result in injury. As reported in the literature, assuming a CAI subject has 2.6^o of joint position sense error, and the error is normally distributed, an error of that magnitude is made more than once every 10,000 steps.[62] If the FAI group is extremely variable in their inversion foot position during the stance phase, this may be an explanation for the mechanism of injury and repeated sprains.

The comparison group displayed decreased $\log_e$ CV vertical GRF compared to the MAI and FAI groups. This difference was small (with small effect sizes) but even a minimal difference in vertical GRF may accumulate over time. The unstable ankle groups appear to be more variable in the amount of vertical GRF they experience across all the tasks. Alterations in movement pattern at the ankle may be responsible for this. As changes in the plantar flexion angle occurred, the ability of the lower extremity to absorb forces may be altered if the subject cannot repeat the task in the same manner. There were no differences in magnitude of any of the GRF, so magnitude did not likely influence variability.[119] A previous study assessed the degree of “injury proneness” and task difficulty on joint kinetic variability and reported that in less challenging tasks, healthy subjects had greater variability, while injured subjects had less variability. That relationship reversed when the task became more challenging.[119] The authors hypothesized a relationship between degree of joint kinetic variability and overuse injury proneness, in which healthy subjects perceived decreased need for consistency in landing from a low height, preventing overuse injury by changing the stresses on the lower limb. In contrast, when landing from a higher height, the healthy subjects displayed less variability. They may have decided to risk overuse injury in order to protect themselves from an acute injury. The increased variability in vertical GRF may increase contact stress at the articular cartilage of the talus, possibly leading to increased joint degeneration in CAI individuals.

The main effects for group in the $\log_e$ SD and CV of the tibialis anterior, peroneals, and lateral gastrocnemius indicated the FAI group was more variable in EMG mean amplitude expressed as a percentage of MVIC when compared to the other two groups. Only in the SD of the tibialis anterior did we observe a difference between the MAI and comparison groups, in which case the comparison was more variable than the MAI. The FAI group may not be using the muscles of the leg appropriately as dynamic stabilizers acting on the ankle joint. If these muscles were not active enough during the stance phases of the task to help protect the ankle joint, their lack of stabilization may offer another reason for increased sprains in the FAI group. Alternately, it appears there is little variability in the MAI group, who may be "supra-activating" their muscles in an attempt to dynamically stabilize the joint and make up for lack of ligamentous stability.[83] This large and consistent contraction in muscles in the lower extremity may be a strategy to increase stability at the ankle in the MAI group.

Only $\log_e$ SD ankle inversion and knee valgus had a CLR greater than 2. This lack of precision compared to other variables' 95% CI may call the results into question. The rest of the CLR appear to be fairly precise. All of the kinetic variables had CLR less than 2, and only the $\log_e$ SD soleus had CLR that were just greater than 2.

Interactions: The FAI group appeared to be more variable than the comparison group in the $\log_e$ CV ankle inversion, with interactions occurring in the walk, drop jump, and stop jump (Figure 15). Interestingly, these tasks had a range of difficulty and were not just the most demanding. The FAI group may not pay attention to their ankle position or attempt to control it as strictly during tasks with low demand.

Both unstable groups demonstrated greater variability on the vertical ground reaction force when compared to the comparison group, but only on the step up and stop jump tasks, two of the more demanding tasks (Figure 16). The unstable groups may have more difficulty controlling their vertical ground reaction force on tasks with higher impact forces. We found differences in plantar flexion angle and sagittal plane displacement in the unstable groups, and this variability in vertical ground reaction force may be accounted for by the differences in ankle motion. If there is less angular displacement at the ankle joint, the vertical ground reaction forces encountered may not be absorbed in a similar manner.

In the EMG measures of the peroneal muscle, we observed an interaction in which the FAI group displayed increased variability than the MAI and comparison groups on a number of tasks (Figure 17). Lack of adequate muscle control at the ankle could put the FAI group at risk for an inversion injury if their dynamic stabilizers are not functioning appropriately. The comparison group also demonstrated more variability versus the MAI group on the run and the walk. The MAI group may be strongly co-contracting in an attempt to maximize dynamic stability. They appear to limit variability even on tasks with relatively low functional demands. These initial EMG findings are difficult to interpret. There is little literature with which to compare, and due to the high degree of variability both within and between subjects, clear patterns are difficult to discern. Overall, there appear to be differences in variability between the MAI and FAI groups.

Other interactions noted with 95% CI indicated that the MAI group was less variable in plantar flexion angle than the comparison group on two of the harder tasks (Figure 18). The MAI group may be restricting the ankle in the sagittal plane to limit exposure to potentially injurious situations. By landing in the same manner every time and avoiding plantar flexion, the MAI group may be attempting to avoid injury.[64, 119] This finding fits with the other kinematic sagittal plane data and the theory of a coping mechanism developed to avoid sprain. Interestingly, the same relationship did not hold for ankle inversion variability. The MAI group was actually more variable than the comparison and FAI groups on a number of tasks, except the stop jump, where the FAI group was more variable (Figure 19). The MAI group may not be receiving proper proprioceptive feedback from the ankle in the frontal plane if the calcaneofibular ligament has been stretched and/or damaged. With increased available active range of motion in that plane and possible changes in proprioception, the MAI group may not have the ability to safely replicate a landing pattern that is normal and avoids lateral ankle sprain.

A number of interactions were noted for EMG variables, including primarily less variability for the MAI group compared to the FAI and comparison groups across several tasks for the tibialis anterior, lateral gastrocnemius, and soleus. This further supports our hypothesis that the MAI group "supraactivates" the ankle musculature to rely on dynamic stability to supplant damaged ligamentous structures that do not provide adequate static stability (Figures 20-22). Decreased variability may indicate a reliance on constant levels of activity to provide support to the ankle complex during tasks of varying functional demands.

Additional Analyses

Several additional analyses were performed to ensure consistency between groups in different measures. A one-way ANOVA was used to test for differences in active range of motion measures recorded during subject screening. For the range of motion measures, each group was compared on ankle plantar flexion, dorsiflexion, inversion, and eversion on both ankles (Table 18) ($F_{(2,60)}=0.35$ to 3.24, with $p \geq 0.05$ on all measures), For left ankle inversion and eversion, the p-value approached significance ($p=0.47$ and $p=0.055$). Using 95% CI, the MAI and FAI estimated marginal mean for left ankle inversion fell beyond the comparison group's upper limit. The MAI group's estimated marginal mean for left ankle eversion also fell beyond the comparison and FAI group's 95% CI upper limit. The MAI group's right ankle estimated marginal mean for eversion also fell beyond the 95% CI upper limit for the FAI and comparison groups. Thus, it appears the unstable ankle groups had greater left ankle inversion versus the comparison group, and the MAI group had increased right and left ankle eversion compared to the FAI and comparison groups. We would expect to see increased range of motion if the subjects were mechanically lax, because they were lacking ligamentous restraints. The FAI group was not clinically positive in laxity in inversion, but they likely had some stretching of the ligament, which appeared as increased range of motion. These differences in active range of motion may influence our results, but we were looking for effects of the injury.

For the MVIC values, the mean and peak force of the three trials for each muscle were averaged. The averages were then compared between groups using a one-way ANOVA. No significant differences were found in any muscles average mean or average peak force between groups ($F_{(2,60)}$=0.003 to 0.80, p>0.05). Using 95% CI, no group mean exceeded the upper or lower limits. Thus, it appears each group's performance on the MVICs was equivalent.

A repeated measures ANOVA was used to determine whether sacral velocity was consistent between groups and met the criteria established in the methods. Because Mauchly's test of sphericity was significant ($p < 0.05$), the Greenhouse-Geiser adjustment was used. No significant group x task interactions were observed ($F_{(5.12, 153.59)} = 0.965$; $p > 0.05$), nor was any main effect for group ($F_{(2, 60)} = 0.795$; $p > 0.05$). Levene's test for equality of variance was checked prior to proceeding with all analyses.

Limitations

There are a number of potential limitations with this study. The first is the reliance on self-report data of ankle injury history. Although subjects reported repeated episodes of spraining, rolling, and giving way at the ankle, the actual incidence and degree of instability in the MAI and FAI groups was uncertain. Identifying individuals with FAI is difficult, since the population presents with a wide range of symptoms and degree of instability. We made an effort to match subjects between groups as best as possible, but there are inherent differences in length of time with ankle instability, degree of mechanical laxity, and mechanisms that evoke feelings of instability. The FAI group we tested likely encompassed a broad spectrum of recreationally active individuals with varying degrees of instability. The heterogeneous nature of this group may have clouded some results. Additionally, our comparison group of "copers" did not demonstrate mechanical laxity. An ideal comparison group would have consisted of individuals with mechanical laxity who do not suffer episodes of instability, and thus are effectively coping with mechanical laxity of the lateral ligaments. These individuals are difficult to find and there is no history of their use in the CAI literature.

Laxity testing was performed using clinical orthopedic tests and one examiner. Lack of an objective and quantifiable measure of instability is problematic. There is likely some error in the motion capture equipment and processing of data as well. Finally, the low power we observed (<0.70) on a number of measures increased the chances of making a type I error.

Using the $\log_e$ transformed SD and CV is a very simplistic method of analyzing variability in movement. The complex nature and relationships between the joints in the lower extremity may be better characterized with more advanced methods of variability measurement, such as non-linear analysis. Finally, the reported power levels for the interactions and group main effects on the repeated measures ANOVA for both $\log_e$ CV and $\log_e$ SD variables were typically low. Power was never greater than 0.37 for any of the kinetic or EMG variables, and only one kinematic variable had power greater than 0.40.

Conclusions

Our most important finding was that the MAI group demonstrated altered movement patterns at the ankle joint compared to the FAI and comparison groups on a number of variables across and within tasks. The MAI group appeared to display a pattern of increased dorsiflexion and eversion, increased frontal plane displacement, and decreased sagittal plane displacement over a series of tasks. The MAI group's time to peak anterior ground reaction was slower than the comparison group. We found no differences between groups at the knee or in the peak ground reaction force variables. This altered movement pattern may act to place the MAI subjects' ankle in a close pack and more stable position, thus helping to avoid lateral ankle sprains and stressing the anterior talofibular ligament. There may be long-term consequences to this movement pattern, as it could increase joint degeneration over time.

Our other important finding was greater variability in frontal and sagittal plane ankle joint motion of the unstable ankle groups versus the comparison group. Greater variability in the frontal plane may place the FAI and MAI groups at greater risk for inversion sprains, and offer an explanation for the pathomechanics of FAI subjects who do not demonstrate mechanical laxity of the lateral ligaments.

We observed differences in EMG mean amplitude reported as a percentage of MVIC, with the FAI group demonstrating increased tibialis anterior mean amplitude but decreased lateral gastrocnemius mean amplitude across tasks. Interactions revealed the MAI group displayed consistently larger mean amplitude of the lateral gastrocnemius than the FAI group across four of the tasks. The MAI group was also less variable in EMG mean amplitude in three of the four muscles. It appears the MAI group consistently has more activity in their leg muscles than the FAI group, and may be strongly co-contracting on each trial to maximize dynamic stabilizers, while the FAI group did not. This may help explain why the FAI group suffers repeated sprains.

Based on these results, we recommend that MAI and FAI subjects be differentiated in future research, and not combined into one CAI group. Mechanical laxity appears to be an important mitigating factor in movement patterns, and may impact other variables of interest in CAI research, including postural stability, reaction time, electromyography, and others. If CAI subjects are not separated based on lateral ligament laxity, confounding mechanical laxity may cloud the results. Thus, stricter criteria for defining chronic ankle instability, as well as its subgroups, are necessary.

Rehabilitation programs should consider these findings and work to address them. Specifically, emphasis should be placed on frontal plane motion and encouraging repeatability of ankle position at landing to avoid ankle sprains. MAI subjects may also be encouraged to undergo more knee flexion during landing in an attempt to offset the lack of sagittal plane motion at the ankle. Future research is necessary to increase sample size and power, and determine if there are long term deficits associated with chronic ankle instability. Future research should also explore up the kinetic chain to see if differences occur proximally.

Table 5. Subject Demographics by Group and Gender

Group	Gender	Age (years)			Height (cm)			Mass (kg)		
		Mean	(SD)	Range (Minimum and Maximum)	Mean	(SD)	Range (Minimum and Maximum)	Mean	(SD)	Range (Minimum and Maximum)
MAI	Male	23.00	5.12	18-33	179.81	10.02	165.00-193.00	76.73	13.80	55.17-101.36
	Female	21.70	3.30	19-28	166.33	5.47	155.00-173.00	65.73	9.75	53.28-86-74
FAI	Male	22.45	4.27	18-31	178.08	6.45	168.00-188.00	77.59	12.00	60.23-93.00
	Female	21.80	3.49	19-29	165.10	7.72	152.00-177.00	67.91	13.01	46.69-89.72
Comparison	Male	21.27	4.17	18-33	182.10	4.16	177.80-191.00	75.38	7.65	63.58-86.90
	Female	22.20	5.69	18-35	167.70	5.48	160.00-178.00	63.92	10.55	48.13-82.21

MAI: Mechanical ankle instability group; FAI: functional ankle instability group; SD: Standard deviation

Table 6. Subject Ankle Stability Questionnaire Scores by Group and Gender

Group	Gender	AAQ			FADI			FADI-S		
		Mean	(SD)	Range (Minimum and Maximum)	Mean	(SD)	Range (Minimum and Maximum)	Mean	(SD)	Range (Minimum and Maximum)
MAI	Male	70.81	6.85	57-84	90.50	8.36	71.20-99.00	78.10	13.12	56.30-96.40
	Female	65.10	6.61	50-72	87.62	7.98	74.00-97.10	75.00	11.67	46.90-87.50
FAI	Male	74.36	9.10	58-91	93.75	4.76	84.60-99.00	77.52	9.10	65.60-93.80
	Female	71.50	16.94	38-98	94.68	3.92	88.50-100.00	85.95	10.02	75.00-100.00
Comparison	Male	89.55	4.70	85-97	96.67	5.53	80.80-100.00	89.45	12.42	62.50-100.00
	Female	92.60	4.17	85-98	97.45	1.90	93.80-100.00	92.65	5.75	84.00-100.00

MAI: Mechanical ankle instability group; FAI: functional ankle instability group; SD: Standard deviation; AAQ: Ankle Assessment Questionnaire; FADI: Foot and Ankle Disability Index; FADI-S: Foot and Ankle Disability Index Sport

Table 7. One-Way ANOVA with Tukey Post-Hoc Testing for Subject Matching Between Groups

Measure	**F-value** $_{\textbf{(Degrees of Freedom)}}$	**P-value**	**Post-Hoc Testing (α = 0.05)**
Age (yrs)	$F_{(2, 60)} = 0.127$	0.881	None
Height (cm)	$F_{(2,60)} = 0.632$	0.535	None
Mass (kg)	$F_{(2,60)} = 0.323$	0.726	None
AAQ score	$F_{(2,60)} = 37.296$	<0.001	MAI = FAI < Comparison
FADI score	$F_{(2,60)} = 9.99$	<0.001	MAI < FAI < Comparison
FADI-S score	$F_{(2,60)} = 9.582$	<0.001	MAI = FAI < Comparison

MAI: Mechanical ankle instability group; FAI: functional ankle instability group; SD: Standard deviation; AAQ: Ankle Assessment Questionnaire; FADI: Foot and Ankle Disability Index; FADI-S: Foot and Ankle Disability Index Sport

Table 8. Repeated Measures ANOVA Group Main Effects for Kinematic Variables in the Ankle

Variable (in degrees)	Group	Estimated Marginal Mean	Standard Error	F-Value df(2,60)	P-Value	Power Level	95% Confidence Interval Lower Limit	95% Confidence Interval Upper Limit	Tukey Post-Hoc*	CLR
Ankle plantarflexion angle at IC	MAI	17.26	1.79	3.48	0.04	0.63	13.68	20.85	MAI-Comp	1.52
	FAI	21.38					17.79	24.96		1.40
	Comparison	23.89					20.31	27.48		1.35
Ankle inversion angle at IC	MAI	-5.10	1.05	0.11	0.90	0.07	-7.20	-3.00	None	2.40
	FAI	-5.79					-7.90	-3.69		2.14
	Comparison	-5.36					-7.46	-3.25		2.30
Maximum ankle plantarflexion	MAI	25.00	1.59	3.32	0.04	0.61	21.81	28.18	None	1.29
	FAI	30.10					26.91	33.28		1.24
	Comparison	29.94					26.75	33.18		1.24
Maximum ankle dorsiflexion	MAI	-14.29	1.20	1.69	0.19	0.34	-16.70	-11.88	None	1.41
	FAI	-16.56					-18.97	-14.15		1.34
	Comparison	-17.28					-19.69	-14.88		1.32
Maximum ankle inversion	MAI	-8.44	0.97	0.46	0.63	0.12	-10.39	-6.50	None	1.60
	FAI	-8.18					-10.13	-6.24		1.62
	Comparison	-7.19					-9.14	-5.25		1.74
Maximum ankle eversion	MAI	4.86	0.86	3.92	0.03	0.69	3.15	6.57	MAI-FAI	2.09
	FAI	1.86					0.15	3.58		23.87
	Comparison	1.98					0.27	3.70		13.70
Ankle sagittal plane displacement	MAI	39.28	1.91	5.40	0.01	0.83	35.48	43.09	MAI-FAI	1.21
	FAI	46.65					42.84	50.46	MAI-Comp	1.18
	Comparison	47.22					43.41	51.03		1.18
Ankle frontal plane displacement	MAI	-13.30	0.90	5.86	0.001	0.86	-15.10	-11.57	MAI-FAI	1.30
	FAI	-10.05					-11.85	-8.25	MAI-Comp	1.44
	Comparison	-9.17					-10.97	-7.38		1.49

MAI mechanical ankle instability; FAI functional ankle instability; IC initial contact; *significant at the $p < 0.05$ level. CLR: ratio of maximum absolute upper to lower 95% confidence limits. Plantarflexion +; Dorsiflexion -; Inversion -; Eversion +;

Table 9. Repeated Measures ANOVA Group Main Effects for Kinematic Variables at the Knee

Variable (in degrees)	Group	Estimated Marginal Means	Standard Error	F-Value	P-Value	Power Level	95% Confidence Interval		Tukey Post-Hoc*	CLR
							Lower Limit	Upper Limit		
Knee flexion angle at IC	MAI	13.70	1.17	0.80	0.92	0.06	11.36	16.03	None	1.41
	FAI	14.34					12.00	16.67		1.39
	Comparison	14.15					11.82	16.49		1.40
Knee valgus angle at IC	MAI	1.59	1.01	0.76	0.47	0.17	-0.43	3.61	None	8.40
	FAI	2.57					0.55	4.59		8.35
	Comparison	0.70					-1.33	2.72		2.05
Maximum knee flexion	MAI	43.00	1.53	0.12	0.89	0.07	39.95	46.05	None	1.15
	FAI	43.88					40.83	46.93		1.15
	Comparison	43.94					40.89	46.99		1.15
Maximum knee extension	MAI	9.17	1.07	0.49	0.61	0.13	7.02	11.31	None	1.61
	FAI	10.47					8.32	12.62		1.52
	Comparison	10.48					8.33	12.63		1.52
Maximum knee valgus	MAI	3.34	1.21	0.87	0.42	0.19	0.93	5.76	None	6.19
	FAI	5.00					2.59	7.42		2.86
	Comparison	2.85					0.43	5.26		12.23
Maximum knee varus	MAI	-8.62	1.69	0.67	0.52	0.16	-12.01	-5.24	None	2.29
	FAI	-6.12					-9.51	-2.74		3.47
	Comparison	-8.41					-11.80	-5.03		2.35
Knee sagittal plane displacement	MAI	33.84	1.12	0.04	0.96	0.06	31.59	36.08	None	1.14
	FAI	33.41					31.17	35.66		1.14
	Comparison	33.46					31.22	35.71		1.14
Knee frontal plane displacement	MAI	11.97	0.81	0.31	0.73	0.10	10.34	13.59	None	1.31
	FAI	11.12					9.50	12.75		1.34
	Comparison	11.26					9.64	12.88		1.34

MAI mechanical ankle instability; FAI functional ankle instability; IC initial contact; *significant at the $p < 0.05$ level. CLR: ratio of maximum absolute upper to lower 95% confidence limits. Knee flexion +: extension -; valgus +; varus -.

Table 10. Repeated Measures ANOVA Group Main Effects for Kinetic Variables

Variable	Group	Estimated Marginal Mean	Standard Error	F-Value	P-Value	Power Level	95% Confidence Interval		Tukey Post-Hoc*	CLR
							Lower Limit	Upper Limit		
Peak normalized vertical GRF (xBM)	MAI	-2.36	0.07	1.20	0.31	0.25	-2.49	-2.23	None	1.12
	FAI	-2.38					-2.51	-2.25		1.12
	Comparison	-2.24					-2.38	-2.11		1.13
Peak normalized anterior GRF (xBM)	MAI	0.41	0.02	0.71	0.50	0.16	0.37	0.45	None	1.22
	FAI	0.44					0.40	0.47		1.18
	Comparison	0.41					0.37	0.44		1.19
Peak normalized posterior GRF (xBM)	MAI	-0.23	0.01	0.13	0.88	0.07	-0.26	-0.20	None	1.30
	FAI	-0.23					-0.26	-0.20		1.30
	Comparison	-0.22					-0.25	-0.19		1.32
Peak normalized medial GRF (xBM)	MAI	-0.19	0.02	0.43	0.65	0.12	-0.24	-0.15	None	1.60
	FAI	-0.16					-0.21	-0.12		1.75
	Comparison	-0.17					-0.22	-0.13		1.69
Peak normalized lateral GRF (xBM)	MAI	0.15	0.02	1.09	0.34	0.23	0.11	0.20	None	1.82
	FAI	0.18					0.13	0.22		1.69
	Comparison	0.13					0.08	0.18		2.25
Time to peak normalized VGRF (ms)	MAI	135.55	9.16	0.87	0.42	0.19	117.23	153.87	None	1.31
	FAI	132.40					114.18	150.82		1.32
	Comparison	148.60					130.29	166.92		1.28
Time to peak normalized AGRF (ms)	MAI	63.06	3.18	1.12	0.32	0.25	56.70	69.43	None	1.22
	FAI	59.65					53.29	66.02		1.24
	Comparison	56.16					49.79	62.52		1.26
Time to peak normalized PGRF (ms)	MAI	266.61	13.77	0.90	0.41	0.20	239.07	294.15	None	1.23
	FAI	288.68					261.14	316.22		1.21
	Comparison	289.81					262.26	317.35		1.21
Time to peak normalized MGRF (ms)	MAI	66.60	7.12	0.11	0.89	0.07	52.37	80.84	None	1.54
	FAI	63.43					49.19	77.66		1.58
	Comparison	68.09					53.85	82.33		1.53
Time to peak normalized LGRF (ms)	MAI	115.98	12.68	0.29	0.75	0.09	90.62	141.34	None	1.56
	FAI	123.93					98.58	149.29		1.51
	Comparison	129.54					104.18	154.90		1.49

MAI mechanical ankle instability; FAI functional ankle instability; GRF ground reaction force; V vertical; A Anterior; P posterior; M medial; L lateral.
*Significant at the $p < 0.05$ level. CLR ratio of maximum absolute upper to lower 95% confidence limits. Vertical -; anterior +; posterior -; medial -; lateral +. BM is body mass. Ms is milliseconds.

Table 11. Repeated Measures ANOVA Group Main Effects for Surface Electromyography Variables Reported as % of Maximum Voluntary Isometric Contraction

Variable	Group	Group Mean	Standard Error	F-Value	P-Value	Power Level	95% Confidence Interval		Tukey Post-Hoc*	CLR
							Lower Limit	Upper Limit		
Tibialis anterior mean amplitude	MAI	43.08	3.56	1.53	0.23	0.31	35.96	50.21	None	1.40
	FAI	46.90					39.78	54.03		1.36
	Comparison	38.12					30.99	45.24		1.46
Peroneals mean amplitude	MAI	108.14	10.89	0.11	0.89	0.07	86.36	129.92	None	1.50
	FAI	101.11					79.34	122.89		1.55
	Comparison	106.54					84.77	128.32		1.51
Lateral gastrocnemius mean amplitude	MAI	158.28	16.04	2.02	0.14	0.40	126.19	190.36	None	1.51
	FAI	114.94					82.85	147.03		1.77
	Comparison	148.89					116.80	180.98		1.55
Soleus mean amplitude	MAI	257.96	39.81	0.70	0.93	0.06	178.32	337.60	None	1.89
	FAI	276.91					197.27	356.55		1.81
	Comparison	275.41					195.80	355.07		1.81

MAI mechanical ankle instability; FAI functional ankle instability. *Significant at the $p < 0.05$ level. CLR ratio of maximum absolute upper to lower 95% confidence limits.

Table 12. Kinematic Coefficient of Variation and Mean Standard Deviation Values

Variable	Group	Estimated Marginal Mean	Standard Error	95% Confidence Interval		CLR
				Lower Limit	Upper Limit	
CV Ankle plantarflexion	MAI	19.05	2.24	14.57	23.53	1.61
	FAI	19.57		15.08	24.05	1.59
	Comparison	20.22		15.73	24.70	1.57
CV Ankle inversion	MAI	20.84	6.48	7.89	33.79	4.28
	FAI	37.42		24.48	50.38	2.06
	Comparison	22.38		9.39	35.29	3.76
CV Knee flexion	MAI	18.17	1.56	15.06	21.29	1.41
	FAI	15.50		12.39	18.62	1.50
	Comparison	16.08		12.97	19.19	1.45
CV Knee valgus	MAI	20.52	4.07	12.38	23.66	1.91
	FAI	24.83		16.69	32.97	1.98
	Comparison	28.71		20.56	36.85	1.79
SD Ankle plantarflexion	MAI	3.40	0.31	2.78	4.01	1.44
	FAI	4.07		3.45	4.68	1.36
	Comparison	3.77		3.15	4.39	1.39
SD Ankle inversion	MAI	1.78	0.23	1.33	2.23	1.68
	FAI	2.30		1.84	2.75	1.49
	Comparison	1.38		0.93	1.84	1.97
SD Knee flexion	MAI	3.84	0.22	3.41	4.27	1.25
	FAI	3.64		3.20	4.07	1.27
	Comparison	3.29		2.86	3.73	1.30
SD Knee valgus	MAI	1.88	0.15	1.59	2.18	1.37
	FAI	2.01		1.72	2.31	1.34
	Comparison	1.64		1.35	1.93	1.43

CV Coefficient of Variation; SD Standard Deviation; MAI mechanical ankle instability; FAI functional ankle instability; CLR ratio of maximum absolute upper to lower 95% confidence limits.

Table 13. Kinetic Coefficient of Variation and Mean Standard Deviation Values

Average Variable	Group	Estimated Marginal Mean	Standard Error	95% Confidence Interval Lower Limit	95% Confidence Interval Upper Limit	CLR
CV	MAI	13.45	0.78	11.90	15.00	1.26
normalized	FAI	13.32		11.78	14.87	1.26
VGRF	Comparison	11.96		10.41	13.51	1.30
CV	MAI	36.53	1.67	33.21	39.85	1.20
normalized	FAI	34.67		31.36	37.99	1.21
APGRF	Comparison	34.72		31.40	38.03	1.21
CV	MAI	62.70	6.90	48.89	76.50	1.56
normalized	FAI	45.51		31.70	59.31	1.87
MLGRF	Comparison	56.96		43.15	70.77	1.64
SD	MAI	0.16	0.01	0.15	0.18	1.20
normalized	FAI	0.16		0.15	0.17	1.13
VGRF	Comparison	0.15		0.13	0.16	1.23
SD	MAI	0.06	0.003	0.06	0.07	1.17
normalized	FAI	0.06		0.06	0.07	1.17
APGRF	Comparison	0.06		0.05	0.06	1.20
SD	MAI	0.04	0.001	0.03	0.04	1.33
normalized	FAI	0.04		0.03	0.04	1.33
MLGRF	Comparison	0.03		0.03	0.04	1.33

CV Coefficient of Variation; SD Standard Deviation; MAI mechanical ankle instability; FAI functional ankle instability; CLR ratio of maximum absolute upper to lower 95% confidence limits.

Table 14. Surface Electromyography Coefficient of Variation and Mean Standard Deviation Values

Average Variable	Group	Estimated Marginal Mean	95% Confidence Interval		CLR
			Lower Limit	Upper Limit	
CV Tibialis	MAI	46.29	42.41	50.18	1.18
Anterior	FAI	19.26	45.38	53.15	1.17
	Comparison	49.08	45.20	52.97	1.17
CV Peroneals	MAI	59.47	53.32	62.62	1.17
	FAI	69.67	63.52	75.81	1.19
	Comparison	61.22	55.07	67.37	1.22
CV Lateral	MAI	68.46	59.21	77.70	1.31
Gastrocnemius	FAI	72.81	63.56	82.05	1.29
	Comparison	68.64	59.40	77.89	1.31
CV Soleus	MAI	57.40	52.70	62.09	1.18
	FAI	58.62	53.92	63.32	1.17
	Comparison	62.20	57.50	66.89	1.16
SD Tibialis	MAI	0.57	0.51	0.63	1.23
Anterior	FAI	0.51	0.45	0.57	1.27
	Comparison	0.49	0.43	0.55	1.28
SD Peroneals	MAI	0.65	0.57	0.73	1.28
	FAI	0.57	0.49	0.65	1.33
	Comparison	0.59	0.51	0.67	1.31
SD Lateral	MAI	0.62	0.53	0.70	1.32
Gastrocnemius	FAI	0.47	0.39	0.56	1.44
	Comparison	0.55	0.46	0.63	1.37
SD Soleus	MAI	0.76	0.68	0.85	1.25
	FAI	0.71	0.62	0.80	1.29
	Comparison	0.73	0.65	0.81	1.25

CV Coefficient of Variation; SD Standard Deviation; MAI mechanical ankle instability; FAI functional ankle instability; CLR ratio of maximum absolute upper to lower 95% confidence limits.

Table 15. Repeated Measures ANOVA Group Main Effects for Kinematic Log_e Transformed Coefficient of Variation and Mean Standard Deviation Measures

Average Variable	Group	Estimated Marginal Mean	Standard Error	F-Value	P-Value	Power Level	95% Confidence Interval Lower Limit	95% Confidence Interval Upper Limit	Tukey Post-Hoc*	CLR
CV Ankle plantarflexion	MAI	2.66	0.11	0.52	0.60	0.13	2.44	2.88	None	1.18
	FAI	2.74					2.52	2.96		1.17
	Comparison	2.82					2.60	3.04		1.17
CV Ankle inversion	MAI	2.49	0.21	1.46	0.24	0.30	2.07	2.91	None	1.41
	FAI	2.87					2.45	3.28		1.34
	Comparison	2.40					1.97	2.81		1.42
CV Knee flexion	MAI	2.67	0.08	0.74	0.48	0.17	2.52	2.82	None	1.12
	FAI	2.55					2.39	2.70		1.13
	Comparison	2.58					2.43	2.73		1.12
CV Knee valgus	MAI	2.65	0.14	0.45	0.64	0.12	2.38	2.92	None	1.23
	FAI	2.74					2.47	3.02		1.22
	Comparison	2.83					2.56	3.10		1.21
SD Ankle plantarflexion	MAI	1.12	0.05	1.17	0.32	0.25	1.01	1.22	None	1.21
	FAI	1.22					1.12	1.33		1.19
	Comparison	1.21					1.11	1.32		1.19
SD Ankle inversion	MAI	0.46	0.06	5.17	0.008	0.81	0.34	0.58	MAI-Comp	1.71
	FAI	0.46					0.34	0.58	FAI-Comp	1.71
	Comparison	0.22					0.10	0.34		3.40
SD Knee flexion	MAI	1.21	0.05	1.48	0.24	0.30	1.11	1.31	None	1.18
	FAI	1.16					1.06	1.25		1.18
	Comparison	1.09					1.00	1.19		1.19
SD Knee valgus	MAI	0.46	0.06	1.99	0.15	0.40	0.34	0.59	None	1.74
	FAI	0.50					0.38	0.62		1.63
	Comparison	0.33					0.21	0.46		2.19

CV Coefficient of Variation; SD Standard Deviation; MAI mechanical ankle instability; FAI functional ankle instability; * Significant at the $p < 0.05$ level. CLR ratio of maximum absolute upper to lower 95% confidence limits. Note: Due to log_e transformation, values are unitless.

Table 16. Repeated Measures ANOVA Group Main Effects for Kinetic Log_e Transformed Coefficient of Variation and Mean Standard Deviation Measures

Average Variable	Group	Estimated Marginal Mean	Standard Error	F-Value	P-Value	Power Level	95% Confidence Interval		Tukey Post-Hoc*	CLR
							Lower Limit	Upper Limit		
CV	MAI	2.46	0.04	1.84	0.17	0.37	2.37	2.55	None	1.08
normalized	FAI	2.44					2.35	2.53		1.08
VGRF	Comparison	2.35					2.26	2.43		1.08
CV	MAI	3.51	0.04	0.63	0.54	0.15	3.43	3.58	None	1.04
normalized	FAI	3.45					3.37	3.52		0.94
APGRF	Comparison	3.46					3.38	3.53		1.04
CV	MAI	3.97	0.14	0.91	0.41	0.20	3.70	4.25	None	1.15
normalized	FAI	3.72					3.44	4.00		1.16
MLGRF	Comparison	3.92					3.64	4.19		1.15
SD	MAI	-2.01	0.04	1.84	0.17	0.37	-2.10	-1.93	None	1.09
normalized	FAI	-2.01					-2.10	-1.93		1.09
VGRF	Comparison	-2.12					-2.20	-2.03		1.08
SD	MAI	-3.01	0.04	0.58	0.56	0.14	-3.09	-2.92	None	1.06
normalized	FAI	-3.00					-3.08	-2.91		1.06
APGRF	Comparison	-3.06					-3.14	-2.97		1.06
SD	MAI	-3.50	0.04	1.46	0.24	0.30	-3.58	-3.42	None	1.05
normalized	FAI	-3.50					-3.58	-3.42		1.05
MLGRF	Comparison	-3.58					-3.66	-3.50		1.05

CV Coefficient of Variation; SD Standard Deviation; MAI mechanical ankle instability; FAI functional ankle instability; * Significant at the $p < 0.05$ level. CLR ratio of maximum absolute upper to lower 95% confidence limits. Note: due to log_e transformation values are unitless.

Table 17. Repeated Measures ANOVA Group Main Effects for Surface Electromyography Log_e Transformed Coefficient of Variation and Mean Standard Deviation Measures

Average Variable	Group	Estimated Marginal Mean	Standard Error	F-Value	P-Value	Power Level	95% Confidence Interval		Tukey Post-Hoc*	CLR
							Lower Limit	Upper Limit		
CV Tibialis Anterior	MAI	4.21	0.03	0.48	0.62	0.13	4.14	4.28	None	1.03
	FAI	4.24					4.17	4.31		1.03
	Comparison	4.26					4.19	4.32		1.03
CV Peroneals	MAI	4.06	0.03	2.43	0.10	0.47	4.00	4.12	None	1.03
	FAI	4.15					4.09	4.21		1.03
	Comparison	4.09					4.03	4.15		1.03
CV Lateral Gastrocnemius	MAI	4.16	0.05	0.12	0.87	0.07	4.07	4.26	None	1.05
	FAI	4.19					4.10	4.29		1.05
	Comparison	4.19					4.09	4.28		1.05
CV Soleus	MAI	4.03	0.03	0.79	0.46	0.18	3.97	4.10	None	1.03
	FAI	4.04					3.98	4.11		1.03
	Comparison	4.09					4.02	4.15		1.03
SD Tibialis Anterior	MAI	-0.70	0.06	2.59	0.08	0.50	-0.82	-0.58	None	1.41
	FAI	-0.82					-0.94	-0.70		1.34
	Comparison	-0.89					-1.01	-0.77		1.31
SD Peroneals	MAI	-0.56	0.08	2.44	0.09	0.47	-0.72	-0.39	None	1.85
	FAI	-0.82					-0.98	-0.65		1.51
	Comparison	-0.69					-0.86	-0.52		1.65
SD Lateral Gastrocnemius	MAI	-0.69	0.11	2.49	0.09	0.48	-0.90	-0.47	None	1.91
	FAI	-1.02					-1.24	-0.81		1.53
	Comparison	-0.83					-1.02	-0.59		1.73
SD Soleus	MAI	-0.40	0.08	0.47	0.63	0.12	-0.56	-0.24	None	2.33
	FAI	-0.51					-0.67	-0.35		1.91
	Comparison	-0.45					-0.61	-0.29		2.10

CV Coefficient of Variation; SD Standard Deviation; MAI mechanical ankle instability; FAI functional ankle instability; * Significant at the $p < 0.05$ level. CLR ratio of maximum absolute upper to lower 95% confidence limits. Note: due to log_e transformation values are unitless.

Table 18. Descriptives and One-Way ANOVA for Range of Motion Measures Between Groups

Average Variable	Group	Group Mean	Standard Deviation	F-Value	P-Value	95% Confidence Interval Upper Limit	95% Confidence Interval Lower Limit	*Tukey Post-Hoc	CLR
R ankle dorsiflexion	MAI	5.30	3.84	1.01	0.37	3.50	7.10	None	2.03
	FAI	6.00	2.96			4.62	7.38		1.60
	Comparison	6.79	2.94			5.37	8.20		1.53
R ankle plantar flexion	MAI	62.60	6.81	0.35	0.71	59.41	65.79	None	1.11
	FAI	62.75	7.65			59.17	66.33		1.12
	Comparison	60.26	14.89			53.09	67.44		1.27
R ankle inversion	MAI	15.00	6.43	0.74	0.48	11.99	18.01	None	1.50
	FAI	13.85	5.81			11.12	16.57		1.49
	Comparison	12.79	4.62			10.56	15.02		1.42
R ankle eversion	MAI	6.85	3.00	1.71	0.19	5.45	8.25	None	1.51
	FAI	5.60	2.37			4.49	6.71		1.49
	Comparison	5.42	2.52			4.20	6.64		1.58
L ankle dorsiflexion	MAI	7.25	3.60	0.37	0.30	5.57	8.93	None	1.60
	FAI	7.40	3.56			5.73	9.07		1.58
	Comparison	8.79	2.90			7.39	10.19		1.38
L ankle plantarflexion	MAI	57.75	6.16	1.22	0.69	54.87	60.63	None	1.10
	FAI	59.60	6.72			56.45	62.75		1.11
	Comparison	58.47	7.67			54.78	62.17		1.13
L ankle inversion	MAI	16.30	6.56	3.24	0.05	13.23	19.37	MAI-Comp	1.46
	FAI	14.35	6.60			11.26	17.44	p=0.04	1.55
	Comparison	11.47	4.31			9.40	13.55		1.44
L ankle eversionn	MAI	6.75	2.38	3.05	0.06	5.64	7.86	MAI-Comp	1.39
	FAI	5.25	2.31			4.17	6.33	P=0.08	1.51
	Comparison	5.11	2.25			4.02	6.19		1.54

R right; L left; MAI mechanical ankle instability; FAI functional ankle instability. *Significant at the $p<0.05$ level. CLR is ratio of maximum absolute upper to lower limit 95% confidence limits.

Table 19. Descriptives and One-Way ANOVA for Maximum Voluntary Isometric Contractions

Variable (N)	Group	Group Mean	Standard Deviation	F-Value	P-Value	95% Confidence Interval Upper Limit	95% Confidence Interval Lower Limit	*Tukey Post-Hoc	CLR
TA Mean Peak	MAI	217.78	38.64	0.003	0.99	200.19	235.37	None	1.18
	FAI	217.59	28.03			204.83	230.35		1.12
	Comparison	218.41	42.50			199.07	237.75		1.19
TA Mean Average	MAI	205.87	37.61	0.23	0.79	188.75	222.99	None	1.18
	FAI	207.24	25.32			195.71	218.76		1.12
	Comparison	212.40	34.11			196.87	227.07		1.15
PL Mean Peak	MAI	116.60	30.88	0.22	0.80	102.55	130.66	None	1.27
	FAI	118.76	40.66			100.25	137.27		1.37
	Comparison	115.59	38.11			94.08	128.77		1.37
PL Mean Average	MAI	111.76	27.92	0.55	0.58	99.05	124.47	None	1.26
	FAI	118.25	41.50			99.36	137.14		1.38
	Comparison	106.86	35.60			90.65	123.06		1.36
LG Mean Peak	MAI	194.03	53.20	0.37	0.69	169.81	218.25	None	1.29
	FAI	196.92	35.70			180.67	213.17		1.18
	Comparison	185.18	47.04			163.76	206.59		1.26
LG Mean Average	MAI	183.09	49.26	0.48	0.62	160.67	205.52	None	1.28
	FAI	186.57	34.81			170.73	202.42		1.19
	Comparison	173.51	48.20			151.57	195.45		1.29
SL Mean Peak	MAI	200.35	56.09	0.80	0.45	174.82	225.88	None	1.29
	FAI	186.35	30.11			172.64	200.06		1.16
	Comparison	201.99	41.88			182.93	221.07		1.21
SL Mean Average	MAI	190.37	48.80	0.71	0.50	168.15	212.58	None	1.26
	FAI	178.14	28.26			165.28	191.01		1.16
	Comparison	191.02	38.77			173.37	208.67		1.20

TA tibialis anterior; PL peroneals; LG lateral gastrocnemius; SL soleus. MAI mechanical ankle instability; FAI functional ankle instability. Mean peak is the peak force in N averaged over 3 trials; Mean average is the average force of the trial averaged over 3 trials. CLR is ratio of maximum absolute upper to lower limit 95% confidence limits.

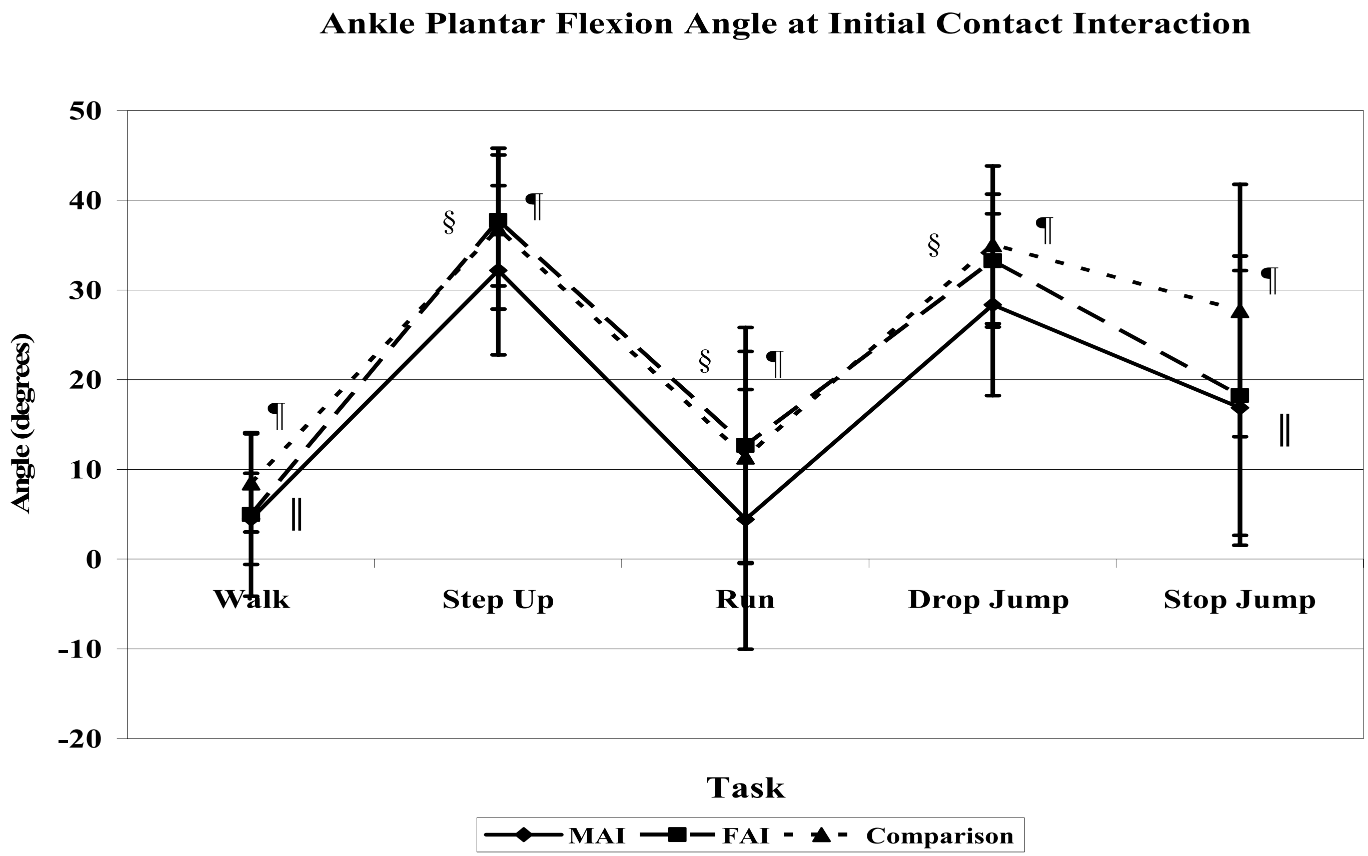

Figure 4. Group x Task Interaction for Ankle Plantar Flexion Angle at Initial Contact
$F_{(5.98,179.35)}=1.96$; $p=0.074$; power=0.71
MAI is mechanical ankle instability; FAI is functional ankle instability. Using p-values: *Significant difference between MAI and FAI ($p<0.05$); †Significant difference between MAI and comparison ($p<0.05$); ‡Significant difference between FAI and comparison ($p<0.05$)
Using 95% Confidence intervals: §Differences between MAI and FAI; ¶Difference between MAI and comparison; ‖Difference between FAI and comparison.

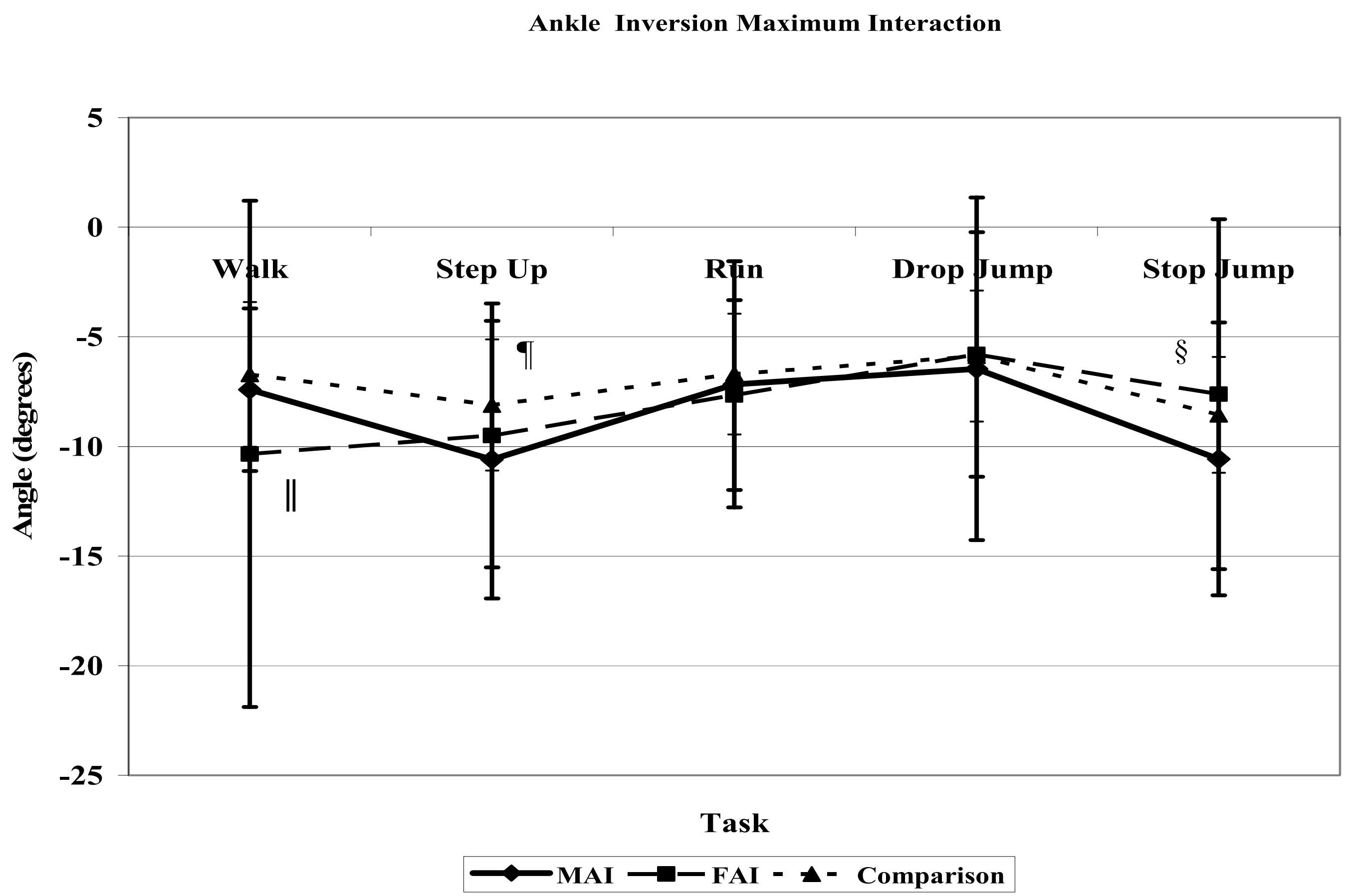

Figure 5. Group x Task Interaction for Ankle Inversion Maximum
$F_{(5.85,175.53)}=1.68$; $p=0.13$; power=0.62
MAI is mechanical ankle instability; FAI is functional ankle instability. Using p-values: *Significant difference between MAI and FAI ($p<0.05$); †Significant difference between MAI and comparison ($p<0.05$); ‡Significant difference between FAI and comparison ($p<0.05$)
Using 95% Confidence intervals: §Differences between MAI and FAI; ¶Difference between MAI and comparison; ‖Difference between FAI and comparison.

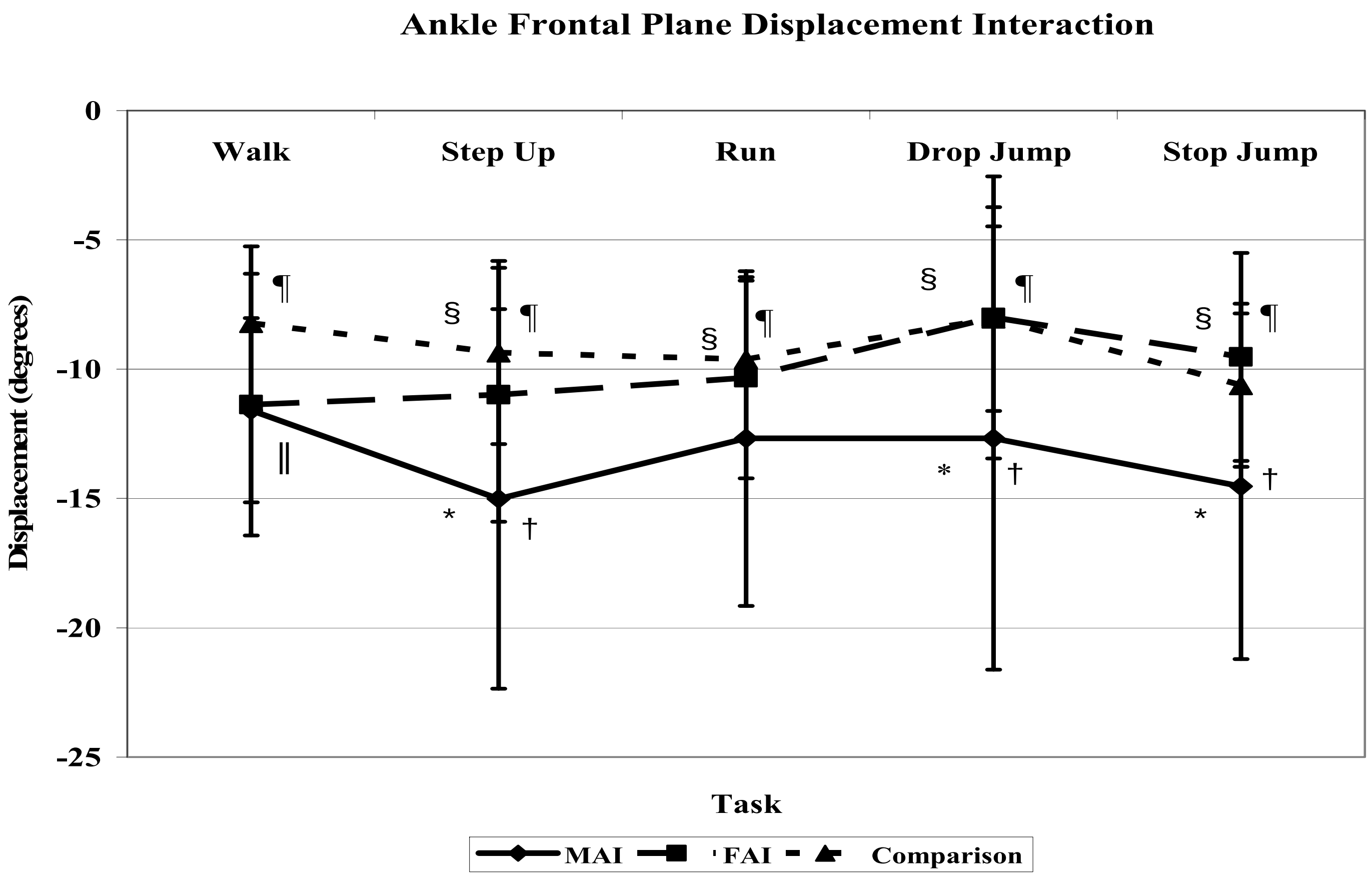

Figure 6. Group x Task Interaction for Ankle Frontal Plane Displacement.
$F_{(5.84,\ 175.33)}=2.25$; $p=0.042$, power=0.77
MAI is mechanical ankle instability; FAI is functional ankle instability. Using p-values: *Significant difference between MAI and FAI ($p<0.05$); †Significant difference between MAI and comparison ($p<0.05$); ‡Significant difference between FAI and comparison ($p<0.05$)
Using 95% Confidence intervals: §Differences between MAI and FAI; ¶Difference between MAI and comparison; ‖Difference between FAI and comparison.

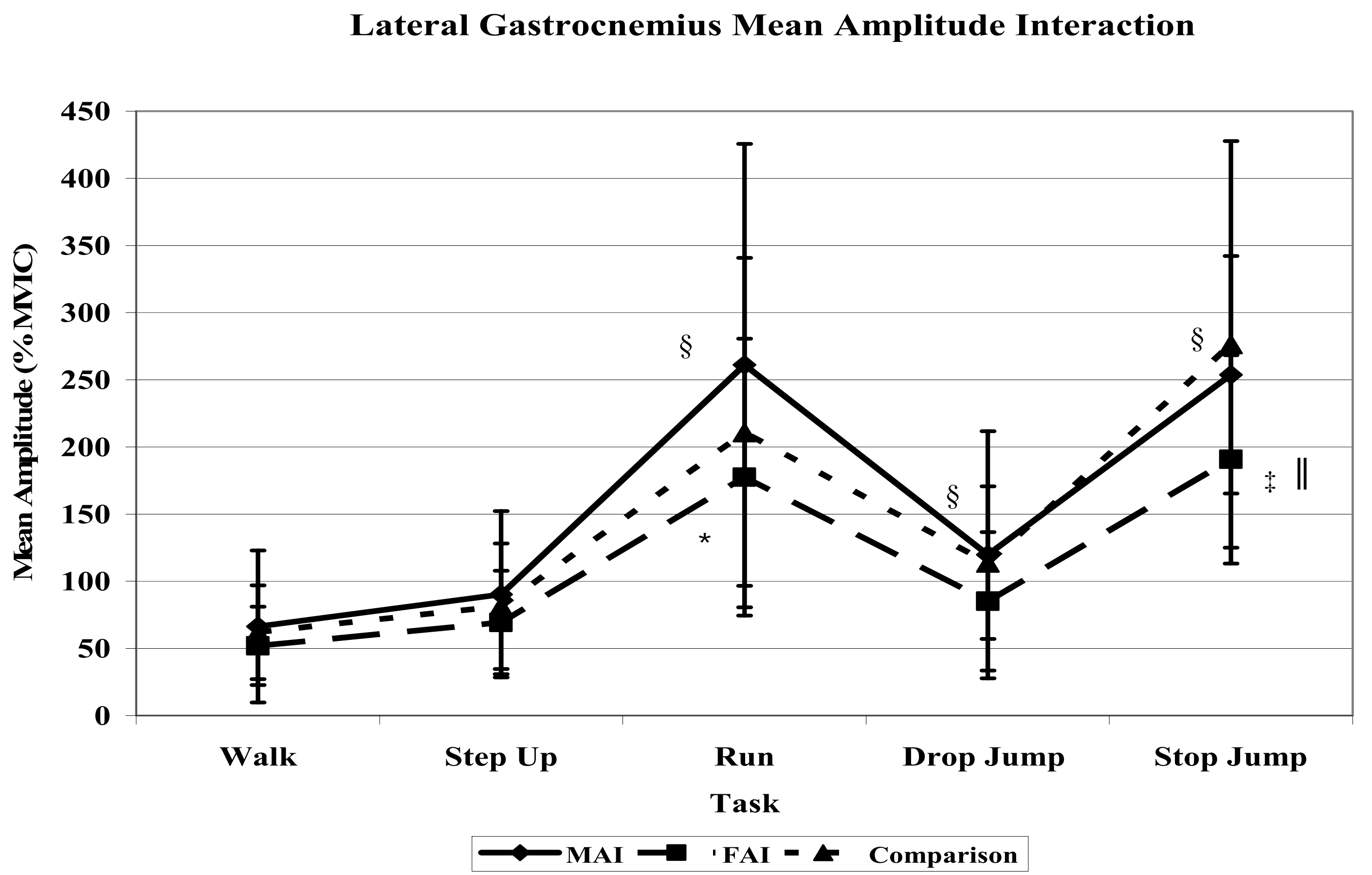

Figure 7. Group x Task Interaction for Lateral Gastrocnemius Mean Amplitude
$F_{(4.31,132.92)}=2.78$; $p=0.025$; power=0.78
MAI is mechanical ankle instability; FAI is functional ankle instability. Using p-values: *Significant difference between MAI and FAI ($p<0.05$); †Significant difference between MAI and comparison ($p<0.05$); ‡Significant difference between FAI and comparison ($p<0.05$)
Using 95% Confidence intervals: §Differences between MAI and FAI; ¶Difference between MAI and comparison; ‖Difference between FAI and comparison.

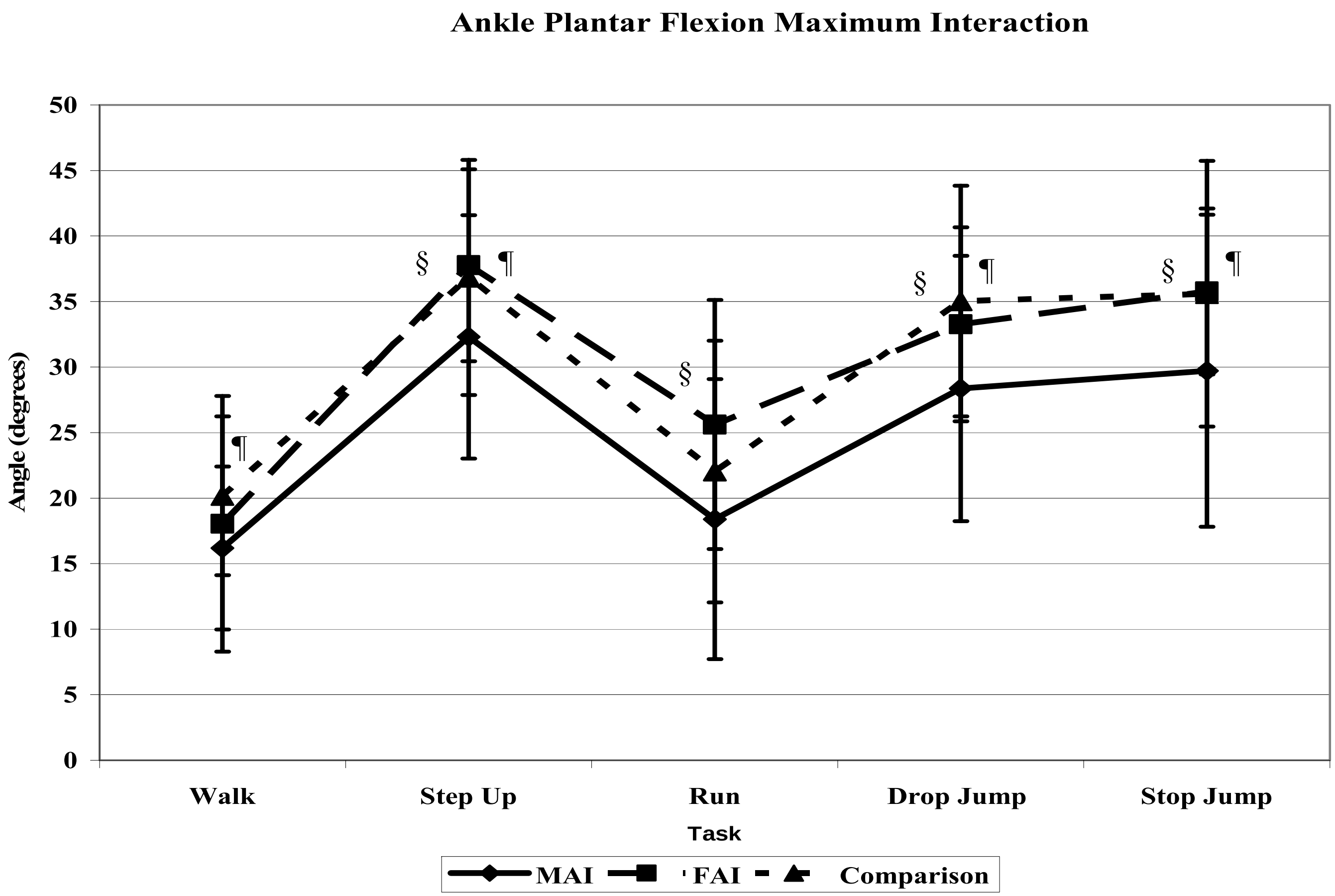

Figure 8. Group x Task Interaction for Ankle Plantar Flexion Maximum
$F_{(6.56,196.88)}=1.11$; $p=0.36$; power=0.46
MAI is mechanical ankle instability; FAI is functional ankle instability. Using p-values: *Significant difference between MAI and FAI ($p<0.05$); †Significant difference between MAI and comparison ($p<0.05$); ‡Significant difference between FAI and comparison ($p<0.05$)
Using 95% Confidence intervals: §Differences between MAI and FAI; ¶Difference between MAI and comparison; ‖Difference between FAI and comparison.

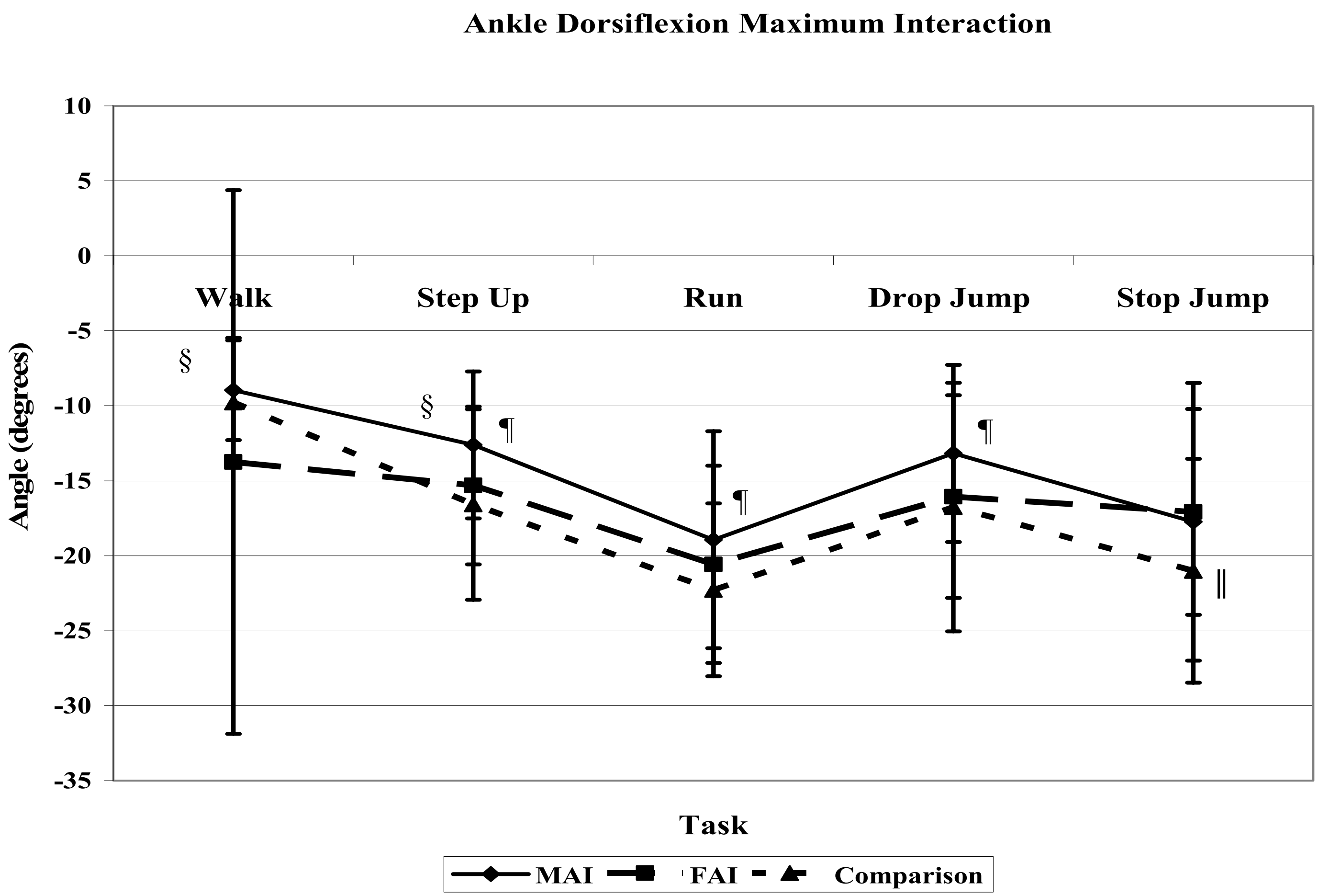

Figure 9. Group x Task Interaction for Ankle Dorsiflexion Maximum
$F_{(4.24,127.23)}$=1.27; p=0.26; power=0.40
MAI is mechanical ankle instability; FAI is functional ankle instability. Using p-values: *Significant difference between MAI and FAI (p<0.05); †Significant difference between MAI and comparison (p<0.05); ‡Significant difference between FAI and comparison (p<0.05)
Using 95% Confidence intervals: §Differences between MAI and FAI; ¶Difference between MAI and comparison; ‖Difference between FAI and comparison.

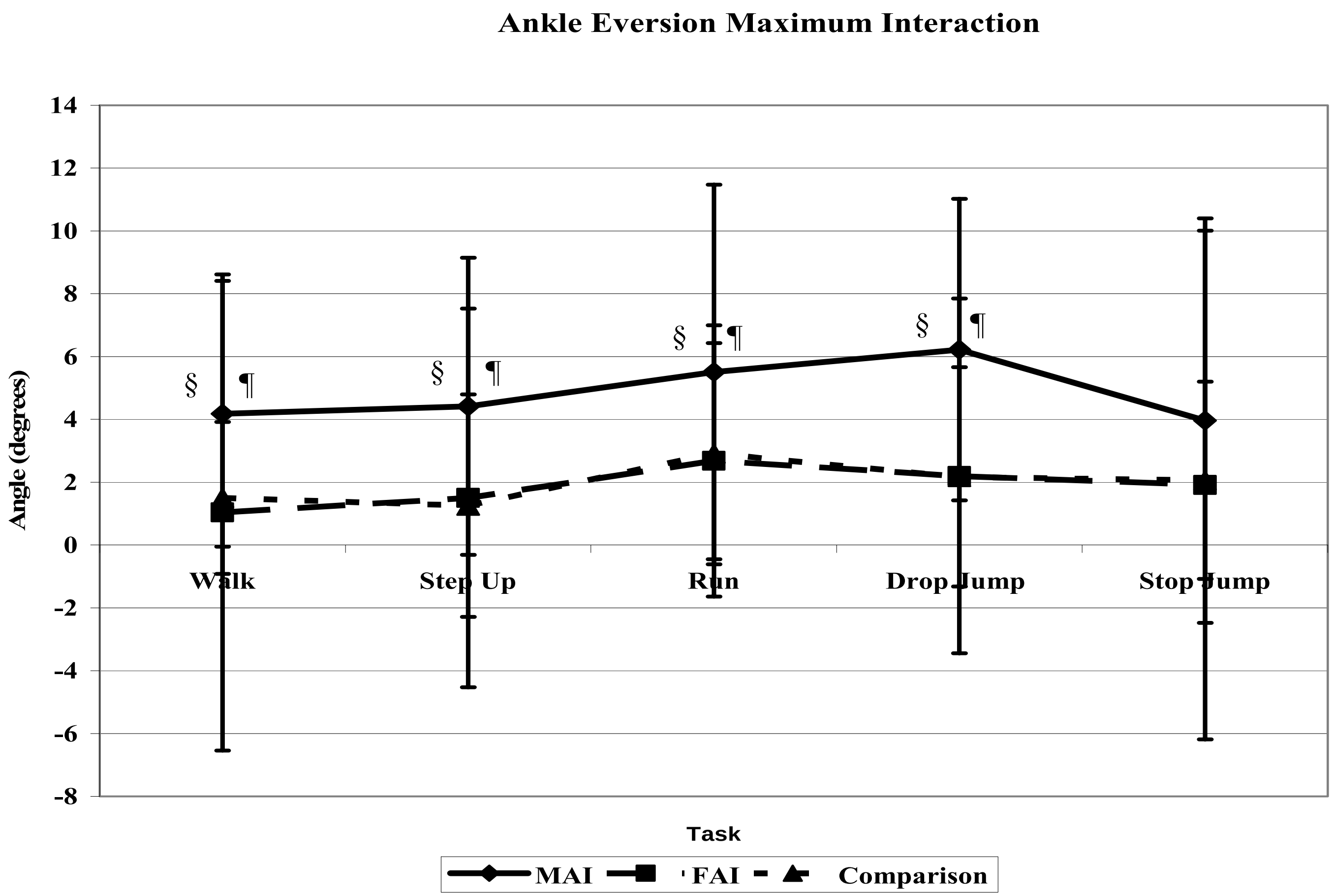

Figure 10. Group x Task Interaction for Ankle Eversion Maximum
$F_{(5.63,19.15)}$=0.29; p=0.94; power=0.13
MAI is mechanical ankle instability; FAI is functional ankle instability. Using p-values: *Significant difference between MAI and FAI (p<0.05); †Significant difference between MAI and comparison (p<0.05); ‡Significant difference between FAI and comparison (p<0.05)
Using 95% Confidence intervals: §Differences between MAI and FAI; ¶Difference between MAI and comparison; ‖Difference between FAI and comparison.

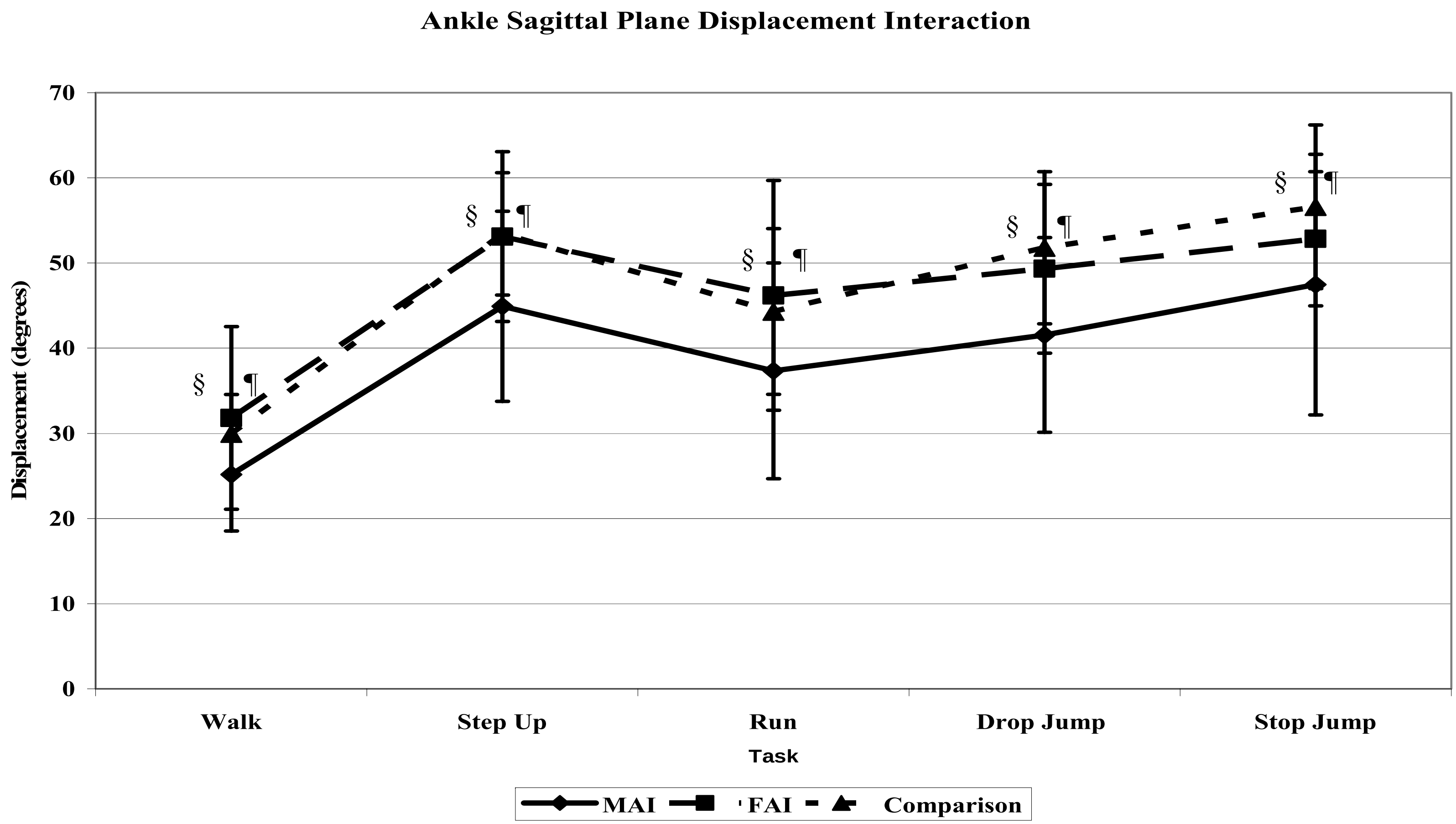

Figure 11. Group x Task Interaction for Ankle Sagittal Plane Displacement
$F_{(6.48,194.41)}=1.19$; $p=0.31$; power=0.48
MAI is mechanical ankle instability; FAI is functional ankle instability. Using p-values: *Significant difference between MAI and FAI ($p<0.05$); †Significant difference between MAI and comparison ($p<0.05$); ‡Significant difference between FAI and comparison ($p<0.05$)
Using 95% Confidence intervals: §Differences between MAI and FAI; ¶Difference between MAI and comparison; ‖Difference between FAI and comparison.

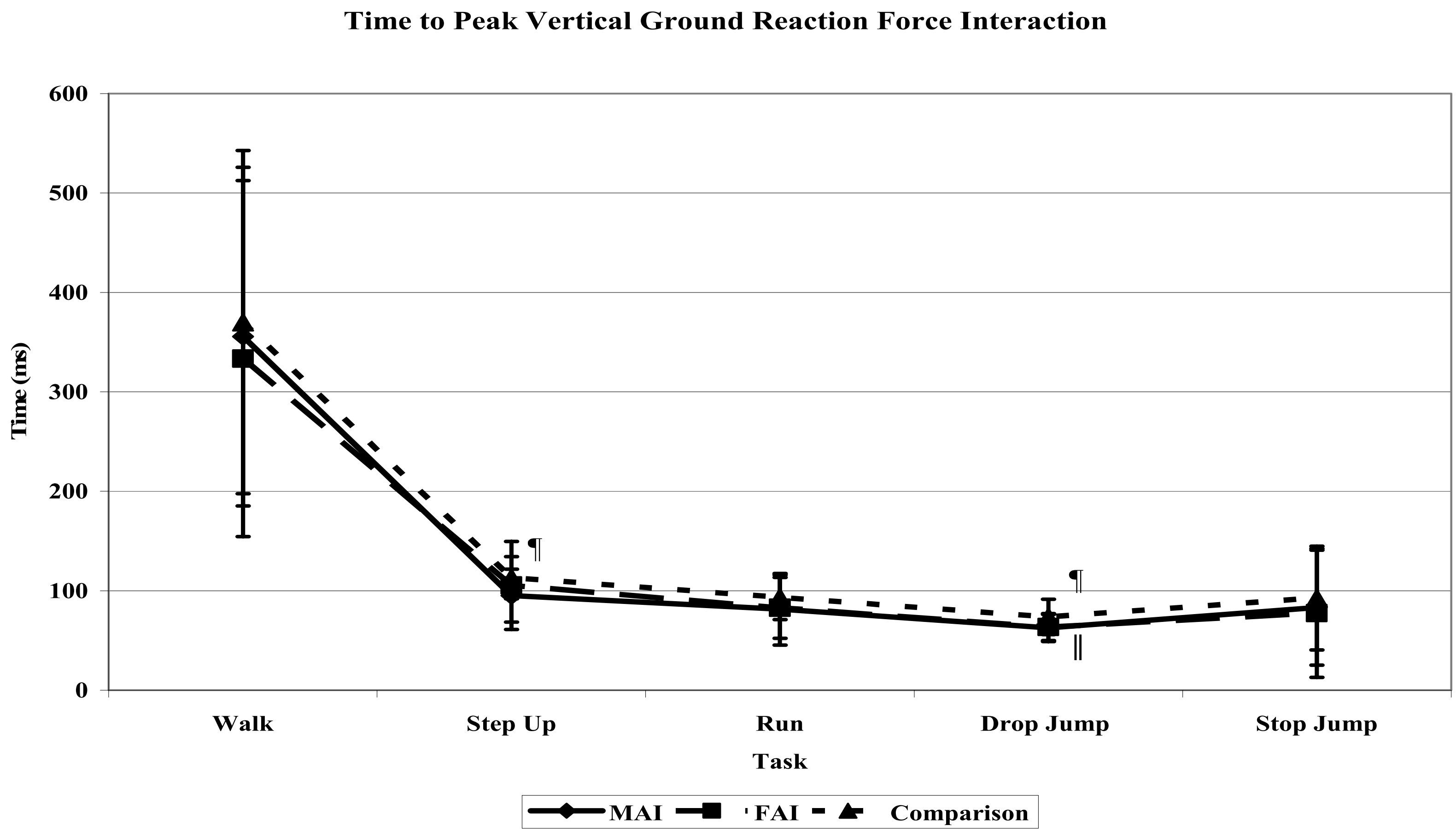

Figure 12. Group x Task Interaction for Time to Peak Vertical Ground Reaction Force
$F_{(2.58,77.31)}=0.15$; $p=0.90$; power=0.08
MAI is mechanical ankle instability; FAI is functional ankle instability. Using p-values: *Significant difference between MAI and FAI ($p<0.05$); †Significant difference between MAI and comparison ($p<0.05$); ‡Significant difference between FAI and comparison ($p<0.05$)
Using 95% Confidence intervals: §Differences between MAI and FAI; ¶Difference between MAI and comparison; ‖Difference between FAI and comparison.

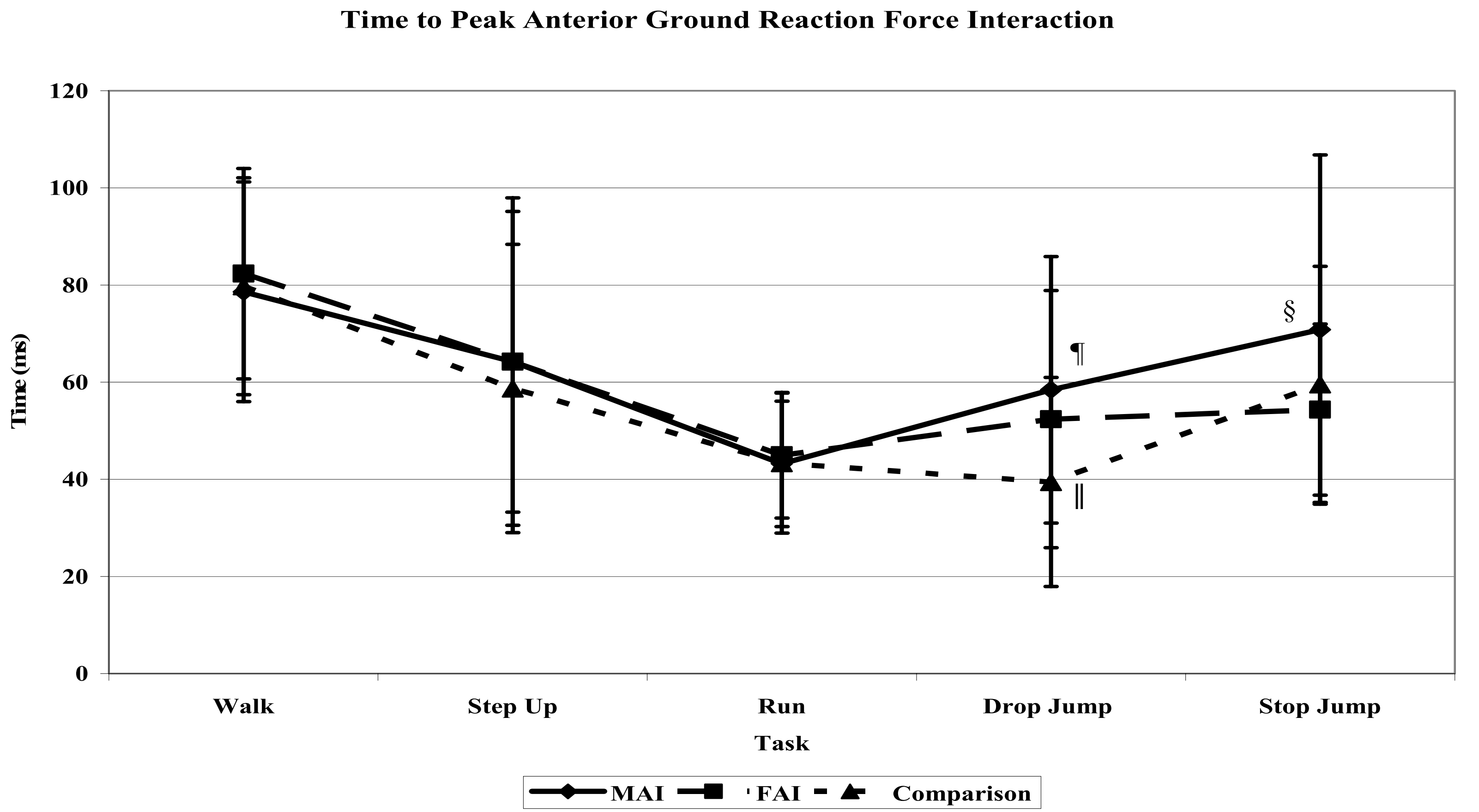

Figure 13. Group x Task Interaction for Time to Peak Anterior Ground Reaction Force
$F_{(6.67,199.94)}=1.28$; $p=0.26$; power=0.53
MAI is mechanical ankle instability; FAI is functional ankle instability. Using p-values: *Significant difference between MAI and FAI ($p<0.05$); †Significant difference between MAI and comparison ($p<0.05$); ‡Significant difference between FAI and comparison ($p<0.05$)
Using 95% Confidence intervals: §Differences between MAI and FAI; ¶Difference between MAI and comparison; ‖Difference between FAI and comparison.

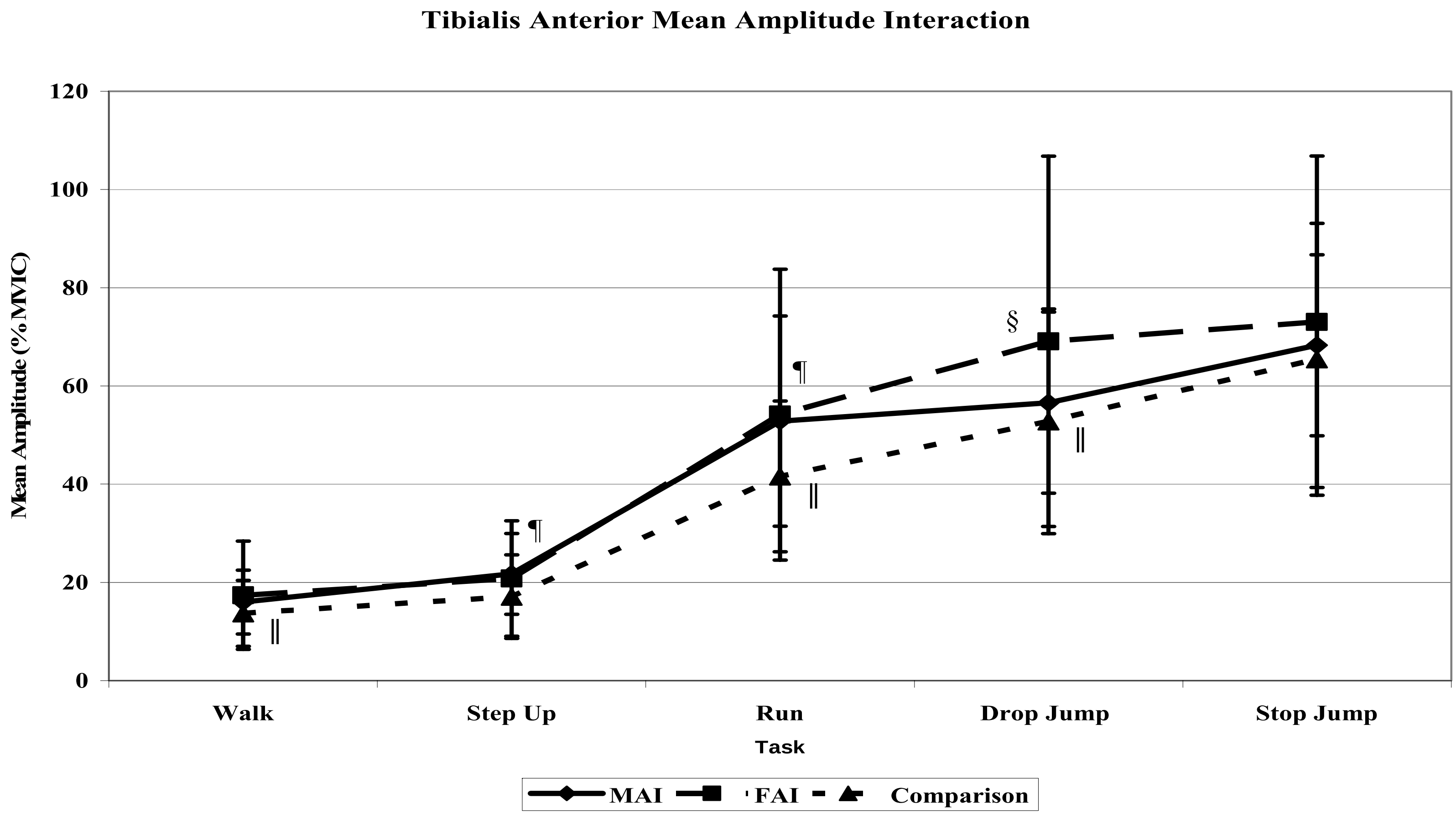

Figure 14. Group x Task Interaction for Tibialis Anterior Mean Amplitude
$F_{(5.24,157.07)}=1.16$; $p=0.33$; power=0.42
MAI is mechanical ankle instability; FAI is functional ankle instability. Using p-values: *Significant difference between MAI and FAI ($p<0.05$); †Significant difference between MAI and comparison ($p<0.05$); ‡Significant difference between FAI and comparison ($p<0.05$)
Using 95% Confidence intervals: §Differences between MAI and FAI; ¶Difference between MAI and comparison; ‖Difference between FAI and comparison.

Log$_e$ Coefficient of Variation Ankle Inversion Interaction

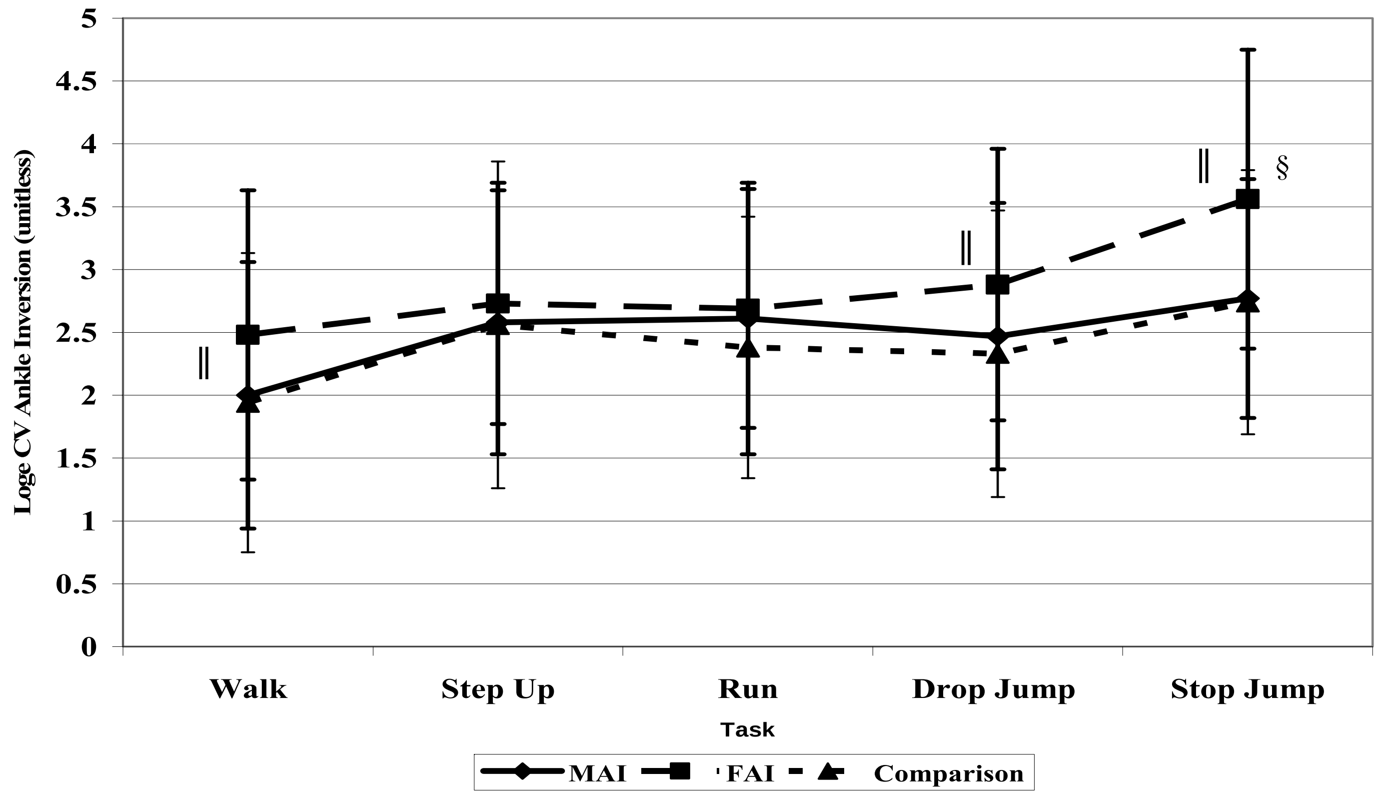

Figure 15. Group x Task Interaction for Log$_e$ Coefficient of Variation Ankle Inversion
$F_{(5.58, 167.43)}=1.57$; $p=0.16$; power=0.57
MAI is mechanical ankle instability; FAI is functional ankle instability. Using p-values: *Significant difference between MAI and FAI ($p<0.05$); †Significant difference between MAI and comparison ($p<0.05$); ‡Significant difference between FAI and comparison ($p<0.05$)
Using 95% Confidence intervals: §Differences between MAI and FAI; ¶Difference between MAI and comparison; ‖Difference between FAI and comparison.

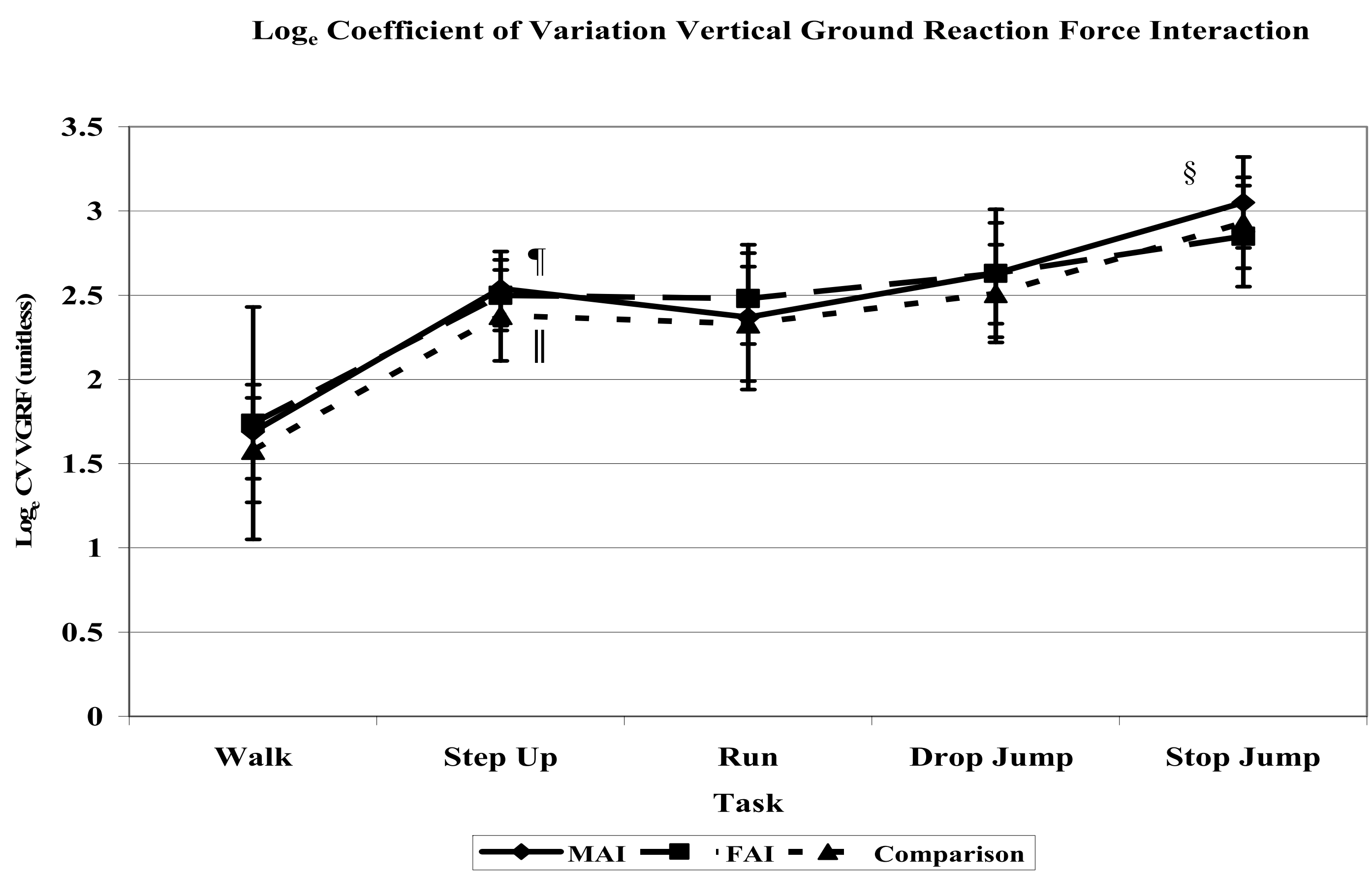

Figure 16. Group x Task Interaction for Log$_e$ Coefficient of Variation Vertical Ground Reaction Force
$F_{(6.67,199.94)}=0.96$; p-value=0.459; power=0.40
MAI is mechanical ankle instability; FAI is functional ankle instability. Using p-values: *Significant difference between MAI and FAI ($p<0.05$); †Significant difference between MAI and comparison ($p<0.05$); ‡Significant difference between FAI and comparison ($p<0.05$)
Using 95% Confidence intervals: §Differences between MAI and FAI; ¶Difference between MAI and comparison; ‖Difference between FAI and comparison.

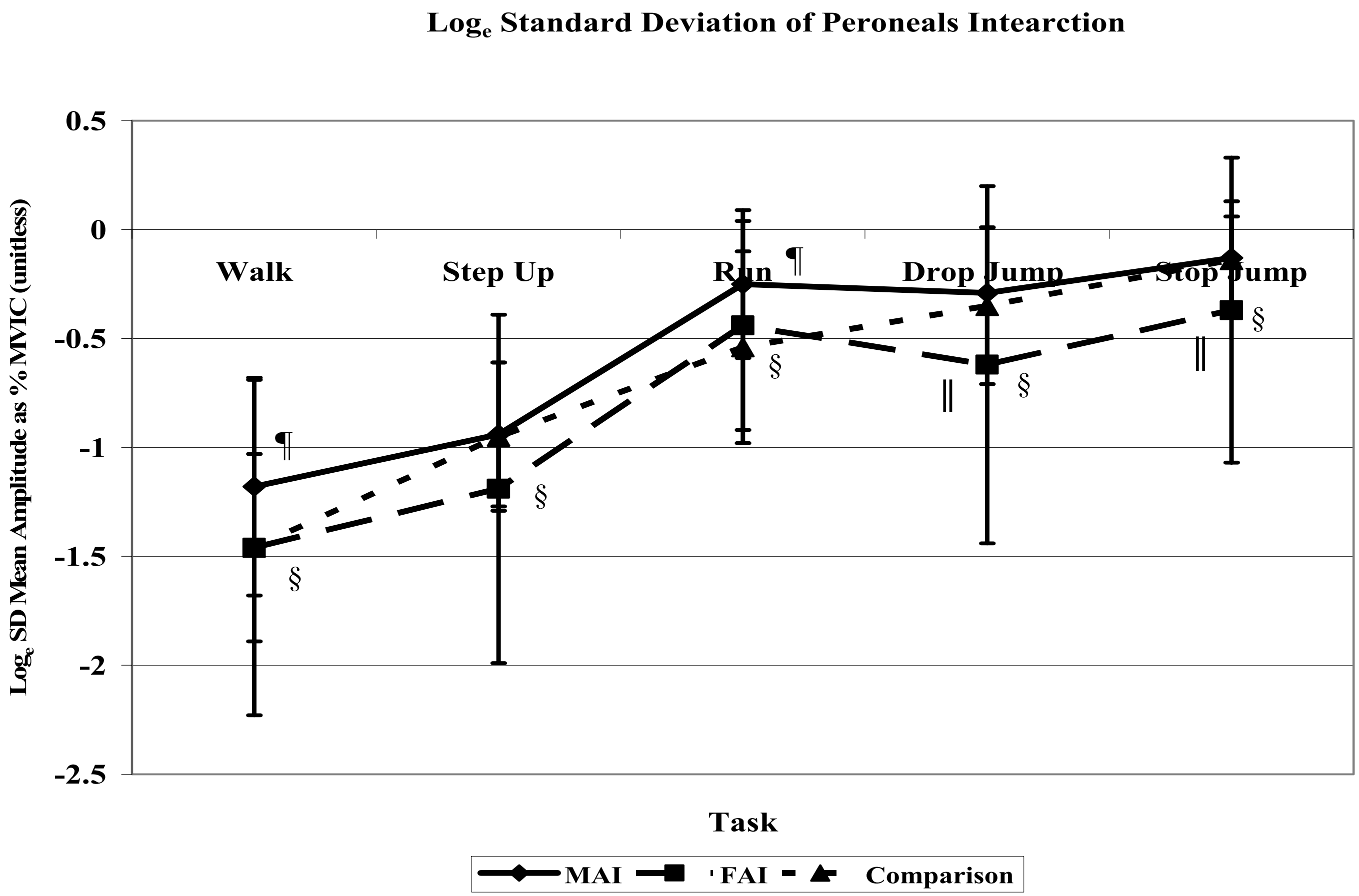

Figure 17. Group x Task Interaction for Log$_e$ Standard Deviation of Peroneal Mean Amplitude
$F_{(4.00,120.07)}=1.26$; $p=0.289$; power=0.385
MAI is mechanical ankle instability; FAI is functional ankle instability. Using p-values: *Significant difference between MAI and FAI ($p<0.05$); †Significant difference between MAI and comparison ($p<0.05$); ‡Significant difference between FAI and comparison ($p<0.05$)
Using 95% Confidence intervals: §Differences between MAI and FAI; ¶Difference between MAI and comparison; ‖Difference between FAI and comparison.

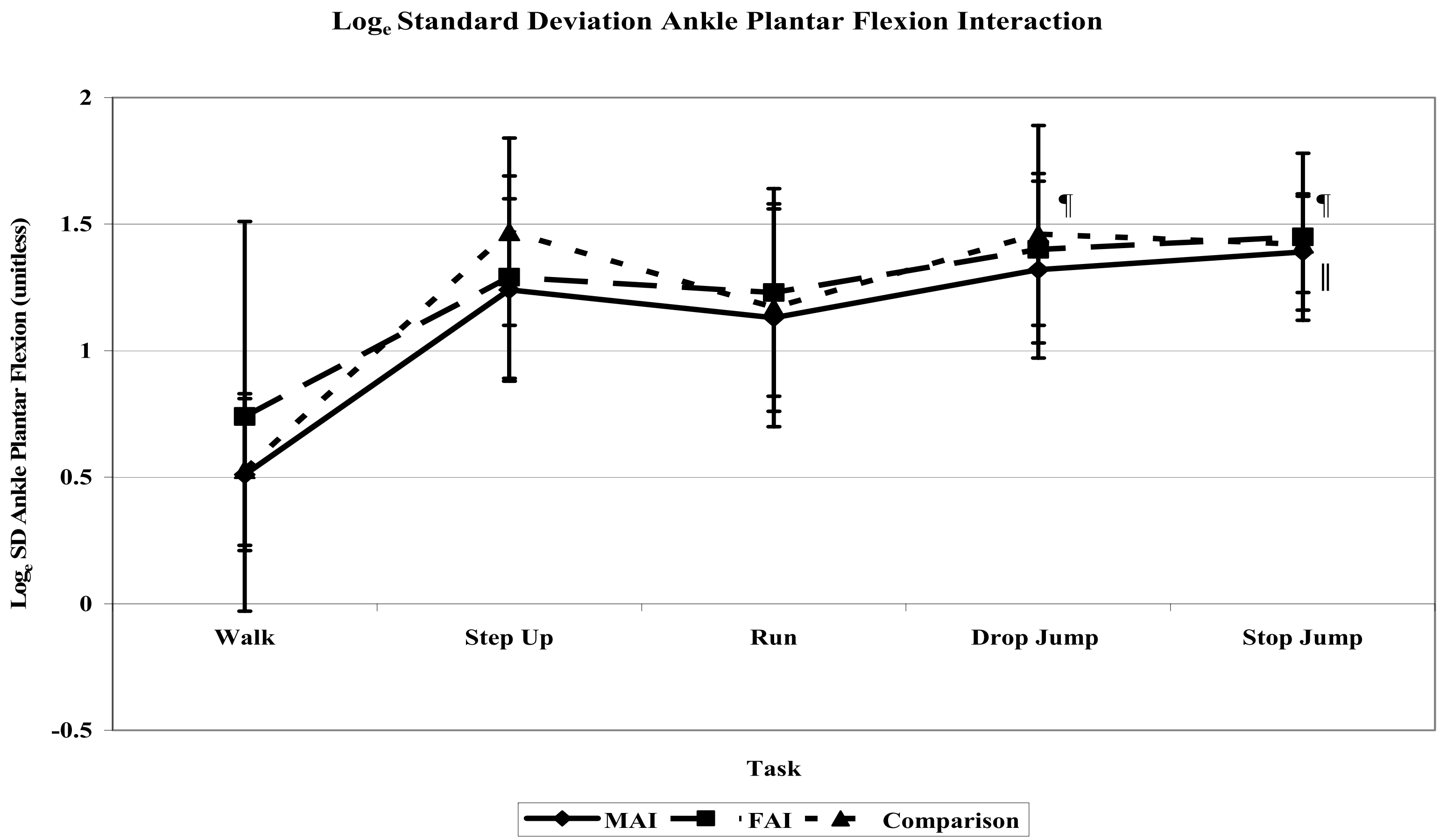

Figure 18. Group x Task Interaction for Log$_e$ Standard Deviation Ankle Plantar Flexion
$F_{(6.27,188.17)}=1.02$; $p=0.42$; power=0.41
MAI is mechanical ankle instability; FAI is functional ankle instability. Using p-values: *Significant difference between MAI and FAI ($p<0.05$); †Significant difference between MAI and comparison ($p<0.05$); ‡Significant difference between FAI and comparison ($p<0.05$)
Using 95% Confidence intervals: §Differences between MAI and FAI; ¶Difference between MAI and comparison; ‖Difference between FAI and comparison.

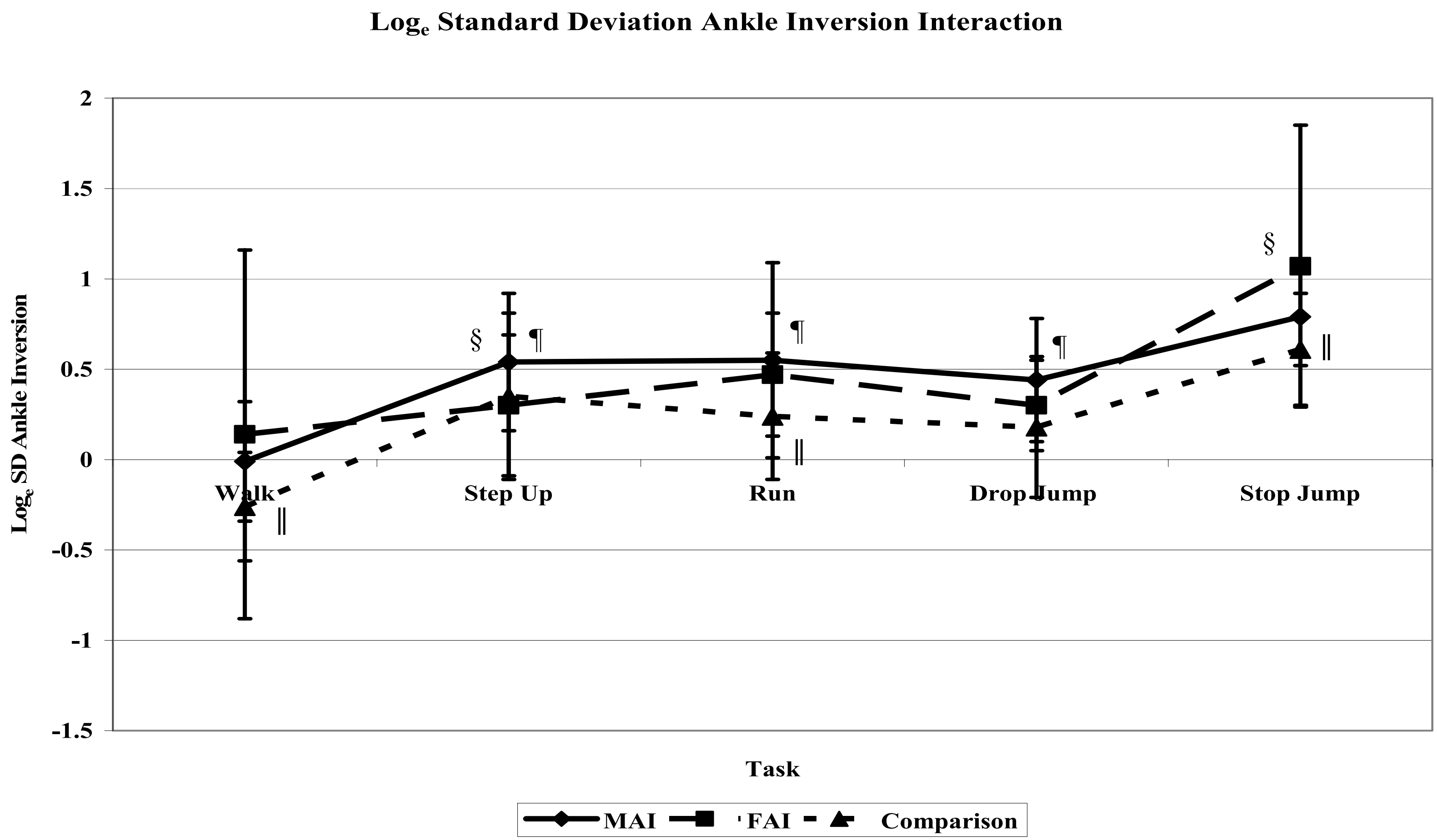

Figure 19. Group x Task Interaction for Log$_e$ Standard Deviation Ankle Inversion
$F_{(6.51,195.34)}=1.77$; $p=0.10$; power=0.69
MAI is mechanical ankle instability; FAI is functional ankle instability. Using p-values: *Significant difference between MAI and FAI ($p<0.05$); †Significant difference between MAI and comparison ($p<0.05$); ‡Significant difference between FAI and comparison ($p<0.05$)
Using 95% Confidence intervals: §Differences between MAI and FAI; ¶Difference between MAI and comparison; ‖Difference between FAI and comparison.

Log_e Standard Deviation Tibialis Anterior Interaction

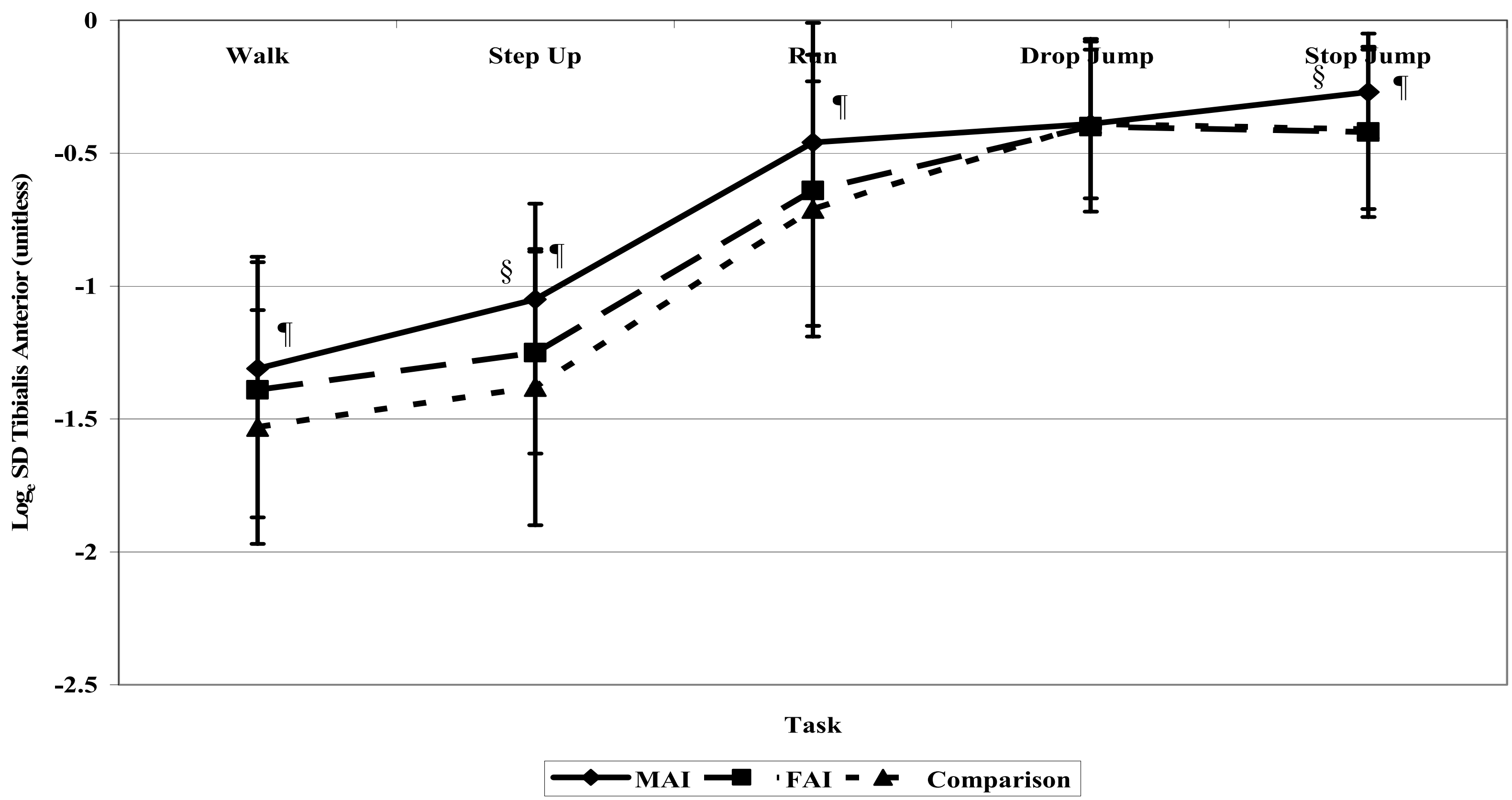

Figure 20. Group x Task Interaction for Log_e Standard Deviation Tibialis Anterior
$F_{(6.08,182.44)}=0.89$; $p=0.50$; power=0.35
MAI is mechanical ankle instability; FAI is functional ankle instability. Using p-values: *Significant difference between MAI and FAI ($p<0.05$); †Significant difference between MAI and comparison ($p<0.05$); ‡Significant difference between FAI and comparison ($p<0.05$)
Using 95% Confidence intervals: §Differences between MAI and FAI; ¶Difference between MAI and comparison; ‖Difference between FAI and comparison.

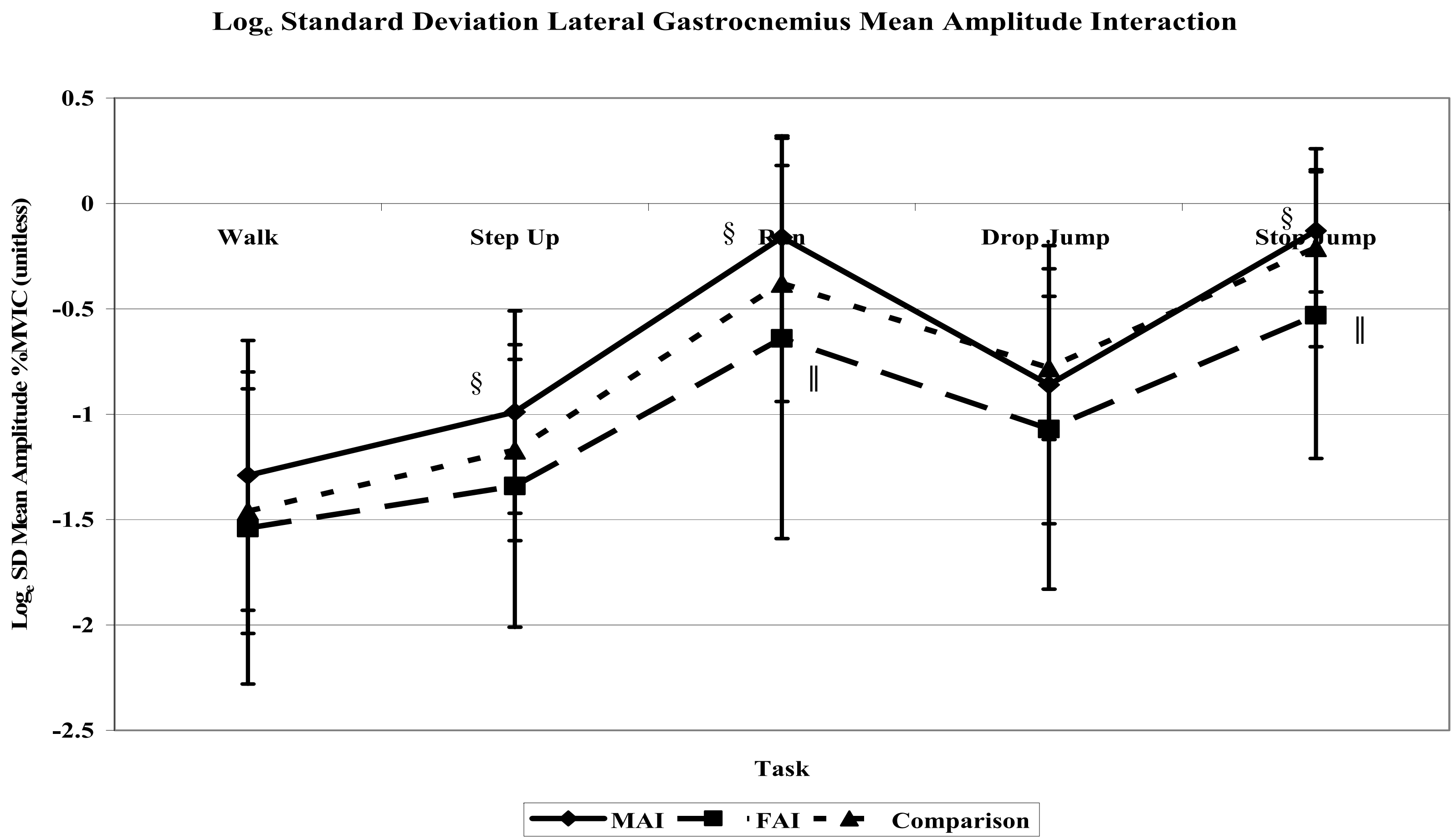

Figure 21. Group x Task Interaction for Log$_e$ Standard Deviation Lateral Gastrocnemius
$F_{(5.95,178.54)}=0.88$; $p=0.51$; power=0.34
MAI is mechanical ankle instability; FAI is functional ankle instability. Using p-values: *Significant difference between MAI and FAI ($p<0.05$); †Significant difference between MAI and comparison ($p<0.05$); ‡Significant difference between FAI and comparison ($p<0.05$)
Using 95% Confidence intervals: §Differences between MAI and FAI; ¶Difference between MAI and comparison; ‖Difference between FAI and comparison.

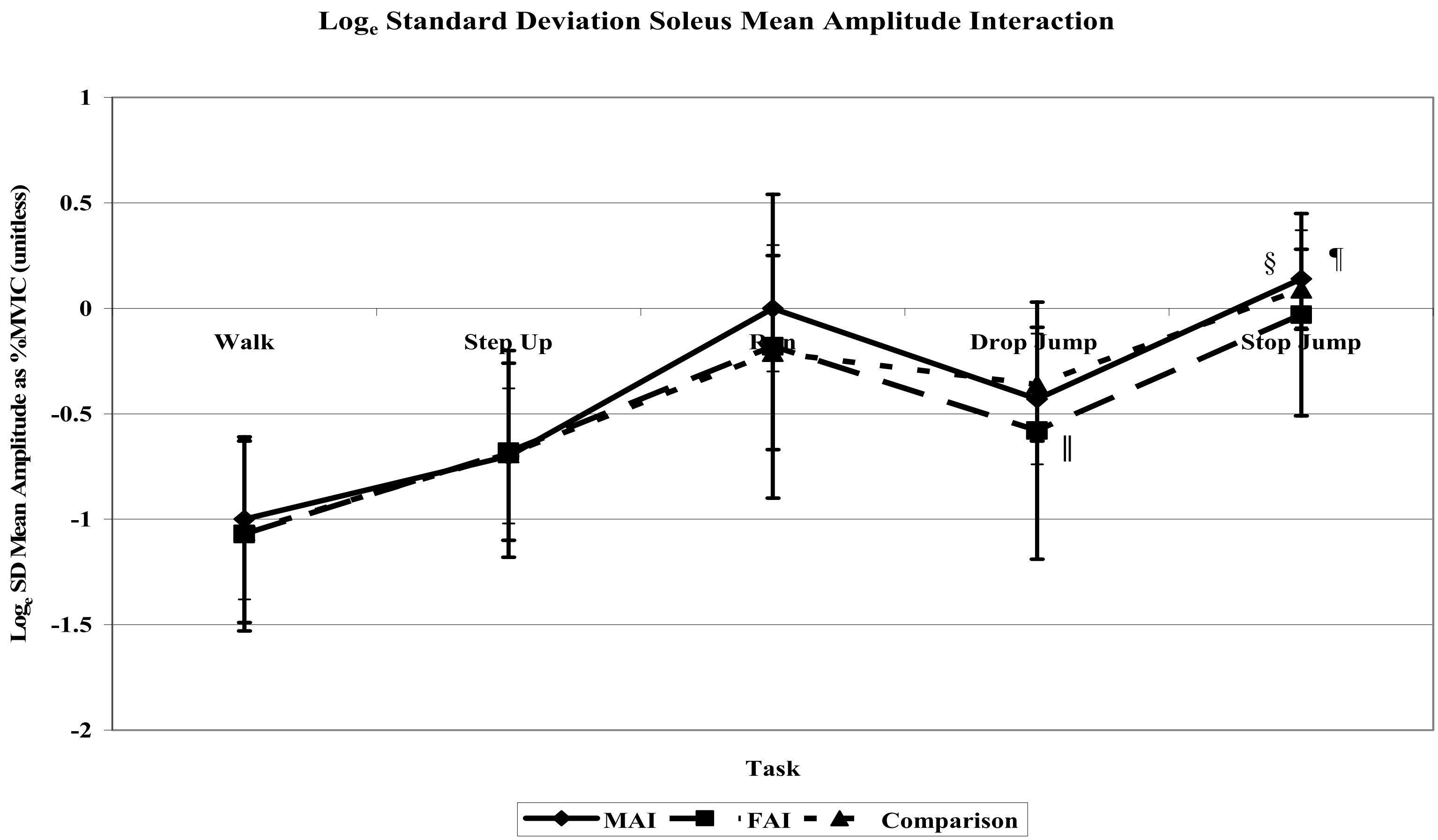

Figure 22. Group x Task Interaction for Log$_e$ Standard Deviation Soleus
$F_{(6.40,192.04)}=1.64$; $p=0.13$; power=0.64
MAI is mechanical ankle instability; FAI is functional ankle instability. Using p-values: *Significant difference between MAI and FAI ($p<0.05$); †Significant difference between MAI and comparison ($p<0.05$); ‡Significant difference between FAI and comparison ($p<0.05$)
Using 95% Confidence intervals: §Differences between MAI and FAI; ¶Difference between MAI and comparison; ‖Difference between FAI and comparison.

APPENDIX A

Manuscript I

Manuscript I

Motion Analysis in Individuals with Mechanical and Functional Ankle Instability

Context: Chronic ankle instability commonly develops following ankle sprain, and limited motion analysis has been performed to determine if there are perpetuating factors.

Objective: To determine whether differences exist in kinematics and kinetics between a group of recreational athletes with mechanical (MAI) or functional ankle instability (FAI) and a comparison group on walking, stepping up and over, running, drop jump, and stop jump tasks.

Design: A quasi-experimental, case-control design.

Setting: Laboratory.

Patients or Other Participants: Sixty-three recreational athletes, 21 in each group (11 males, 10 females) matched for gender, age, height, mass, and limb dominance.

Main Outcome Measures: We measured ankle flexion and inversion, knee flexion and valgus, peak ground reaction forces (GRF), and time to peak GRF in three directions, during the stance phase of 5 tasks.

Results: Based on estimates of adjusted means, 95% confidence intervals, and effect sizes from repeated measures ANOVAs, the MAI group displayed less plantar flexion at initial contact than the comparison group on each task and the FAI group on 3 tasks. The MAI group also displayed larger maximum inversion than the comparison group in the step up and the FAI in the stop jump. The MAI group frontal plane displacement was greater than the comparison group on each task, and the FAI group on 4 tasks. The MAI group also demonstrated decreased maximum plantar flexion and dorsiflexion than the FAI and comparison groups, but larger eversion maximum than the comparison group in several tasks. The MAI group demonstrated faster time to peak vertical ground reaction force but longer time to peak anterior ground reaction force than the comparison group in selected tasks. No differences were observed at the knee or other GRF.

Conclusions: The MAI group demonstrated a movement pattern placing the ankle in a closed-pack position, possibly increasing reliance on bony stability and avoiding stressing the anterior talofibular ligament. This may help avoid ankle sprain in the short term, but may increase the risk of ankle joint degeneration in the long term. The MAI and FAI groups exhibit different movement patterns and should be separated in ankle instability studies.

Key Words: chronic ankle instability, kinematics, kinetics

Introduction

Ankle sprains are one of the most common sports-related injuries. Data collected through the National Collegiate Athletic Association's Injury Surveillance System indicated lateral ankle sprains were the most common injury in soccer, volleyball, and basketball in all three collegiate divisions.[1] It is also a very common injury in the recreationally active population, with injury rates reported as 3.85/1000 exposures in recreational basketball[2] and 5.7/100 participants per season in high school sports studies.[3]

Chronic ankle instability (CAI), defined as subjective and repeated episodes of giving way and spraining of the ankle, is often the end-result of an initial ankle sprain,[4] as approximately 47-73% will suffer from recurrent sprains.[5, 6] CAI encompasses two possible causes of repetitive ankle sprains: mechanical instability and functional instability, and may be attributable to either independently or some combination of both.[4] Some individuals may develop CAI due to mechanical ankle instability (MAI) or physiologic laxity at the ankle joint following severe or repeated ankle sprains. However, some individuals with CAI have no mechanical laxity, and instead may be attributable to functional ankle instability (FAI).[4] First introduced by Freeman,[7] FAI is thought to be due to deafferentation or tearing of neural tissue within the ligament, causing deficits in proprioception and neuromuscular control.

The causes and factors that contribute to CAI after initial sprain are currently unknown, and because these two factors, MAI and FAI, have either been combined or ignored in most previous research, little information exists regarding any differences they might cause in CAI.[8] Fundamental differences in the nature of the ankle pathology could influence explanations for the continued episodes of giving way, and may require different rehabilitation exercises and protocols to best address the deficits. Some of the current contradictions in the literature on whether or not CAI groups demonstrate altered joint position sense, postural stability, functional capacity, and movement in comparison to control groups may be due to the lack of differentiation between MAI and FAI groups. Separating these two types of pathologies may clarify some of the contradictions and offer insight into goals for future research and rehabilitation.

Though CAI and lateral ankle sprains are common, the pathophysiology is still not clear, and the long-term effects of CAI on ankle joint health are not well documented.[9] Unlike knee instability, most ankle arthritis is secondary to trauma and not due to overuse or wear.[10, 11] Individuals with a history of CAI displayed increased articular lesions, degeneration, and defects in the ankle.[9] There are currently no adequate surgical procedures to correct this articular damage, so prevention is the key to avoiding ankle joint degeneration. Preventing and treating chronic ankle instability may be an important step in ensuring long-term joint health, especially in later life.

Lack of standardization in subject selection is also a problem: defining criteria for MAI, FAI, and "control" subjects has proven difficult due to the continuum of ankle instability severity. Few studies to date have used "copers," or a comparison group of individuals with a history of previous initial sprain but no complaints of instability. Similar "coper" groups have been used successfully in the anterior cruciate ligament (ACL) injury literature,[12, 13] and may be applicable to ankle studies. Rather than compare CAI subjects to individuals who have never suffered an ankle sprain, a more appropriate comparison may be made between CAI subjects and individuals with a similar ankle injury history, who did not subsequently develop or experience repeated episodes of giving way. These individuals' ability to "cope" and recover from the injury may highlight differences that developed following initial sprain.

To date, few studies have obtained a complete biomechanical picture of ankle instability.[14-19] Most ankle literature has focused on static balance (with conflicting results)[20-23] and jump landing, a complex and highly demanding task.[24-26] While some studies reported differences between groups with these tasks, little attention has been paid to other tasks that produce injury or may illuminate deficits, such as walking,[18] running, and stepping-up and over. Subjects and groups may utilize different strategies and movements, and different biomechanical demands may create different results. Identifying differences in motion patterns may allow for targeted rehabilitation aimed at decreasing exposure to risky or injurious positions and ensure proper joint mechanics during functional tasks. No study to date has combined different tasks (walking, step-up and over, running, drop jump, and stop jump) in a progression to identify if or where kinematic and kinetic differences can be observed between groups. Obtaining a complete biomechanical picture requires a large number of variables, at the ankle and knee in both the sagittal and frontal planes, as well as ground reaction forces (GRF) in all directions. Previous studies observed differences in knee and ankle sagittal plane motion and vertical GRF,[15, 16, 18] however, the sample size was fairly small and the variables and planes of motion were limited. Thus, the purpose of this study was to identify kinematic and kinetic factors that may contribute to ankle instability and ankle injury.

Methods

Subjects

A total of 63 subjects between 18-35 years old participated in this study, 21 (11 males, 10 females) in each of three groups. Subjects were individually matched across all three groups on gender, age (±2year), height (±10%), mass (±10%), and limb dominance. Subject demographics are reported in Table 1. A-priori power calculations were performed to determine necessary sample size using the conservative t-test model. Based on estimated means from graphic data from a similar study, an n of 10 provided power of 0.60-0.99 in kinematic variables at the ankle and knee. The effect sizes were 0.93-1.15.[16] Additionally, pilot data from 4 chronically unstable ankle subjects and 4 comparison subjects indicated that variables of primary interest (ankle variables for plantar flexion at initial contact, inversion-eversion at initial contact, maximum plantar flexion and maximum eversion) all required 20 subjects or fewer to achieve a power of 0.80.

Inclusion criteria for all subjects was recreational activity defined as performing at least 1.5 total hours of cardiovascular, resistance, sport-related, or other physical activity per week. In addition, each subject had a history of acute inversion ankle sprain that required immobilization or non-weight bearing for at least 3 days within the past 1-5 years. The MAI and FAI groups reported repeated episodes of "giving way" and complaints of ankle instability secondary to the initial sprain, with a minimum of 2 episodes of giving way or spraining in the past 12 months. The MAI group demonstrated clinically positive anterior drawer and/or talar tilt to orthopedic exam, rated as 4/5 "loose" or 5/5 "very" loose on a laxity scale.[27] The FAI group demonstrated negative anterior drawer and/or talar tilt tests (2/5 "hypomobile" or 3/5 "normal" on a laxity scale).[27] One researcher rated ankle laxity for all subjects. Pilot testing using an intraclass correlation coefficient (ICC 2,1) determined interrater reliability, which was greater than 0.80 on both tests. The standard error of the measurement (SEM) was less than 0.25 for both tests. The comparison group reported no repeated episodes of "giving way" or complaints of ankle instability, with one or fewer episodes of giving way or spraining in the past 12 months and no sprain within the past 3 months. The comparison group also demonstrated negative anterior drawer and/or talar tilt tests.[27]

Exclusion criteria for all groups included a history of surgery in either leg and any previous ankle fracture in either leg, a lower extremity injury in the last three months (other than an episode of ankle sprain or giving way in the MAI and FAI groups), and obvious swelling or discoloration. Ankle pain, gross limitations in ankle range of motion, self-reported instability of the knee and hip, and current enrollment in a formal rehabilitation program were also exclusion criteria.

Instrumentation

A piezoelectric non-conductive forceplate (Model #4060-NC Bertec Co., Columbus, OH) with a frequency response of 400 Hz in the vertical direction and 300 Hz in both horizontal directions measured the subject's mass (in kg) and the kinetic variables. The Flock of Birds (Ascension Technologies, Burlington, VT) with 6 sensor "birds" and the Motion Monitor software (Version 6, Innovative Sports Training, Chicago, IL) controlling it collected kinematic variables. We used the standard range transmitter (72 inches) with 6 birds, one of which was moveable and attached to a stylus for digitization of joints. An A/D board in the Flock input and time synchronized kinematic and forceplate data through the Motion Monitor software.

Prior to data collection, the electromagnetic field for the tracking system was established, along with the stylus, forceplate, and global axis system. The standard range transmitter was mounted on a non-metal stand 32 cm from the forceplate at a height of 42cm. The axes system had +x in the direction the subject faced, +y to the right and +z in the upward vertical direction. All digitization occurred with a 15.4cm long wooden stylus, whose length was established by a 20-point digitization around a stationary point. Root mean square (RMS) error of the stylus was always less than 0.003 and was recorded.

Data Collection Procedures

Prior to testing, subjects signed an informed consent as approved by the University's Institutional Review Board. We collected demographic data, anthropometric measurements (range of motion and limb dominance),[28] and an ankle injury history. Subjects underwent a brief orthopedic exam by a certified athletic trainer (ATC) to determine laxity using the anterior drawer and talar tilt tests[29] for entry into one of the three ankle stability groups. Subjects also completed the Foot and Ankle Disability Index (FADI) and its Sports Subscale (FADI-S) to assess functional status.[30]

Once placed into the appropriate group, sensors were attached. The lateral femur sensor was attached over the iliotibial band midway between the hip joint and the knee joint. The tibial sensor was placed on the antero-medial portion of the tibia, 3-5 cm distal to the tibial tuberosity. The calcaneal sensor was placed on the most inferior portion of the bone on the midline of the shank. The foot sensor was placed between the 2nd-3rd metatarsals, at the midpoint of the metatarsals. Sensors were placed over areas with minimal muscle mass to decrease potential skin movement. The sensors were positioned so the cords were oriented cephally and cords were looped and secured to subjects' legs and feet using double-sided tape, surgical tape, and athletic tape to avoid tension and movement artifact (Figure 1). Before digitization, the following bony landmarks were palpated and marked with a felt-tip pen: the most medial and lateral points knee joint line, the most prominent portions of the medial and lateral malleoli, the most prominent portions of the 1^{st} and 5^{th} metatarsal heads, and the most inferior portion of the calcaneus on either side of the calcaneal sensor just above where the heel contacts the ground. Initial digitization included the medial and lateral knee joint line points, the medial and lateral malleoli points, and the tip of the second phalanx. Following initial digitization, a similar process was undertaken for each of the segments and joints of interest. The proximal and distal ends of the longitudinal axis, a 3^{rd} point on the plane, a 4^{th} point above and on the positive side, and the origin were digitized for each joint/segment. Each origin was a centroid, or calculated midpoint, between two bony landmarks at a joint. The proximal end of the longitudinal axis of the thigh was one point on the most prominent portion of the greater trochanter, as palpated. The distal end was the centroid of the marked points on the medial and lateral knee joint lines. The 3^{rd} point on the plane was the lateral joint line point, and the 4^{th} point was digitized around the subject's abdomen. The origin of the thigh was the centroid between the medial and lateral knee joint line points. The proximal end of the longitudinal axis of the shank was the centroid of the medial and lateral knee joint line marks. The distal end was the centroid of the marked points on the medial and lateral malleoli. The 3^{rd} point on the plane was the lateral malleolus, and the 4^{th} point was digitized above the subjects' knee on the anterior side of the body. The origin of the shank was the centroid of the medial and lateral malleoli points. The proximal end of the longitudinal axis of the foot for the metatarsal sensor was the centroid between the medial and lateral malleoli points. The distal end was the centroid between the 1^{st} and 5^{th} metatarsal heads. The 3^{rd} point on the plane was the 1^{st} metatarsal head and the 4^{th} point was digitized at the midline of the shank, superior and anterior to the foot. The origin of the metatarsal sensor was the centroid of the 1^{st} and 5^{th} metatarsal heads. The proximal end of the longitudinal axis of the foot for the calcaneal sensor was the centroid of the two marks on either side of the calcaneal sensor. The distal end was the centroid of the marks on the 1^{st} and 5^{th} metatarsal heads. The 3^{rd} point on the plane was the mark on the medial side of the calcaneal sensor, and the 4^{th} point was at the midline of the foot, anterior to the tibia. The origin of the foot for the calcaneal sensor was the centroid of the two marks on either side of the calcaneal sensor. A final set up visual check and then a real-time view check ensured the joints and segments were digitized correctly.

The forceplate was used to measure mass. Height was entered into the software. A static calibration trial 3 seconds long was collected to define anatomic neutral position for the motions of interest.

Test Tasks

During the testing session, the subjects performed five different tasks. The tasks were walking at a speed of 1.2-1.4 m/s,[31, 32] stepping-up and over a 32 cm high box, running at 2.5-3.5 m/s,[33, 34] performing a single leg drop jump from a box of height 32 cm, and performing a stop jump with the same velocity as the running task. These speeds reflect typical daily living and game speed for the respective tasks. For the drop jump trials, subjects were instructed not to jump "up" off the box to minimize upward vertical movement but instead to "step off" the box to standardize vertical distance traveled. Single leg drop jump trials were completed without any touch-downs or stepping or stumbling with the other leg. The subject balanced for approximately 3 seconds at the end of each drop jump trial. For the walking, running, and stop jump trials, anterior linear velocity was used to measure the speed of movement during the trial. No instructions were provided other than to make contact with the forceplate with the entire foot. Real time data was presented as feedback to subjects to perform within the ranges for walking and running speed on each trial. Only trials within the speed range were used for analyses. Each task was practiced a minimum of 3 times, followed by 8 test trials.[35] Subjects received at least 30 seconds rest in between all trials. The test tasks were performed in the order stated, however the choice of first task was counterbalanced across subjects to reduce confounding from fatigue, learning, or practice.

Pilot testing with 4 CAI and 4 comparison subjects indicated the kinematic ankle variables on the drop jump task had intraclass correlation coefficient (ICC; 2,1) values of 0.67-0.88 with standard error of the measurement (SEM) of 2-5º. The knee variables had ICC values of 0.68-0.97 (SEM = 1-5º). The ICC for vertical ground reaction forcee variables was low (0.44) in the CAI group with a large SEM (0.77 x body mass), but high in the comparison group (0.93) with a smaller SEM (0.50 x body mass).

Data processing

The Flock of Birds sampling rate was 144 Hz. The axes system was established as a left-handed system (origin starting in the left corner of the forceplate). Using the left hand screw rule, the following motions were positive: flexion, eversion/valgus, and external rotation.[36] Data were aligned to this configuration, regardless of side. The order of rotations of Euler angles at the ankle and knee was Y, X', Z'' or flexion, eversion/valgus, and external rotation. The last rotation was not analyzed in either joint because it was not a variable of interest, was the 3rd rotation with the most error, and it had the smallest range of motion. Kinetic data were collected at 1440 Hz and time synchronized with the kinematic data. Ground reaction forces for each task were normalized to body mass.

Impact artifacts were observed on some kinematic variables and trials on each subject. A custom Mat Lab (The Mathworks, Natick, RI) program was used to identify artifacts visually on position-time graphs. The frame at the beginning and end of the artifact was identified on the graph and a linear interpolation was used to connect the beginning and ending of the artifact. There were no more than two artifacts in each trial, thus this procedure was performed no more than two times in each trial. In the majority of cases, the artifact was 1-3 frames long.

Custom DataPac 2K2 programs (Version 3.11, RUN Technologies, Mission Viejo, CA) filtered the kinematic data with a low-pass 4th-order, non-recursive Butterworth filter (cut-off frequency of 15 Hz). This cut-off frequency was calculated using previously established methods.[37] No filtering was performed on the kinetic data. DataPac identified variables during the stance phase, defined as initial contact (forceplate registered vertical ground reaction force greater than 10N) to toe off (forceplate registered vertical ground reaction force less than 10N) in the walking, step-up and over, running, and stop jump trials. During the drop jump trials, those variables were located in the 250ms after initial contact. For the test tasks kinematic data were demeaned using the static calibration trial recorded with the Motion Monitor. Nine subjects were missing one trial. The average of the 7 remaining trials was used for analysis. For all other subjects, the average of the 8 trials was used. Following reduction, data were initially explored for descriptive qualities and checked for validity.

Data Reduction, Analysis, and Interpretation

Reduced data from DataPac were transferred to the Statistical Program for the Social Sciences (Version 13.0, SPSS Inc., Chicago, IL) software for analysis. Histograms of all subject data for each variable in each task were checked for normality and extreme outliers. Identified outliers were checked for validity and if not valid, were re-exported. The majority of data appeared sufficiently normally distributed to meet the ANOVA assumptions, however, some variables did appear skewed, particularly the GRF data. Scatterplots of the Observed vs. Standardized Residuals were assessed. If a data point appeared to be separated from the group (i.e. an outlier), that data point was identified using histograms and box plots and assessed for how much it skewed the distribution of data from normal. If there was potential influence, the analysis was re-run excluding the data point(s) in question. All the changes in p-value were minor and all subjects were retained in the final analysis.

Estimates of adjusted means and 95% confidence intervals (CI) from 3x5 mixed model ANOVAs were used to determine if interactions or main effects for group were present on each kinematic and kinetic variable. For selected interactions, an overall within subjects p-value was assessed, and if it was below 0.05, 95% CI were used to check for differences between groups in each task. If an adjusted mean fell outside the 95% CI of another group, that mean was considered different from the other group. Post-hoc testing used Tukey's Honestly Significant Difference (HSD) were also performed.[38] Selected interactions without significant p-values were then assessed and reported using only 95% CI to determine differences between groups at each task. Only 95% CI were used to establish differences between groups as main effects. Effect sizes were reported to indicate the magnitude of the differences. Additionally, the ratio of upper to lower 95% confidence level (CLR) was presented to indicate precision and stability of the confidence interval.[39] This method was modified from the published description, taking the absolute values of the CI limits, and finding the ratio of the larger to the smaller to maintain consistent ratios.[39] Because of their long-standing use in statistical analyses and interpretation, we also reported traditional F-values and p-values. This was as a supplement to the CI and to aid in interpreting the relatively new use of the CI. Levene's tests for equality of variances were checked for each variable. Because Mauchly's test of sphericity was significant on all the repeated measures ANOVAs, the Greenhouse-Geiser adjustment was used during analysis. A preliminary one-way ANOVA was used to ensure the groups were statistically equivalent in age, height, and mass and statistically different in ankle function as reported in the FADI and FADI-S.

Results

Preliminary Analyses

The mean scores from each group on the FADI and FADI-S are reported in Table 2. The initial 1-Way ANOVA (Table 3) demonstrated the groups were equivalent in age, height, and mass ($p > 0.05$). The MAI and FAI groups reported significantly lower scores than the comparison group on the FADI-S ($p < 0.05$). On the FADI, the MAI group scored significantly lower than the FAI, which scored significantly lower than the comparison group ($p < 0.05$). Thus, it appears the groups were appropriately matched by gender, age, height, mass and limb dominance. The two ankle instability groups also reported less function in the test ankle than the comparison group did.

Kinematic Ankle Variables

There were a number of interactions observed using both p-values and 95% CI, as well as group differences in the ankle kinematic variables. Interactions are depicted in Figures 2-8, and group differences are detailed with observed power and CLR in Tables 4-5. Using p-values of <0.05 and 95% CI, an interaction was observed for the ankle plantar flexion angle at initial contact. The estimated marginal means for the groups on each task were compared, and the MAI group means fell outside the comparison group's 95% CI on each task, with effect sizes ranging from 0.44-1.19 (Figure 2). The MAI means were outside the FAI's 95% CI on the drop jump, run, and step up tasks, with effect sizes ranging from 0.54-0.91. The FAI group demonstrated less plantar flexion at initial contact (more dorsiflexion) than the comparison group in the stop jump and walking tasks, with means beyond the comparison group's 95% CIs and effect sizes of 1.04 and 0.39 respectively.

A group x task interaction was observed in the maximum ankle inversion variable. The MAI group mean was below the 95% CI lower limit for the comparison group in the step up and over task (effect size 0.52), and below the FAI 95% CI lower limit in the stop jump task (effect size 0.61). The FAI group mean was below the 95% CI lower limit for the comparison group in the walk task (effect size 0.75) (Figure 3).

A group x task interaction was observed for ankle frontal plane displacement (Figure 4). Based on the 95% CI criteria, the MAI group means for each task were greater than the comparison group's upper limit (effect sizes 0.86-1.44). Additionally, the MAI group demonstrated greater frontal plane displacement than the FAI group on the step up and over, run, drop jump, and stop jump tasks (effect size 0.70-1.49), while the FAI group had more displacement than the comparison group on the walk (effect size 0.94). For ankle frontal plane (inversion-eversion) displacement, the estimated marginal MAI mean fell outside the 95% CI for both the FAI and comparison groups, with effect sizes of 0.36 and 0.46, respectively.

Additional interactions were observed using only the 95% CI, with p-values >0.05. For maximum ankle plantar flexion angle, the FAI group demonstrated greater plantar flexion than the MAI group on the step up, run, drop jump, and stop jump tasks. The comparison group demonstrated greater maximum plantar flexion than the MAI group on all the tasks except running (Figure 5) with effect sizes of 0.63-0.95. The MAI group demonstrated less maximum dorsiflexion than the FAI group on the walk and step up tasks and than the comparison group on the run and drop jump tasks, and the FAI group exhibited less maximum dorsiflexion than the comparison group only on the stop jump (Figure 6). Effect sizes were 0.32-0.57. In maximum ankle eversion, the MAI group demonstrated larger means than the FAI and comparison groups in the walk, step up and over, run, and drop jump tasks (Figure 7), with effect sizes of 0.44-0.94. The MAI group also demonstrated less sagittal plane displacement than the FAI and comparison groups on each task (Figure 8) with effect sizes of 0.72-1.54.

Because the last interactions above were not significant at the $p<0.05$ level, the main effects for group were also noted using 95% CI. A main effect for group was noted on maximum ankle plantar flexion angle with the MAI estimated marginal mean outside the 95% CI for both the FAI and comparison groups, with effect sizes of 0.31 and 0.32, respectively. The MAI group demonstrated smaller maximum plantar flexion angles (more dorsiflexion) than the FAI and comparison groups. In maximum ankle dorsiflexion, the comparison group estimated marginal mean was outside the CI for the MAI group, with an effect size of 0.25. The MAI group demonstrated smaller maximum ankle dorsiflexion angles than the comparison group (Table 4).

For maximum ankle eversion, we observed the estimated marginal mean for the MAI group was outside the 95% CI for both the FAI and comparison groups. The effect sizes were 0.34 and 0.35. The MAI group demonstrated greater maximum eversion angles than the FAI and comparison groups (Table 4). For ankle sagittal plane (plantar flexion-dorsiflexion) displacement, the estimated marginal MAI mean was outside the 95% CI for both the FAI and comparison groups, with effect sizes of 0.39 and 0.42. No interactions or group differences were observed for inversion at initial contact.

Kinematic Knee Variables

There were no interactions or main effects for group noted in any knee variables using p-values or 95% CI as described above (Table 5).

Kinetic Variables

No interactions were noted in any of the ground reaction forces (GRF) variables in any direction using $p<0.05$. There were interactions using only 95% CI, however. In the time to peak vertical GRF, the MAI group had faster time to peak than the comparison group in the step up and drop jump tasks. The FAI group was faster than the comparison in the drop jump task as well (Figure 9), with effect sizes of 0.07-0.13. The MAI group was slower in time to peak anterior GRF than the comparison group in the drop jump task, and the FAI group in the stop jump. Additionally, the FAI group was slower than the comparison group in the drop jump (Figure 10), with effect sizes of 0.48-0.69.

Because the interactions noted above were not significant at the $p<0.05$ level, the main effects using 95% CI were also noted. The MAI group's estimated marginal mean for time to peak anterior GRF (63.06 ms) was outside the comparison group 95% CI upper limit (Table 6). The effect size was 0.22, with an approximately 11% difference between means. It appears the MAI group had a slower time to peak GRF in the anterior direction than the comparison group. No other variables displayed group differences.

Discussion

Kinematics

Comparing across the five tasks, the MAI group demonstrated more dorsiflexion (less plantar flexion) and more eversion, as well as less sagittal plane and more frontal plane displacement than both the FAI and comparison groups depending on task. In combination, these findings may be interpreted as a coping mechanism designed to avoid lateral ankle sprain. The most common mechanism for lateral ankle sprain is plantar flexion and inversion.[4] By avoiding excessive plantar flexion and keeping the ankle more everted, the MAI group may be able to avoid a position of injury and decrease the number of sprains experienced. Clinically, this seems logical, as this close pack position maximizes joint congruency and is the most stable for the joint. It may be effective to avoid these risky positions, as an increase in plantar flexion angle was found to correlate with increased sprains using a forward dynamics model of the lower extremity.[40] Although this movement pattern seems to try to avoid a "risky position," it is not completely effective, as participants still reported episodes of spraining and giving way at the ankle in similar tasks to those in the study.

At initial contact, the MAI group displayed less plantar flexion (more dorsiflexion) than the comparison group on all the tasks and the FAI group on 3 of the tasks (Figure 2). It appears that no matter what type of task is being performed, whether the performance demand is great or not, the MAI group contacts the ground in a more dorsiflexed position. Because the lateral ligaments exhibit laxity in the MAI group, landing in a more dorsiflexed position may offer protection against feelings of instability. The fact the MAI group was more dorsiflexed than the FAI group (who did not display laxity in the lateral ligaments) in a number of tasks, lends credence to this interpretation. To an extent, the FAI group demonstrated a similar strategy, landing in less plantar flexion (more dorsiflexion) than the comparison group in the stop jump and walk. Since the FAI ligaments are more intact, there may not be a similar impetus to adopt this landing strategy. There does not appear to be a pattern between the demands of the task and whether or not the FAI group displayed decreased plantar flexion.

The increased dorsiflexion pattern we observed is consistent with previous studies using single leg jump landings,[16] walking, and a step-up task.[41] However, neither of these studies distinguished whether the participants had mechanically or functionally unstable ankles, so it is unclear if the type of pathology influenced their results. A limitation of this study is that we do not know if the motion pattern we observed was exhibited before the injury or adopted after the initial sprain to avoid additional injuries.

The MAI group reported similar scores to the FAI group in the FADI-S, with the comparison group scoring significantly higher. Only in the FADI questionnaire did the MAI group report decreased function compared to the FAI group, while the comparison group still scored higher than both other groups. Despite reporting similar functional abilities in sports-related tasks (such as those participants performed during testing), the unstable ankle groups demonstrated different ankle motion patterns from each other. This may be due to the altered arthrokinematics of the MAI group compared to the FAI group. If the mechanical laxity of the lateral ligaments was great enough, the MAI subjects may have been relying on bony stability instead of ligaments to support the ankle joint.[4, 42]

Ankle ligament laxity may also create greater articular incongruency at the ankle. Ankle arthritis is secondary to trauma, and instability at the ankle increases contact stress and can damage articular cartilage.[10] For example, talar displacement of more than 1 mm decreased the weight-bearing surface of the ankle by 42.3%, creating asymmetric loading of the articular surface.[43] Asymmetric loading may help explain why individuals with CAI have more medial talar articular cartilage lesions than individuals without CAI.[9] Only small amounts of articular displacement were necessary to create abnormal shearing forces.[43] By remaining in a more closed-pack position to maximize bony congruency (dorsiflexion and eversion), MAI subjects may have been trying to increase the stability of the ankle joint and avoid destabilizing forces.

Two different reasons may account for the ankle maximum inversion and frontal plane displacement interactions (Figures 3 and 4). Individuals who suffer an ankle sprain most often injure the anterior talofibular ligament, with the calcaneofibular ligament being the second-most injured.[4, 42] The role of the calcaneofibular ligament is to limit inversion and help control frontal plane motion at the ankle.[4, 42] It is very likely the calcaneofibular ligament was excessively stretched or torn in the MAI group because they demonstrated greater joint laxity to the talar tilt test, designed to detect deficiency in that ligament.[29] Thus, because of their mechanical laxity, this group may demonstrate greater motion in this plane. We observed earlier that the MAI group was oriented more towards eversion and had a greater maximum eversion angles (Figure 7). Although excessive frontal plane motion may be detrimental in terms of joint stability, if the MAI group was oriented toward more eversion, it may represent an adaptive movement pattern designed to avoid lateral ankle sprain. With greater maximum eversion, it seems logical the group would also undergo more frontal plane (inversion-eversion) displacement during foot contact. Thus, this finding may be attributed to joint instability in that plane following injury or to a movement pattern designed to avoid injury. There were no differences between the FAI and comparison groups, which makes the mechanical laxity seem the factor involved with the group differences.

We observed differences in the maximum inversion angles at the ankle as well (Figure 3), although the differences depended on the task and group and were not consistent. The MAI group demonstrated larger maximum inversion angles than the comparison group in the step up and over, and the FAI group in the stop jump. Both tasks required landing from a height and the increased angle may predispose the MAI group to injury if they cannot avoid a position of injury. We also observed greater displacement in the frontal plane, so these subjects may have greater motion available in that plane. The FAI group also demonstrated greater maximum inversion angle than the comparison group in the walk task. Again, if the FAI group is more inverted during stance, they may be closer to a position of injury.

Interestingly, there appear to be few differences in ankle and knee movement patterns between the FAI and comparison groups, despite differences in reported function. Without mechanical laxity, the FAI group may lack the impetus to adopt an altered movement pattern at the ankle, despite repeated sprains. The differences observed between the MAI and comparison groups, and the lack of differences between the FAI and comparison groups, may elucidate some of the conflicting results in previous CAI literature. Most previous studies have not separated CAI subjects by mechanical or functional instability. A number of studies reported no differences when comparing CAI to controls in multiple variables, and our results may account for that lack of difference.[21, 22, 24, 44-48] Based on our results, it appears to be important to differentiate individuals with MAI and FAI. By separating the two pathologies, clearer differences between individuals with ankle instability and controls may become evident in the literature. The different movement patterns identified here indicated that fundamental differences exist between the two groups, and collapsing them may blur the distinction and make the results confusing and inaccurate. Additionally, the differences in movement pattern may necessitate different rehabilitation protocols. Addressing sagittal plane motion changes may be important tin restoring normal ankle kinematics in MAI individuals.

There were also no differences in knee pattern movements between any of the groups (Table 5). This result is not consistent with a previous study which reported increased knee flexion in the CAI group during jump landing.[16] The previous study utilized a higher jump landing height, which may account for the inconsistency as it necessitated greater ground reaction force absorption. Our results indicate that differences between groups due to instability are centered at the ankle, and do not manifest further up the kinetic chain at the knee. This may occur because the knee does not have any instability and has no need to adapt to differences observed at the ankle. Alternatively, we may not have observed differences at the knee because the hip joint was altered. A previous study reported individuals with CAI used a hip strategy to recover balance following perturbation.[49] The subjects with hypermobile ankles displayed earlier hip muscle recruitment,[49] which is consistent with another study that reported a change in the motor program at the hip following severe ankle injury.[17] Changes may occur proximally at the hip, though we did not test for them in this project. Use of a hip strategy, or changes in proximal joint motor control, may be why we did not observe differences in the knee joint between groups.

Several of the interactions we noted using only 95% CI need to be interpreted with caution. The effect sizes and power are low, and using only 95% CI may have inflated group differences in tasks. Maximum plantar flexion, dorsiflexion, and eversion, had these interactions, which were reflected in group differences across tasks. While these findings support our other interactions and main effects, they should be included with caution. The majority of CLR for the kinematic variables are precise and less than 2.0. However, some variables had much higher CLR. This lack of precision and large differences in CLR between groups calls the results between groups into question. Additionally, three of the knee variables had CLR greater than 2. This lack of precision may have influenced the lack of differences observed between groups.

Kinetics

The kinetic variables were close to equivalent between groups. We observed interactions between groups in the time to peak vertical and anterior GRF, but only by using 95% CI. The MAI group reached peak vertical GRF faster than the comparison group in the step up and drop jump tasks. These two tasks require landing from a height, and may be good indicators of deficits in shock attenuation in MAI groups during landing. Even though the differences between group means were small (Figure 9), the clinical relevance of the difference may impact joint health over years of use. Loading the joint at a faster rate, with decreased ankle joint displacement to absorb the force, may lead to higher incidence of articular cartilage degeneration and osteoarthritis. The time to peak vertical GRF was faster in the unstable ankle groups by 13-16 ms. This was a small difference (8-10%), but, over the long term, the faster loading may contribute to ankle joint degeneration. A previous study, using a similar drop jump task, found no significant differences between the groups in peak vertical GRF, or time to peak vertical force. The authors reported the FAI group experienced peak vertical GRF 10-13ms earlier in than the controls, which matches our findings.[15] Another study, however, reported the unstable ankle group demonstrated faster time to first peak vertical GRF in comparison to controls when performing a v-cut.[19] The nature of the task may explain the difference in results.

The MAI group demonstrated slower time to peak anterior GRF than the FAI and comparison groups on the stop jump and drop jump tasks, respectively (Figure 10). These were the two most challenging tasks, requiring force attenuation during landing and stopping of anterior motion. This may be due to the damage in the anterior talofibular ligament, the most commonly injured ligament in lateral ankle sprains.[4] In a closed kinetic chain with the foot planted (such as in the tasks used in this study), the role of the anterior talofibular ligament is to limit anterior translation of the tibia on the fixed foot.[50] Because of its low load to failure, it is often stretched or completely ruptured following ankle sprain,[50] as was likely the case in our MAI group. Because this group demonstrated laxity in the ligament, this may be a compensatory pattern designed to limit load on the ligament and avoid stressing it during landing. Alternatively, because the ligament was stretched or ruptured, increased anterior translation of the tibia on the fixed foot might have increased the time to peak force.

Our results disagree with previous findings that reported faster time to peak anterior GRF in the unstable ankle group.[15] The contradiction may be due to differences in sample: the previous study did not separate individuals with ankle instability into mechanical and functional groups. Another study reported a CAI group displayed significantly delayed time to peak force under the central-lateral forefoot and toes.[51] The authors attributed the delay to hesitation in transferring weight from heel contact to toe-off, possibly to avoid unstable situations.[51] If the MAI group had a stretched or damaged anterior talofibular ligament, the tibia may have moved more anteriorly during stance or the MAI group may have been avoiding stressing the ligament. In either case, it appears the ligament was deficient in its ability to stop anterior motion of the tibia on the fixed foot. This may have implications for ankle joint stability if the talus is not stable in the mortise and microtrauma can occur to the articular cartilage during episodes of instability. Increased episodes of instability have been associated with ankle joint degeneration.[9]

We observed differences in ankle sagittal plane displacement between the MAI and the other two groups. Given less angular displacement over which to apply the normalized vertical GRF, and with no changes in knee motion, one might expect increases in the peak vertical GRF. The comparison estimated marginal mean for peak normalized vertical GRF (-2.36 body mass) was close to the upper limit of the FAI 95% CI, but the effect size was very small at 0.21 (Table 6). This difference was only 0.12-0.14 times body mass in the unstable ankle groups (approximately 5%), but over months and years, this increase in vertical GRF experience may contribute to the long-term joint degeneration. Perhaps changes in kinematics at the hip were able to compensate for the decreased ankle sagittal plane displacement at the ankle in the MAI group, thus making GRF equivalent, despite less time over which to apply forces. The MAI may have another method to equalize ground reaction forces between the groups. Alternatively, maximum ground reaction forces in the anterior, posterior, medial, and lateral directions were very small in magnitude, and the lack of differences between groups may be attributable to the small values and ranges. With small ranges in the maximum GRF variables, it follows that there would not be differences in the time to those maximum or peak GRF either.

A study comparing FAI to controls in a v-cut found the FAI group had significantly increased first peak vertical GRF on the involved leg compared to the uninvolved leg.[19] Vertical GRF was 0.79 body weight greater on the affected versus unaffected leg in the unstable group.[19] Though not statistically significant, the authors argued it was physiologically relevant, as an 80 kg athlete with a 0.79 body weight difference between sides experiences an increased load of 63.2 kg or 620 N of force for every cut performed.[19] Our results were not of similar magnitude, however, the type of task performed was different.

In the peak normalized medial GRF, the FAI group's estimated marginal mean (-0.16) was the smallest medial force, and was close to the upper limit of the MAI group's 95% CI. The effect size between the FAI and MAI groups was very small at 0.21. The difference between the FAI and other groups was approximately 5-16%. In the peak normalized lateral GRF, the FAI group's estimated marginal mean (0.18) was close to the 95% CI upper limit in the comparison group. The effect size was 0.36, with a 17-27% difference between the comparison group and the unstable ankle groups' means. A previous study reported an FAI group demonstrated more lateral GRF of 5-15% body mass compared to the control group, who exhibited more medial GRF.[15] These results are consistent with our findings, in that the unstable ankle groups had larger lateral GRF and the difference was of similar magnitude. While both the unstable ankle groups in our study had faster time to peak medial and lateral GRF than the comparison group, the differences were minimal and less than 10% between groups.

It is likely we did not observe differences in GRF variables because of the small magnitude and effect sizes on a number of variables simply indicated no differences existed. Additionally, the within and between subjects variability was quite high in the GRF variables. Finally, the body may develop a number of ways to distribute forces up the kinetic chain, thus compensating for kinematic differences we observed at the ankle. The CLR values for kinetic variables were fairly precise. Only peak normalized lateral GRF had a CLR greater than 2.0.

Additional Analyses

Several additional analyses were performed to ensure consistency between groups in different measures. A one-way ANOVA was used to test for differences in active range of motion measures recorded during subject screening. For the range of motion measures, each group was compared on ankle plantar flexion, dorsiflexion, inversion, and eversion on both ankles (Table 7) ($F_{(2,60)}$=0.35 to 3.24, with $p \geq 0.05$ on all measures), For left ankle inversion and eversion, the p-value approached significance (p=0.47 and p=0.055). Using 95% CI, the MAI and FAI estimated marginal mean for left ankle inversion fell beyond the comparison group's upper limit. The MAI group's estimated marginal mean for left ankle eversion also fell beyond the comparison and FAI group's 95% CI upper limit. The MAI group's right ankle estimated marginal mean for eversion also fell beyond the 95% CI upper limit for the FAI and comparison groups. Thus, it appears the unstable ankle groups had greater left ankle inversion range of motion versus the comparison group, and the MAI group had increased right and left ankle eversion compared to the FAI and comparison groups. We would expect to see increased range of motion if the subjects were mechanically lax, because they were lacking ligamentous restraints. The FAI group was not clinically positive in laxity in inversion, but they likely had some stretching of the ligament, which appeared as increased range of motion. These differences in active range of motion may have influenced our results, but we were looking for effects of the injury.

A repeated measures ANOVA was used to determine whether sacral velocity was consistent between groups and met the criteria established in the methods. Because Mauchly's test of sphericity was significant ($p < 0.05$), the Greenhouse-Geiser adjustment was used. No significant group x task interactions were observed ($F_{(5.12, 153.59)} = 0.965$; $p > 0.05$), nor was any main effect for group ($F_{(2, 60)} = 0.795$; $p > 0.05$). Levene's test for equality of variance was checked prior to proceeding with all analyses.

Limitations

There are a number of limitations in this study, primarily that self-reported history and clinical orthopedic exams were the measures used to place subjects into groups. Lack of objective measures to quantify instability made subject selection difficult. The FADI and FADI-S have been shown to be reliable, but have not been used in a sufficiently large enough population to establish strong validity or "cut-off" scores for instability.[30] Identifying individuals with FAI is difficult, since the population presents with a wide range of symptoms and degree of instability. We made an effort to match subjects between groups as best as possible, but there are inherent differences in length of time with ankle instability, degree of mechanical laxity, and mechanisms that evoke feelings of instability. The FAI group we tested likely encompassed a broad spectrum of recreationally active individuals with varying degrees of instability. The heterogeneous nature of this group may have clouded some results. Additionally, our comparison group of "copers" did not demonstrate mechanical laxity. An ideal comparison group would have consisted of individuals with mechanical laxity who do not suffer episodes of instability, and thus are effectively coping with mechanical laxity of the lateral ligaments. These individuals are difficult to find and there is no history of their use in the CAI literature.

There is also some error associated with three-dimensional motion tracking and data processing, which may have influenced results. The low power we observed (<0.70) on a number of measures increased the chances of making a type I error. Specifically, three of the ankle kinematic variables, all of the knee kinematic variables, and all of the ground reaction fore measures had between groups comparisons power of less than 0.50. Additionally, the laboratory environment may not reflect true differences in motion patterns between groups, specifically because there are likely lab-based differences in anticipation, attention, and the constraints of testing parameters.

The design of the study cannot determine whether or not the differences we observed in kinematics and kinetics developed after the injury, or were present prior to developing CAI, and may have contributed to it. The pattern of changes we observed in the MAI group may be explained as a coping mechanism developed to minimize further injury, but without a prospective study, it is impossible to determine that.

Conclusions

Our most important finding was that the MAI group demonstrated altered movement patterns at the ankle joint compared to the FAI and comparison groups on a number of variables across and within tasks. The MAI group appeared to display a pattern of increased dorsiflexion and eversion, increased frontal plane displacement, and decreased sagittal plane displacement over a series of tasks. The MAI group's time to peak anterior GRF was slower than the comparison group, but the time to peak vertical GRF was faster. We found no differences between groups at the knee or in the peak ground reaction force variables. This altered movement pattern may act to place the MAI subjects' ankle in a close pack and more stable position, thus helping to avoid lateral ankle sprains and stressing the anterior talofibular ligament.

There may be long-term consequences to this movement pattern, as it could increase joint degeneration over time. Rehabilitation programs should consider these findings and work to address them. Specifically, emphasis should be placed on frontal plane motion and encouraging movement within a “safe” range of motion at landing to avoid ankle sprains. MAI subjects may also be encouraged to undergo more knee flexion during landing in an attempt to offset the lack of sagittal plane motion at the ankle.

Additionally, based on these results, we recommend that MAI and FAI subjects be differentiated in future research, and not combined into one CAI group. Mechanical laxity appears to be an important mitigating factor in movement patterns, and may impact other variables of interest in CAI research, including postural stability, reaction time, electromyography, and others. If CAI subjects are not separated based on lateral ligament laxity, confounding mechanical laxity may cloud the results. Thus, stricter criteria for defining chronic ankle instability, as well as its subgroups, are necessary. Future research should work to increase sample size and power, and determine if there are long term deficits associated with chronic ankle instability. Future research should also explore up the kinetic chain to see if differences occur proximally.

Table 1. Subject Demographics by Group and Gender

Group	Gender	Age (years)			Height (cm)			Mass (kg)		
		Mean	(SD)	Range (Minimum and Maximum)	Mean	(SD)	Range (Minimum and Maximum)	Mean	(SD)	Range (Minimum and Maximum)
MAI	Male	23.00	5.12	18-33	179.81	10.02	165.00-193.00	76.73	13.80	55.17-101.36
	Female	21.70	3.30	19-28	166.33	5.47	155.00-173.00	65.73	9.75	53.28-86-74
FAI	Male	22.45	4.27	18-31	178.08	6.45	168.00-188.00	77.59	12.00	60.23-93.00
	Female	21.80	3.49	19-29	165.10	7.72	152.00-177.00	67.91	13.01	46.69-89.72
Comparison	Male	21.27	4.17	18-33	182.10	4.16	177.80-191.00	75.38	7.65	63.58-86.90
	Female	22.20	5.69	18-35	167.70	5.48	160.00-178.00	63.92	10.55	48.13-82.21

MAI: Mechanical ankle instability group, FAI: functional ankle instability group, SD: Standard deviation

Table 2. Subject Ankle Stability Questionnaire Scores by Group and Gender

Group	Gender	FADI			FADI-S		
		Mean	(SD)	Range (Minimum and Maximum)	Mean	(SD)	Range (Minimum and Maximum)
MAI	Male	90.50	8.36	71.20-99.00	78.10	13.12	56.30-96.40
	Female	87.62	7.98	74.00-97.10	75.00	11.67	46.90-87.50
FAI	Male	93.75	4.76	84.60-99.00	77.52	9.10	65.60-93.80
	Female	94.68	3.92	88.50-100.00	85.95	10.02	75.00-100.00
Comparison	Male	96.67	5.53	80.80-100.00	89.45	12.42	62.50-100.00
	Female	97.45	1.90	93.80-100.00	92.65	5.75	84.00-100.00

MAI: Mechanical ankle instability group; FAI: functional ankle instability group; SD: Standard deviation; FADI: Foot and Ankle Disability Index; FADI-S: Foot and Ankle Disability Index Sport

Table 3. One-Way ANOVA with Tukey Post-Hoc Testing for Subject Matching Between Groups

Measure	**F-value$_{(Degrees of Freedom)}$**	**P-value**	**Post-Hoc Testing (α = 0.05)**
Age (yrs)	$F_{(2, 60)} = 0.127$	0.881	None
Height (cm)	$F_{(2,60)} = 0.632$	0.535	None
Mass (kg)	$F_{(2,60)} = 0.323$	0.726	None
FADI score	$F_{(2,60)} = 9.99$	<0.001	MAI < FAI < Comparison
FADI-S score	$F_{(2,60)} = 9.582$	<0.001	MAI = FAI < Comparison

MAI: Mechanical ankle instability group; FAI: functional ankle instability group; SD: Standard deviation; FADI: Foot and Ankle Disability Index; FADI-S: Foot and Ankle Disability Index Sport

Table 4. Repeated Measures ANOVA Group Main Effects for Kinematic Variables in the Ankle

Variable (in degrees)	Group	Estimated Marginal Mean	Standard Error	F-Value df(2,60)	P-Value	Power Level	95% Confidence Interval		Tukey Post-Hoc*	CLR
							Lower Limit	Upper Limit		
Ankle plantarflexion angle at IC	MAI	17.26	1.79	3.48	0.04	0.63	13.68	20.85	MAI-Comp	1.52
	FAI	21.38					17.79	24.96		1.40
	Comparison	23.89					20.31	27.48		1.35
Ankle inversion angle at IC	MAI	-5.10	1.05	0.11	0.90	0.07	-7.20	-3.00	None	2.40
	FAI	-5.79					-7.90	-3.69		2.14
	Comparison	-5.36					-7.46	-3.25		2.30
Maximum ankle plantarflexion	MAI	25.00	1.59	3.32	0.04	0.61	21.81	28.18	None	1.29
	FAI	30.10					26.91	33.28		1.24
	Comparison	29.94					26.75	33.18		1.24
Maximum ankle dorsiflexion	MAI	-14.29	1.20	1.69	0.19	0.34	-16.70	-11.88	None	1.41
	FAI	-16.56					-18.97	-14.15		1.34
	Comparison	-17.28					-19.69	-14.88		1.32
Maximum ankle inversion	MAI	-8.44	0.97	0.46	0.63	0.12	-10.39	-6.50	None	1.60
	FAI	-8.18					-10.13	-6.24		1.62
	Comparison	-7.19					-9.14	-5.25		1.74
Maximum ankle eversion	MAI	4.86	0.86	3.92	0.03	0.69	3.15	6.57	MAI-FAI	2.09
	FAI	1.86					0.15	3.58		23.87
	Comparison	1.98					0.27	3.70		13.70
Ankle sagittal plane displacement	MAI	39.28	1.91	5.40	0.01	0.83	35.48	43.09	MAI-FAI	1.21
	FAI	46.65					42.84	50.46	MAI-Comp	1.18
	Comparison	47.22					43.41	51.03		1.18
Ankle frontal plane displacement	MAI	-13.30	0.90	5.86	0.001	0.86	-15.10	-11.57	MAI-FAI	1.30
	FAI	-10.05					-11.85	-8.25	MAI-Comp	1.44
	Comparison	-9.17					-10.97	-7.38		1.49

MAI mechanical ankle instability; FAI functional ankle instability; IC initial contact; *significant at the $p < 0.05$ level. CLR: ratio of maximum absolute upper to lower 95% confidence limits. Plantarflexion +; Dorsiflexion -; Inversion -; Eversion +;

Table 5. Repeated Measures ANOVA Group Main Effects for Kinematic Variables at the Knee

Variable (in degrees)	Group	Estimated Marginal Means	Standard Error	F-Value	P-Value	Power Level	95% Confidence Interval		Tukey Post-Hoc*	CLR
							Lower Limit	Upper Limit		
Knee flexion angle at IC	MAI	13.70	1.17	0.80	0.92	0.06	11.36	16.03	None	1.41
	FAI	14.34					12.00	16.67		1.39
	Comparison	14.15					11.82	16.49		1.40
Knee valgus angle at IC	MAI	1.59	1.01	0.76	0.47	0.17	-0.43	3.61	None	8.40
	FAI	2.57					0.55	4.59		8.35
	Comparison	0.70					-1.33	2.72		2.05
Maximum knee flexion	MAI	43.00	1.53	0.12	0.89	0.07	39.95	46.05	None	1.15
	FAI	43.88					40.83	46.93		1.15
	Comparison	43.94					40.89	46.99		1.15
Maximum knee extension	MAI	9.17	1.07	0.49	0.61	0.13	7.02	11.31	None	1.61
	FAI	10.47					8.32	12.62		1.52
	Comparison	10.48					8.33	12.63		1.52
Maximum knee valgus	MAI	3.34	1.21	0.87	0.42	0.19	0.93	5.76	None	6.19
	FAI	5.00					2.59	7.42		2.86
	Comparison	2.85					0.43	5.26		12.23
Maximum knee varus	MAI	-8.62	1.69	0.67	0.52	0.16	-12.01	-5.24	None	2.29
	FAI	-6.12					-9.51	-2.74		3.47
	Comparison	-8.41					-11.80	-5.03		2.35
Knee sagittal plane displacement	MAI	33.84	1.12	0.04	0.96	0.06	31.59	36.08	None	1.14
	FAI	33.41					31.17	35.66		1.14
	Comparison	33.46					31.22	35.71		1.14
Knee frontal plane displacement	MAI	11.97	0.81	0.31	0.73	0.10	10.34	13.59	None	1.31
	FAI	11.12					9.50	12.75		1.34
	Comparison	11.26					9.64	12.88		1.34

MAI mechanical ankle instability; FAI functional ankle instability; IC initial contact; *significant at the $p < 0.05$ level. CLR: ratio of maximum absolute upper to lower 95% confidence limits. Knee flexion +: extension -; valgus +; varus -.

Table 6. Repeated Measures ANOVA Group Main Effects for Kinetic Variables

Variable	Group	Estimated Marginal Mean	Standard Error	F-Value	P-Value	Power Level	95% Confidence Interval		Tukey Post-Hoc*	CLR
							Lower Limit	Upper Limit		
Peak normalized vertical GRF (xBM)	MAI	-2.36	0.07	1.20	0.31	0.25	-2.49	-2.23	None	1.12
	FAI	-2.38					-2.51	-2.25		1.12
	Comparison	-2.24					-2.38	-2.11		1.13
Peak normalized anterior GRF (xBM)	MAI	0.41	0.02	0.71	0.50	0.16	0.37	0.45	None	1.22
	FAI	0.44					0.40	0.47		1.18
	Comparison	0.41					0.37	0.44		1.19
Peak normalized posterior GRF (xBM)	MAI	-0.23	0.01	0.13	0.88	0.07	-0.26	-0.20	None	1.30
	FAI	-0.23					-0.26	-0.20		1.30
	Comparison	-0.22					-0.25	-0.19		1.32
Peak normalized medial GRF (xBM)	MAI	-0.19	0.02	0.43	0.65	0.12	-0.24	-0.15	None	1.60
	FAI	-0.16					-0.21	-0.12		1.75
	Comparison	-0.17					-0.22	-0.13		1.69
Peak normalized lateral GRF (xBM)	MAI	0.15	0.02	1.09	0.34	0.23	0.11	0.20	None	1.82
	FAI	0.18					0.13	0.22		1.69
	Comparison	0.13					0.08	0.18		2.25
Time to peak normalized VGRF (ms)	MAI	135.55	9.16	0.87	0.42	0.19	117.23	153.87	None	1.31
	FAI	132.40					114.18	150.82		1.32
	Comparison	148.60					130.29	166.92		1.28
Time to peak normalized AGRF (ms)	MAI	63.06	3.18	1.12	0.32	0.25	56.70	69.43	None	1.22
	FAI	59.65					53.29	66.02		1.24
	Comparison	56.16					49.79	62.52		1.26
Time to peak normalized PGRF (ms)	MAI	266.61	13.77	0.90	0.41	0.20	239.07	294.15	None	1.23
	FAI	288.68					261.14	316.22		1.21
	Comparison	289.81					262.26	317.35		1.21
Time to peak normalized MGRF (ms)	MAI	66.60	7.12	0.11	0.89	0.07	52.37	80.84	None	1.54
	FAI	63.43					49.19	77.66		1.58
	Comparison	68.09					53.85	82.33		1.53
Time to peak normalized LGRF (ms)	MAI	115.98	12.68	0.29	0.75	0.09	90.62	141.34	None	1.56
	FAI	123.93					98.58	149.29		1.51
	Comparison	129.54					104.18	154.90		1.49

MAI mechanical ankle instability; FAI functional ankle instability; GRF ground reaction force; V vertical; A Anterior; P posterior; M medial; L lateral.
*Significant at the $p < 0.05$ level. CLR ratio of maximum absolute upper to lower 95% confidence limits. Vertical -; anterior +; posterior -; medial -; lateral +. BM is body mass. Ms is milliseconds.

Table 7. Descriptives and One-Way ANOVA for Range of Motion Measures Between Groups

Average Variable	Group	Group Mean	Standard Deviation	F-Value	P-Value	95% Confidence Interval Upper Limit	95% Confidence Interval Lower Limit	*Tukey Post-Hoc	CLR
R ankle dorsiflexion	MAI	5.30	3.84	1.01	0.37	3.50	7.10	None	2.03
	FAI	6.00	2.96			4.62	7.38		1.60
	Comparison	6.79	2.94			5.37	8.20		1.53
R ankle plantar flexion	MAI	62.60	6.81	0.35	0.71	59.41	65.79	None	1.11
	FAI	62.75	7.65			59.17	66.33		1.12
	Comparison	60.26	14.89			53.09	67.44		1.27
R ankle inversion	MAI	15.00	6.43	0.74	0.48	11.99	18.01	None	1.50
	FAI	13.85	5.81			11.12	16.57		1.49
	Comparison	12.79	4.62			10.56	15.02		1.42
R ankle eversion	MAI	6.85	3.00	1.71	0.19	5.45	8.25	None	1.51
	FAI	5.60	2.37			4.49	6.71		1.49
	Comparison	5.42	2.52			4.20	6.64		1.58
L ankle dorsiflexion	MAI	7.25	3.60	0.37	0.30	5.57	8.93	None	1.60
	FAI	7.40	3.56			5.73	9.07		1.58
	Comparison	8.79	2.90			7.39	10.19		1.38
L ankle plantarflexion	MAI	57.75	6.16	1.22	0.69	54.87	60.63	None	1.10
	FAI	59.60	6.72			56.45	62.75		1.11
	Comparison	58.47	7.67			54.78	62.17		1.13
L ankle inversion	MAI	16.30	6.56	3.24	0.05	13.23	19.37	MAI-Comp	1.46
	FAI	14.35	6.60			11.26	17.44	p=0.04	1.55
	Comparison	11.47	4.31			9.40	13.55		1.44
L ankle eversionn	MAI	6.75	2.38	3.05	0.06	5.64	7.86	MAI-Comp	1.39
	FAI	5.25	2.31			4.17	6.33	P=0.08	1.51
	Comparison	5.11	2.25			4.02	6.19		1.54

R right; L left; MAI mechanical ankle instability; FAI functional ankle instability. *Significant at the p<0.05 level. CLR is ratio of maximum absolute upper to lower limit 95% confidence limits.

Figure 1. Subject Set Up

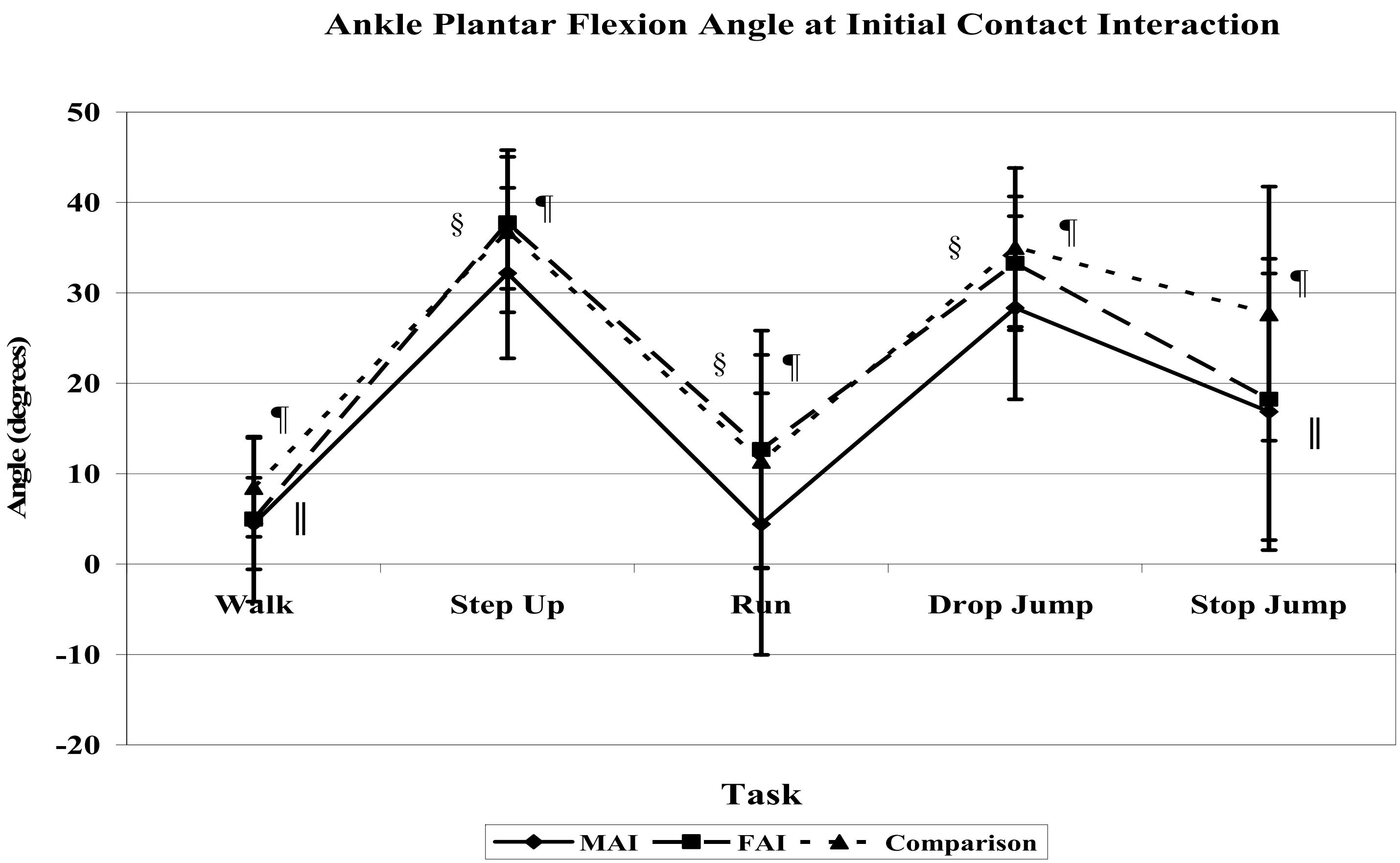

Figure 2. Group x Task Interaction for Ankle Plantar Flexion Angle at Initial Contact
$F_{(5.98,179.35)}=1.96$; $p=0.074$; power=0.71
MAI is mechanical ankle instability; FAI is functional ankle instability. Using p-values: *Significant difference between MAI and FAI ($p<0.05$); †Significant difference between MAI and comparison ($p<0.05$); ‡Significant difference between FAI and comparison ($p<0.05$)
Using 95% Confidence intervals: §Differences between MAI and FAI; ¶Difference between MAI and comparison; ‖Difference between FAI and comparison.

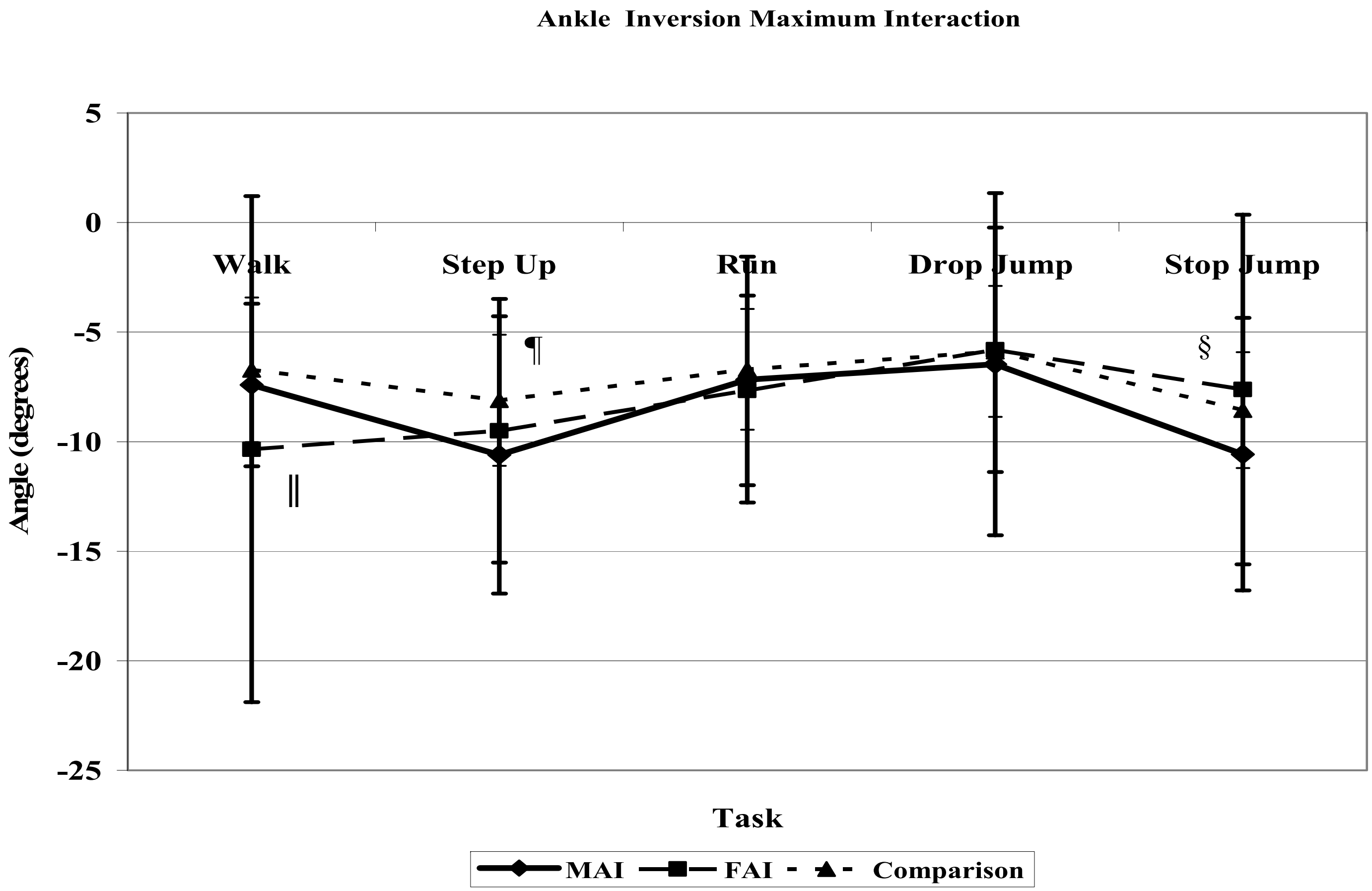

Figure 3. Group x Task Interaction for Ankle Inversion Maximum
$F_{(5.85,175.53)}=1.68$; $p=0.13$; power=0.62
MAI is mechanical ankle instability; FAI is functional ankle instability. Using p-values: *Significant difference between MAI and FAI ($p<0.05$); †Significant difference between MAI and comparison ($p<0.05$); ‡Significant difference between FAI and comparison ($p<0.05$)
Using 95% Confidence intervals: §Differences between MAI and FAI; ¶Difference between MAI and comparison; ‖Difference between FAI and comparison.

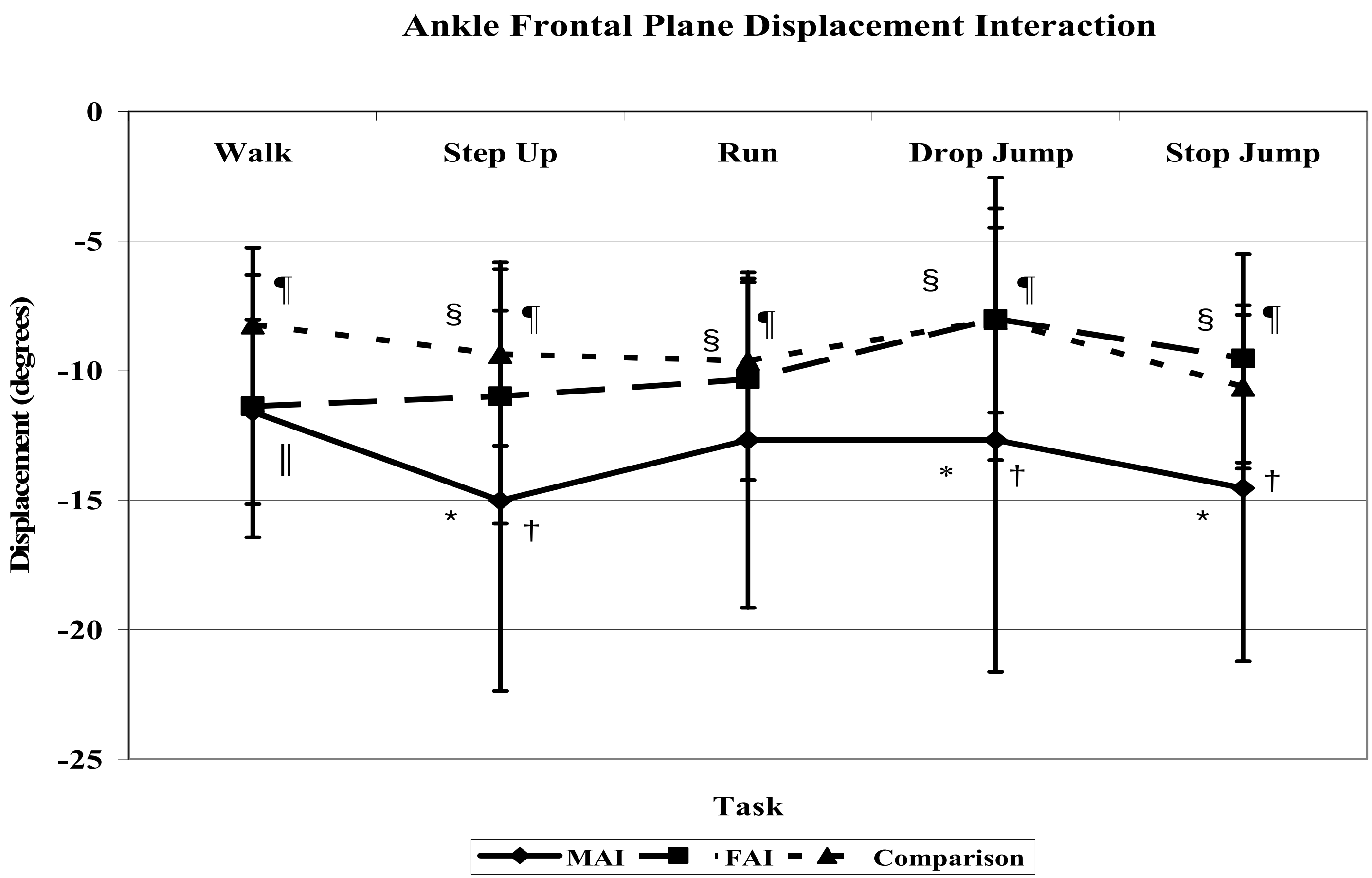

Figure 4. Group x Task Interaction for Ankle Frontal Plane Displacement.
$F_{(5.84,\ 175.33)}=2.25$; $p=0.042$, power=0.77
MAI is mechanical ankle instability; FAI is functional ankle instability. Using p-values: *Significant difference between MAI and FAI ($p<0.05$); †Significant difference between MAI and comparison ($p<0.05$); ‡Significant difference between FAI and comparison ($p<0.05$)
Using 95% Confidence intervals: §Differences between MAI and FAI; ¶Difference between MAI and comparison; ‖Difference between FAI and comparison.

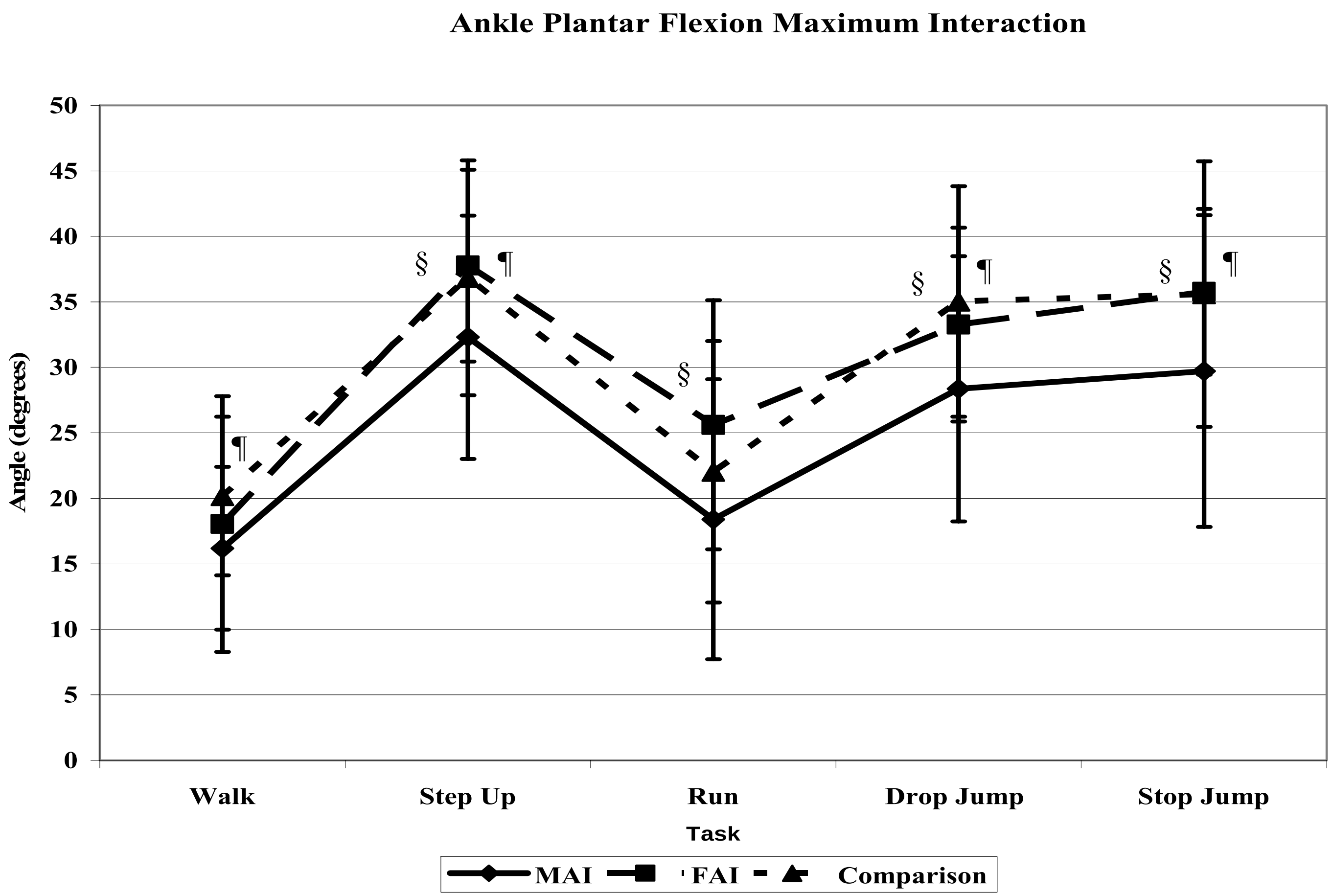

Figure 5. Group x Task Interaction for Ankle Plantar Flexion Maximum
$F_{(6.56,196.88)}=1.11$; $p=0.36$; power=0.46
MAI is mechanical ankle instability; FAI is functional ankle instability. Using p-values: *Significant difference between MAI and FAI ($p<0.05$); †Significant difference between MAI and comparison ($p<0.05$); ‡Significant difference between FAI and comparison ($p<0.05$)
Using 95% Confidence intervals: §Differences between MAI and FAI; ¶Difference between MAI and comparison; ‖Difference between FAI and comparison.

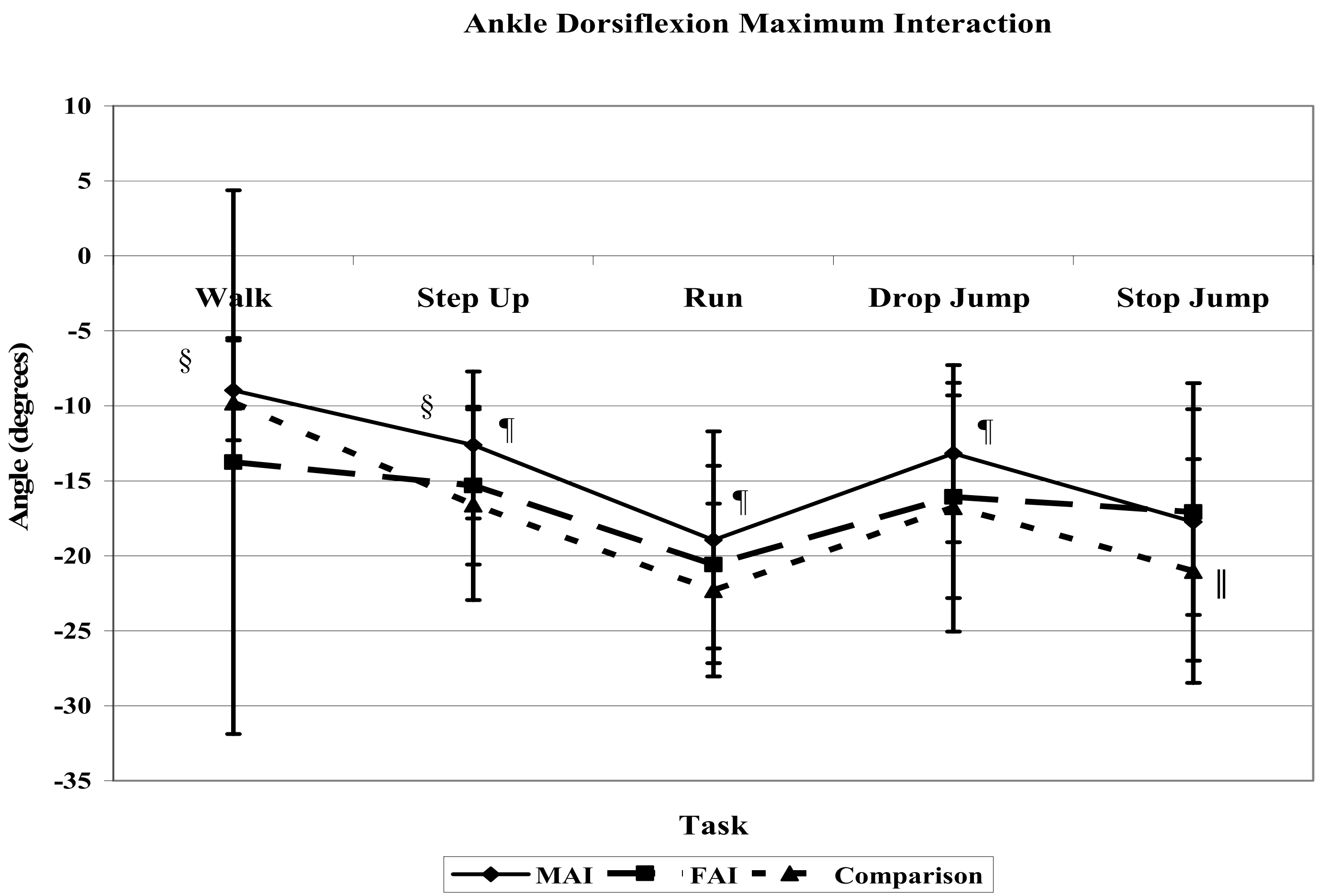

Figure 6. Group x Task Interaction for Ankle Dorsiflexion Maximum
$F_{(4.24,127.23)}=1.27$; $p=0.26$; power=0.40
MAI is mechanical ankle instability; FAI is functional ankle instability. Using p-values: *Significant difference between MAI and FAI ($p<0.05$); †Significant difference between MAI and comparison ($p<0.05$); ‡Significant difference between FAI and comparison ($p<0.05$)
Using 95% Confidence intervals: §Differences between MAI and FAI; ¶Difference between MAI and comparison; ‖Difference between FAI and comparison.

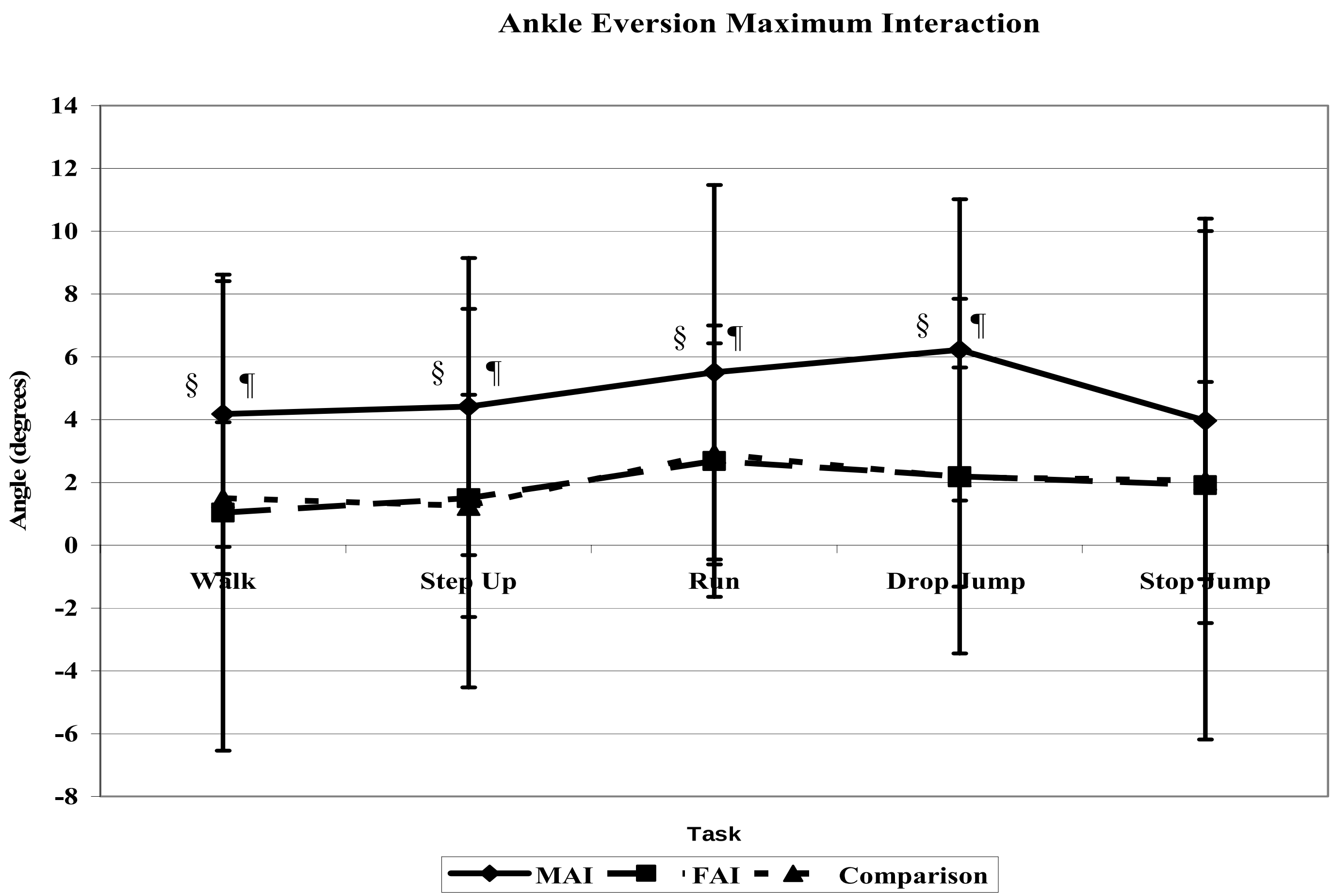

Figure 7. Group x Task Interaction for Ankle Eversion Maximum
$F_{(5.63,19.15)}$=0.29; p=0.94; power=0.13
MAI is mechanical ankle instability; FAI is functional ankle instability. Using p-values: *Significant difference between MAI and FAI (p<0.05); †Significant difference between MAI and comparison (p<0.05); ‡Significant difference between FAI and comparison (p<0.05)
Using 95% Confidence intervals: §Differences between MAI and FAI; ¶Difference between MAI and comparison; ‖Difference between FAI and comparison.

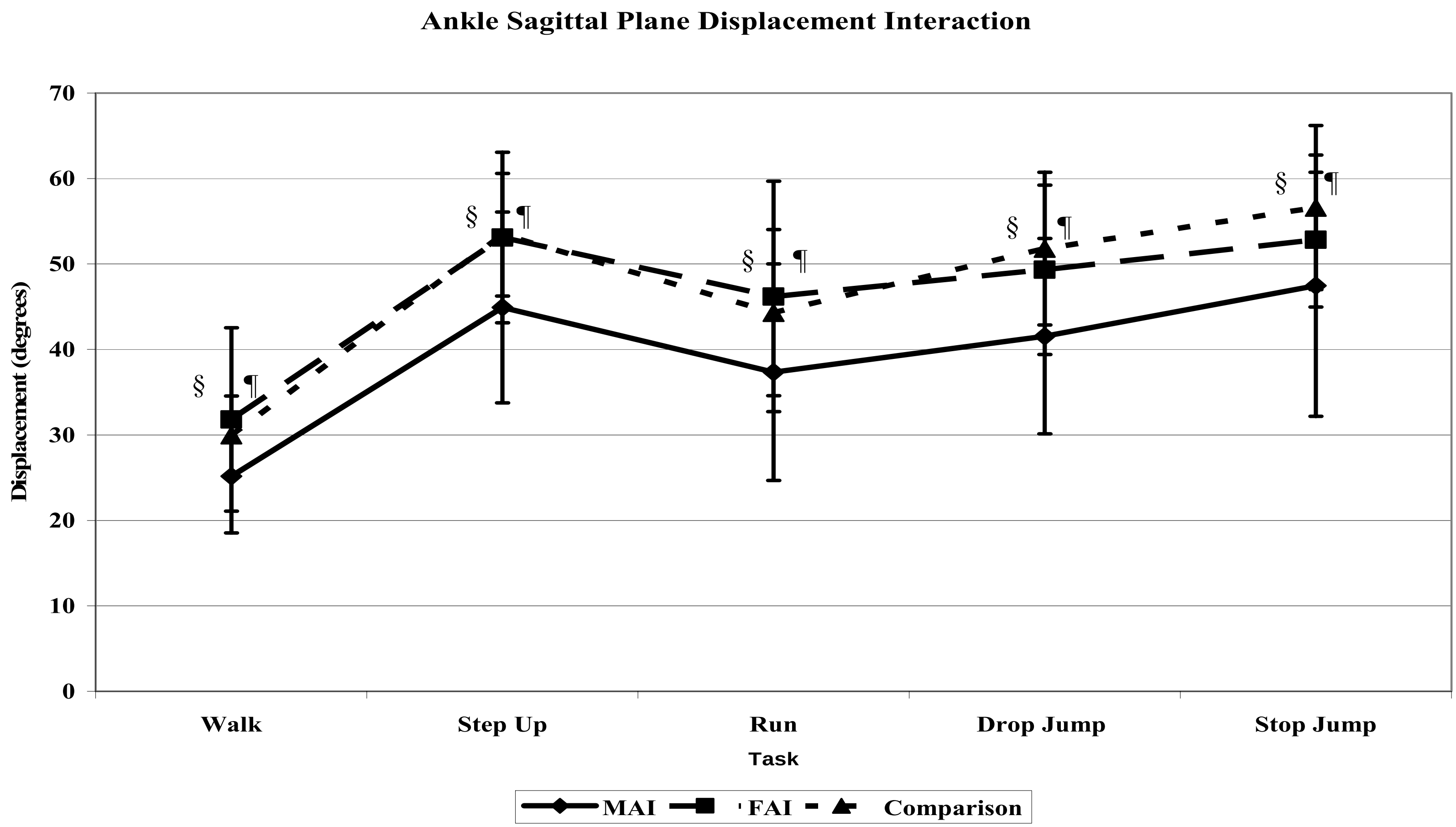

Figure 8. Group x Task Interaction for Ankle Sagittal Plane Displacement
$F_{(6.48,194.41)}=1.19$; $p=0.31$; power=0.48
MAI is mechanical ankle instability; FAI is functional ankle instability. Using p-values: *Significant difference between MAI and FAI ($p<0.05$); †Significant difference between MAI and comparison ($p<0.05$); ‡Significant difference between FAI and comparison ($p<0.05$)
Using 95% Confidence intervals: §Differences between MAI and FAI; ¶Difference between MAI and comparison; ‖Difference between FAI and comparison.

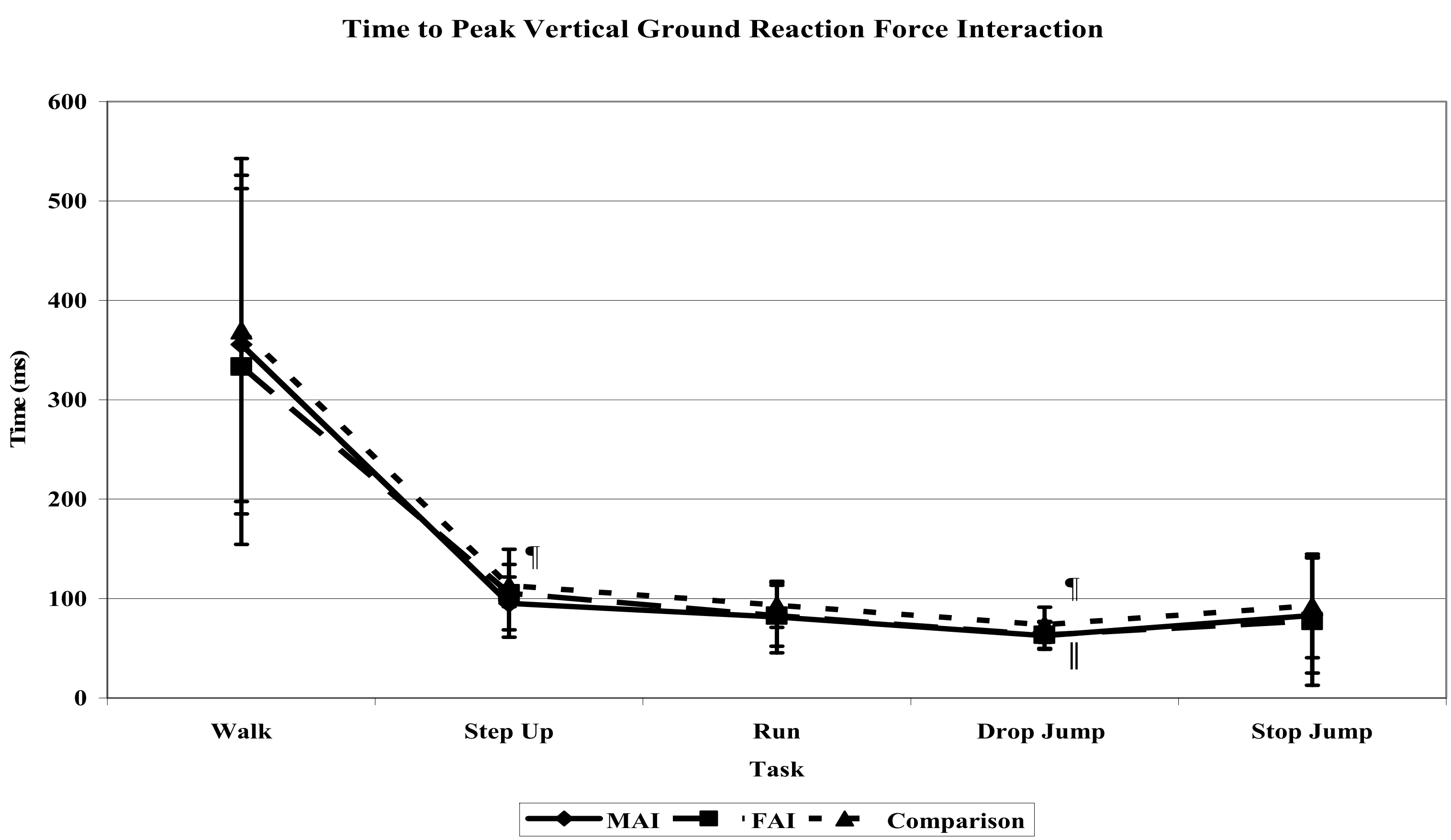

Figure 9. Group x Task Interaction for Time to Peak Vertical Ground Reaction Force
$F_{(2.58,77.31)}=0.15$; $p=0.90$; power=0.08
MAI is mechanical ankle instability; FAI is functional ankle instability. Using p-values: *Significant difference between MAI and FAI ($p<0.05$); †Significant difference between MAI and comparison ($p<0.05$); ‡Significant difference between FAI and comparison ($p<0.05$)
Using 95% Confidence intervals: §Differences between MAI and FAI; ¶Difference between MAI and comparison; ‖Difference between FAI and comparison.

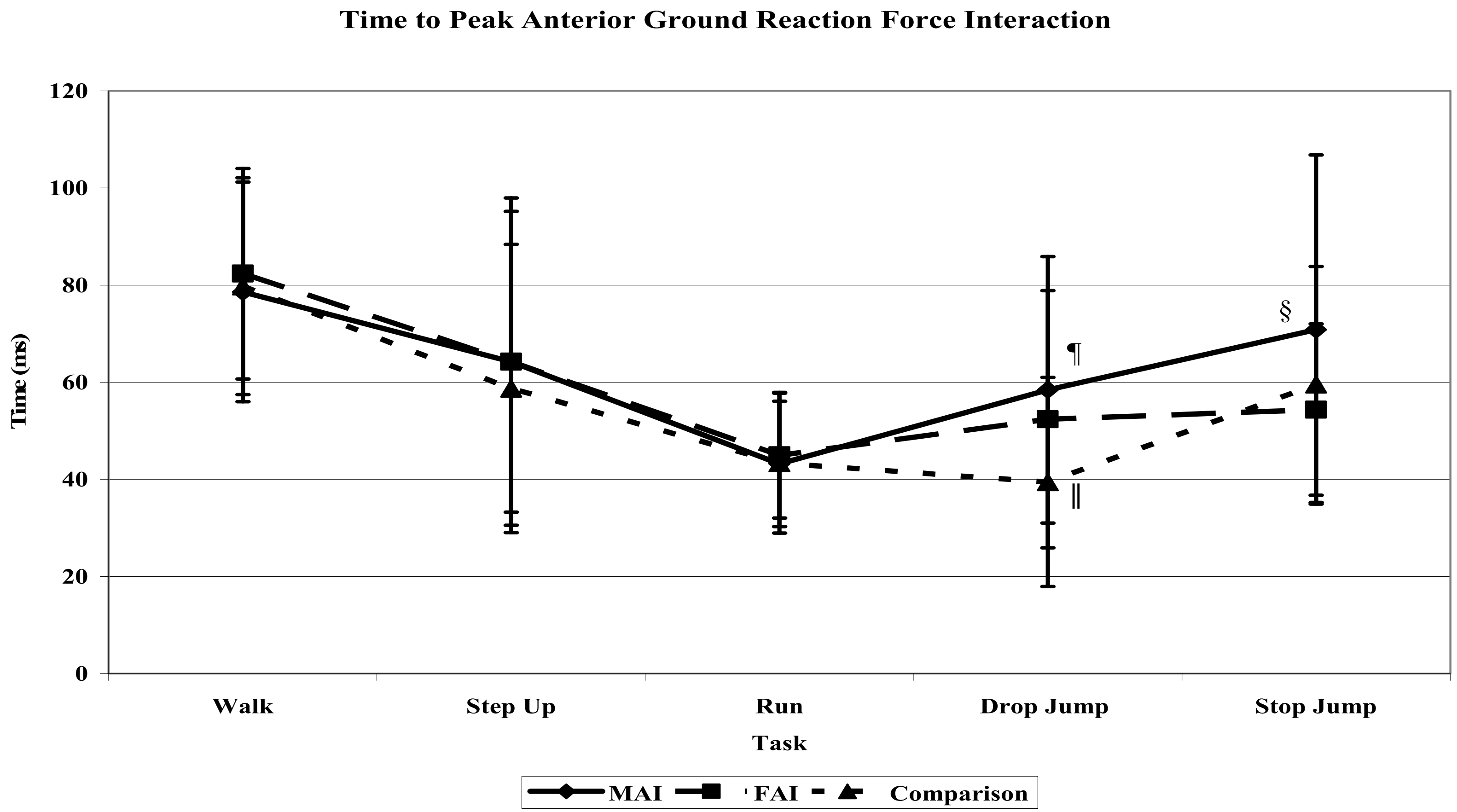

Figure 10. Group x Task Interaction for Time to Peak Anterior Ground Reaction Force
$F_{(6.67,199.94)}=1.28$; $p=0.26$; power=0.53
MAI is mechanical ankle instability; FAI is functional ankle instability. Using p-values: *Significant difference between MAI and FAI ($p<0.05$); †Significant difference between MAI and comparison ($p<0.05$); ‡Significant difference between FAI and comparison ($p<0.05$)
Using 95% Confidence intervals: §Differences between MAI and FAI; ¶Difference between MAI and comparison; ‖Difference between FAI and comparison.

APPENDIX B

Manuscript II

Manuscript II

Variability in Movement of Recreational Athletes with

Chronic Ankle Instability: Using the Coefficient of Variation

Context: Chronic ankle instability commonly develops following ankle sprain. Degree of variability in movement patterns may play a role in perpetuating ankle sprains.

Objective: To determine whether differences exist in movement variability in kinematics and kinetics within and between a group of recreational athletes with mechanical (MAI) or functional ankle instability (FAI) and a comparison group on walking, stepping up and over, running, drop jump, and stop jump tasks.

Design: A quasi-experimental, case-control design.

Setting: Laboratory.

Patients or Other Participants: Sixty-three recreational athletes, 21 in each group (11 males, 10 females) matched for gender, age, height, mass, and limb dominance.

Main Outcome Measures: We measured the coefficient of variation (CV) and standard deviation (SD) of ensemble curves of ankle flexion and inversion, knee flexion and valgus, and ground reaction forces (GRF) during the stance phase of the 5 tasks.

Results: Using estimates of adjusted means, 95% confidence intervals, and effect sizes from repeated measures ANOVAs, the FAI group demonstrated greater CV ankle inversion than the comparison group on 3 tasks and the MAI group on 1 task. The MAI and FAI groups demonstrated greater variability in vertical GRF and SD ankle plantar flexion than the comparison group in selected tasks. The SD ankle inversion also had changes in variability between groups and tasks.

Conclusions: The unstable ankle groups appeared to demonstrate more variability in frontal plane motion and vertical ground reaction force across the 5 tasks. Greater variability in the frontal plane may place these groups at greater risk for inversion sprain by making safe movement patterns more difficult to repeat. Increased variability in vertical ground reaction force could put the unstable groups at risk for long-term ankle joint degeneration

Key Words: chronic ankle instability, kinematics, kinetics, variability

Introduction

Ankle sprains occur very frequently in most sports and physical activities. The National Collegiate Athletic Association's Injury Surveillance System reported lateral ankle sprains were the most common injury in soccer, volleyball, and basketball in all three collegiate divisions.[1] Recreational and high school athletes are also affected with injury rates of 3.85/1000 exposures in recreational basketball[2] and 5.7/100 participants per season in high school sports studies.[3] Of those individuals who experience a lateral ankle sprain, approximately 47-73% will suffer from recurrent sprains.[4, 5] Chronic ankle instability (CAI) is defined as subjective and repeated episodes of giving way and spraining of the ankle and often develops following an initial ankle sprain.[6] CAI may be divided into two categories: mechanical instability and functional instability, which may exist in individuals independently or in some combination.[6] Some individuals with CAI may have mechanical ankle instability (MAI) or physiologic laxity at the ankle joint following severe or repeated ankle sprains. However some individuals with CAI have no mechanical laxity, and instead demonstrate functional ankle instability (FAI).[6] Freeman introduced FAI,[7] and attributed it to deafferentation or tearing of neural tissue within the ligament, causing deficits in proprioception and neuromuscular control.

The pathophysiology behind the mechanism causing CAI is not well understood, so the long-term effects of CAI on activity and joint health are currently unknown. Additionally, the long-term effects of CAI on ankle joint health are not well documented.[8] Most ankle arthritis is secondary to trauma and not due to overuse or wear.[9, 10] Increased articular lesions, degeneration, and defects in the ankle are observed in individuals with a history of instability.[8] No adequate surgical procedures currently exist to correct this articular damage, so prevention is the key to avoiding ankle joint degeneration. Preventing and treating chronic ankle instability is an important step in ensuring long-term joint health, especially in later life.

There is much disagreement in the literature as to whether or not subjects with CAI demonstrate altered joint position sense, postural stability, functional capacity, and movement in comparison to control groups. Some of that disagreement may be due to the lack of separation between MAI and FAI groups. MAI and FAI, have either been combined or ignored in most previous research, little information exists regarding any differences they might cause in CAI.[11] Distinguishing between these two subcategories may clarify some of the contradictions and offer insight into goals for future research and rehabilitation. It is unknown whether or not FAI and MAI exhibit similar kinematics and kinetics during these tasks because they have not been separated in previous literature. Subjects may also use different strategies to compensate for CAI or may not be able to compensate and so have adopted a deleterious or highly variable strategy. Fundamental differences in the nature of the ankle pathology could influence explanations for the continued episodes of giving way. Additionally, the differences in pathology may require different rehabilitation exercises and protocols to best address the deficits.

Few studies to date have used a control group of “copers,” or a comparison group of individuals with a history of previous initial sprain but no complaints of instability. Similar “coper” groups have been used successfully in the anterior cruciate ligament (ACL) injury literature.[12, 13] Using a group with a similar history of initial injury but no repeated episodes of instability may be applicable to ankle studies. Rather than compare CAI subjects to individuals who have never suffered an ankle sprain, a more appropriate comparison may be made between CAI subjects and individuals with a similar ankle injury history, who did not subsequently develop or experience repeated episodes of giving way. These individuals’ ability to “cope” and recover from the injury may highlight differences that developed following initial sprain.

In the movement sciences, variability may be considered the amount which movement patterns change over repetitions of the same task. Variability is inherent in all human movement to some degree,[14] and Bernstein’s dynamical systems theory provides a rationale for its necessity. However, excessive or restrictive variability may also be detrimental to performance.[14] Using a musculoskeletal loading hypothesis, variability has been used to investigate overuse injuries and pathology. Too little variability may result in the accumulation of trauma in certain tissues, while too much variability may place an individual close to the "threshold of injury."[14, 15] However, no direct connection currently exists between movement variability in total and musculoskeletal injury.[14, 15] Musculoskeletal health is thought to be maintained by submaximal loading conditions that repeat over time, creating variation about some level of the characteristics of loading. Too little variability may cause accumulation of trauma by not allowing adaptation of tissue or by loading one tissue area and not spreading forces over an area.[14, 15] Alternatively, too much variability may place individuals in more extreme joint positions or expose them to more extreme forces, increasing the risk of injury. Variability in this study represents an inability to replicate optimal (or safe) movement patterns, which, potentially, places individuals at risk for injury.

Variability in discrete variables such as joint angle in time, timing of an event, or peak magnitude can be assessed through traditional descriptive statistical measures. The Coefficient of Variation (CV) and Standard Deviation (SD) are most commonly used, and have been used previously in human movement science on both discrete and continuous data.[14] The CV is the SD normalized to the mean of the score distribution and represents relative or normalized variability and is variability (SD) converted to a percentage of the mean value. The CV is useful for quantifying the amount of variability compared to the magnitude of the mean.[14, 16] Thus, one can compare performances with very different ranges.[14] Previous literature has suggested that approximately 8 trials are sufficient to capture the variability in a measure such as ground reaction force.[14]

Variability has rarely been assessed in complex multi-joint movement tasks. Additionally, variability in CAI kinematics and kinetics has not been sufficiently addressed in the literature, but it may be an important component in understanding the etiology and pathology of the injury. Increased variability in either the MAI or FAI populations may indicate an inability to safely replicate movement and functional tasks. If the SD or the relative normalized variability (CV) of movement variables is too large, individuals with CAI may place themselves beyond the limits of "safe movement" and cross the injury threshold on a more frequent basis. Over a high number of repetitions, the MAI or FAI subjects exhibit joint angles or loading values that have larger spread of variability, potentially placing them at the edges of safe movement, closer to crossing over into injury. Increased variability has also been linked with overuse injuries.[14] Initial studies of variability between injured and control subjects need to occur to determine what joint measures display variability, whether that variability is minimal or excessive, and how best to pick a measure of variability. If variability in movement is a factor in the CAI population, rehabilitation programs may be designed to target those deficits. The purpose of this study was to investigate variability on kinematic and kinetic measures in a group of subjects classified as having mechanical or functional ankle instability and compare them to a group without ankle instability.

Methods

Subjects

A total of 63 recreational athletes participated in this study, 21 (11 males, 10 females) in each group. These subjects were 18-35 year old individuals who performed at least 1.5 total hours of cardiovascular, resistance, sport-related, or other physical activity per week. Subjects were individually matched across groups on gender, age (±2year), height (±10%), mass (±10%), and limb dominance so that groups were balanced with regard to these factors. Subject demographics are reported in Table 1. A-priori power calculations were performed to determine necessary sample size using the conservative t-test model. Based on estimated means from graphic data from a similar study, an n of 10 provided power of 0.60-0.99 in kinematic variables at the ankle and knee. The effect sizes were 0.93-1.15.[17] Additionally, pilot data from 4 chronically unstable ankle subjects and 4 comparison subjects indicated that for variables of interest, 20 subjects were required to achieve a power of 0.80.

Each subject reported an initial inversion ankle sprain that required immobilization or non-weight bearing for at least 3 days within the past 1-5 years. The comparison group reported no repeated episodes of ankle instability following the initial sprain, with one or fewer episodes of giving way or spraining in the past 12 months and no sprain within the past 3 months. Both the MAI and FAI groups reported repeated episodes of spraining, rolling, or “giving way” at the ankle secondary to the initial sprain, with a minimum of 2 episodes of giving way or spraining in the past 12 months. The MAI group demonstrated clinically positive anterior drawer and/or talar tilt to orthopedic exam, rated as 4/5 “loose” or 5/5 “very” loose on a laxity scale.[18] The FAI group demonstrated negative anterior drawer and/or talar tilt tests (2/5 “hypomobile” or 3/5 “normal” on a laxity scale).[18] The comparison group also demonstrated negative anterior drawer and/or talar tilt tests.[18] One researcher rated ankle laxity for all subjects. Pilot testing using an intraclass correlation coefficient (ICC 2,1) determined interrater reliability, which was greater than 0.80 on both tests. The standard error of the measurement (SEM) was less than 0.25 for both tests. History of surgery in either leg and a previous ankle fracture in either leg were exclusionary criteria for all groups. Subjects were also excluded from participation if they had evident swelling or discoloration at the time of testing or a lower extremity injury in the last three months (other than an episode of ankle sprain or giving way in the MAI and FAI groups). Ankle pain, less than 20 degrees of plantar flexion, inability to dorsiflex past neutral, self-reported instability of the knee and/or hip, and current enrollment in a formal rehabilitation program were also exclusion criteria.

Instrumentation

A three-dimensional electromagnetic motion tracking system (the Flock of Birds, Ascension Technologies, Burlington, VT), controlled by Motion Monitor software (Version 6, Innovative Sports Training, Chicago, IL) was used to collect kinematic data. The software also time synchronized a piezoelectric non-conductive forceplate (Model #4060-NC Bertec Co., Columbus, OH) with a frequency response of 400 Hz in the vertical direction and 300 Hz in both horizontal directions measured the subject’s mass (in kg) and the kinetic variables.

We used a standard range transmitter mounted on a non-metal stand 32 cm from the forceplate at a height of 42 cm. The global axes system was established as +x in the direction the subject faced, +y to the right and +z in the upward vertical direction. All digitization occurred with a

15.4cm long wooden stylus, whose length was established by a 20-point digitization around a stationary point. Root mean square (RMS) error of the stylus was less than 0.003 every trial and was recorded.

Data Collection

Subjects signed an informed consent as approved by the University's Institutional Review Board before we collected demographic data and anthropometric measurements (range of motion and limb dominance).[19] A certified athletic trainer (ATC) determined ankle joint laxity using the anterior drawer and talar tilt tests[20] for entry into the MAI group. All subjects were barefoot for testing. Sensors were attached to the lateral femur over the iliotibial band midway between the hip joint and the knee joint and on the antero-medial portion of the tibia, 3-5 cm distal to the tibial tuberosity. A sensor was placed on the most inferior portion of the calcaneus on the midline of the shank, while another was placed between the 2nd-3rd metatarsals, at the midpoint of the metatarsal. To decrease potential skin movement, sensors were placed in areas with minimal muscle mass, with the cords oriented cephally. Each cord was looped and secured to subjects' legs and feet to avoid tension and movement artifact. Sensors were secured with double-sided tape, surgical tape, and athletic tape (Figure 1). Before digitization, the following bony landmarks were palpated and marked with a felt-tip pen: the most medial and lateral points knee joint line, the most prominent portions of the medial and lateral malleoli, the most prominent portions of the 1st and 5th metatarsal heads, and the most inferior portion of the calcaneus on either side of the calcaneal sensor just above where the heel contacts the ground. Initial digitization included the medial and lateral knee joint line points, the medial and lateral malleoli points, and the tip of the second phalanx. Following initial digitization, a similar process was undertaken for each of the segments and joints of interest. The proximal and distal ends of the longitudinal axis, a 3rd point on the plane, a 4th point above and on the positive side, and the origin were digitized for each joint/segment. Each origin was a centroid, or calculated midpoint, between two bony landmarks around a joint. The proximal end of the longitudinal axis of the thigh was one point on the most prominent portion of the greater trochanter, as palpated. The distal end was the centroid of the marked points on the medial and lateral knee joint lines. The 3^{rd} point on the plane was the lateral joint line point, and the 4^{th} point was digitized around the subject's abdomen. The origin of the thigh was the centroid between the medial and lateral knee joint line points. The proximal end of the longitudinal axis of the shank was the centroid of the medial and lateral knee joint line marks. The distal end was the centroid of the marked points on the medial and lateral malleoli. The 3^{rd} point on the plane was the lateral malleolus, and the 4^{th} point was digitized above the subjects' knee on the anterior side of the body. The origin of the shank was the centroid of the medial and lateral malleoli points. The proximal end of the longitudinal axis of the foot for the metatarsal sensor was the centroid between the medial and lateral malleoli points. The distal end was the centroid between the 1^{st} and 5^{th} metatarsal heads. The 3^{rd} point on the plane was the 1^{st} metatarsal head and the 4^{th} point was digitized at the midline of the shank, superior and anterior to the foot. The origin of the metatarsal sensor was the centroid of the 1^{st} and 5^{th} metatarsal heads. The proximal end of the longitudinal axis of the foot for the calcaneal sensor was the centroid of the two marks on either side of the calcaneal sensor. The distal end was the centroid of the marks on the 1^{st} and 5^{th} metatarsal heads. The 3^{rd} point on the plane was the mark on the medial side of the calcaneal sensor, and the 4^{th} point was at the midline of the foot, anterior to the tibia. The origin of the foot for the calcaneal sensor was the centroid of the two marks on either side of the calcaneal sensor. A final set up visual check and then a real-time view check ensured the joints and segments were digitized correctly.

A static calibration trial 3 seconds long was collected to define anatomic neutral position for the motions of interest. Motions measured included ankle plantar flexion/dorsiflexion and inversion angles, knee flexion-extension and valgus/varus angles, and ground reaction forces in the vertical, anterior-posterior, and medial-lateral directions.

Test Tasks

During the testing session, the subjects performed five tasks in a modified counterbalanced order: walking, stepping up and over, running, a drop jump, and a stop jump. Subjects had a minimum of 3 practice trials, followed by 8 test trials.[14] Walking occurred at a speed of 1.2-1.4 m/s,[21,

[22] a step-up and over and the drop jump occurred on a 32 cm high box, running speed was 2.5-3.5 m/s,[23, 24] and a stop jump was performed following previously published guidelines.[25] These speeds are typical in daily living and athletic activity for the respective tasks. The sacral sensor's anterior linear velocity was used to measure the speed of movement during the trial. Subjects were provided with feedback on their speed and had to stay within the stated ranges for walking and running speed on each trial in order for that trial to be considered "good." Sacral speed was measured just before the subject contacted the forceplate. Subjects received at least 30 seconds rest in between all trials.

Pilot testing with 4 CAI and 4 comparison subjects indicated the kinematic ankle variables on the drop jump task had intraclass correlation coefficient (ICC; 2,1) values of 0.67-0.88 with standard error of the measurement (SEM) of 2-5 degrees. The knee variables had ICC values of 0.68-0.97 (SEM = 1-5 degrees). The ICC for kinetic variables was low (0.44) in the CAI group with a large SEM (0.77 x body mass), but high in the comparison group (0.93) with a smaller SEM (0.50 x body mass).

Data processing

The Flock of Birds sampling rate was 144 Hz. For the test tasks kinematic data was "zeroed" or demeaned to the neutral standing values recorded by the Motion Monitor. The axes system was established as a left-handed system (origin starting in the left corner of the forceplate). Using the left hand screw rule, the following motions were positive: flexion, eversion/valgus, and external rotation.[26] Data were aligned to this configuration, regardless of side. The order of rotations of Euler angles at the ankle and knee was Y, X', Z'' or flexion, eversion/valgus, and external rotation. The last rotation was not analyzed in either joint because it was not a variable of interest, was the 3rd rotation with the most error, and it had the smallest range of motion. Kinetic data were collected at 1440 Hz and time synchronize with the kinematic data. Ground reaction forces for each task were normalized to body mass.

Dependent variables were selected using the Motion Monitor software and exported. Impact artifacts were observed on some variables and trials on each subject. A custom Mat Lab (The

Mathworks, Natick, RI) program was used to identify artifacts visually on position-time graphs. The frame at the beginning and end of the artifact was identified on the graph and a linear interpolation was used to connect the beginning and ending of the artifact. There were no more than two artifacts in each trial, thus this procedure was performed no more than two times in each trial. In the majority of cases, the artifact was 1-3 frames long.

Using DataPac 2K2 (Version 3.11, RUN Technologies, Mission Viejo, CA), a reference event buffer established the stance phase of each task. Stance was defined as initial contact (the forceplate registered more than 10N of vertical force) to toe off (the forceplate registered less than 10N of vertical force). For the drop jump task, the buffer was established as the first 250ms following initial contact, since there was no defined toe off in that task. DataPac filtered the kinematic data with a low-pass 4^{th}-order, non-recursive Butterworth filter (cut-off frequency of 15 Hz). This cut-off frequency was calculated using previously established methods.[27] No filtering was applied to the kinetic data. The signal averaging tool in DataPac was used to normalize the stance phase of each trial to 100 points and average the 8 trials of each task together for each subject. The mean of each data point on the standardized curve and the standard deviation (SD) of the mean for each data point were calculated by the software. Data were exported as ASCII files.

Using equations 1-3 below, a grand mean SD, the SD_{avg} and CV_{avg} were computed using a spreadsheet (Microsoft Inc., Redmond, WA). For the equations, *i* indicates the specific value for the *i*th sample, M_i is the mean for the *i*th sample, x_{ij} is the data value for the *i*th sample and *j*th trial, and *n* is the number of trials.[14] The SD_{avg} is the average of individual point-by-point SD values across all k samples composing the continuous curve. The SD_i is the SD value for the *i*th sample.[14]

$$M_i = \frac{\sum_{j=1}^{n} x_{ij}}{n} \qquad SD_{avg} = \left[\frac{\sum_{i=1}^{k} SD_i^2}{k}\right]^{1/2} \qquad CV_{avg} = \frac{SD_{avg}}{\frac{\sum_{i=1}^{k} |M_i|}{k}} \bullet 100$$

Equation 1 Equation 2 Equation 3

Nine subjects were missing one trial. The average of the 7 remaining trials was used for analysis. For all other subjects, the average of the 8 trials was used. The SD and CV were used as discrete variables. Histograms were initially assessed to check for skewness. Data that were extreme outliers (> 3SD from the mean) in each group in each task were noted and checked for validity. If they were not valid, the data was re-exported. No trials were excluded from analysis based on this check. The SD was utilized primarily to assess within subject variability, but the CV was also used to compare different variables, as it is a value normalized to the mean.

Data Reduction, Analysis, and Interpretation

Reduced CV and SD values were analyzed using the Statistical Program for the Social Sciences (Version 13.0, SPSS Inc., Chicago, IL) software. Histograms of each variable for each task grouping all subjects together were checked for normality. The SD and CV variables were all heavily and positively skewed. Based on the spread of the data, a $\log_e$ transformation was performed, after which the data were approximately normal. Scatterplots of the Observed vs. Standardized Residuals were assessed. If a data point appeared to be distinct from the group in the sense of an outlier, that data point was identified using histograms and box plots and assessed for how much it skewed the distribution of data from normal. If there was skewness, the analysis was re-run excluding the data point(s) in question. Based on this informal analysis of influence, no subjects were excluded in the final analysis. Levene's tests for equality of variances were checked for each variable.

Estimates of adjusted means and 95% confidence intervals (CI) from 3x5 mixed model Analyses of Variance (ANOVAs) were used to determine if selected interactions or main effects for group were present. For interactions, an overall, within-subjects p-value was identified from the

ANOVA for the interaction and assessed if it was less than 0.05. In that interaction, if a group adjusted mean for that task fell outside the 95% CI for another group, that mean was considered different from the other group. Traditional Tukey-post hoc tests were also performed and reported. Selected interactions not meeting the p-value criteria were also assessed using solely the 95% CI in the same manner. If no interaction was noted, main effects for group were assessed, using 95% CI as described above, but for estimates of adjusted means collapsed across tasks. Effect sizes were reported to indicate the magnitude of the differences. Additionally, the ratio of upper to lower 95% confidence level (CLR) was presented to indicate precision of the confidence interval.[28] This method was modified from the published description, taking the absolute values of the CI limits, and finding the ratio of the larger to the smaller.[28]

To ensure the groups were statistically equivalent in age, height, and mass, a preliminary one-way ANOVA was used to compare the groups. Because Mauchly's test of sphericity was significant on all the repeated measures ANOVAs, the Greenhouse-Geiser adjustment was used during analysis.

Results

The initial one-way ANOVA (Table 2) indicated the groups were no different in age, height, and mass ($p > 0.05$). Using the overall within-subjects alpha level of 0.05 criterion, there were no interactions with Tukey post-hoc tests of $p<0.05$. There were interactions noted using estimated marginal means and 95% CI, however. The first occurred in the $\log_e$ CV ankle inversion, with the FAI group means falling outside the upper limits of the 95% CI for the comparison group (Figure 2). The FAI group was more variable in contrast to the comparison group on the walk, drop jump, and stop jump tasks, with effect sizes from 0.78-1.20. The FAI group was also more variable than the MAI group on the stop jump. Another interaction was noted on the $\log_e$ CV vertical GRF variable, with the MAI group falling beyond the 95% CI upper limit of the FAI group on the stop jump task and the comparison group on the step up and over task (effect sizes 0.48 and 0.61 respectively) (Figure 3). Additionally, the FAI group mean was greater than the upper limit of the 95% CI for the comparison group on the step up and over, with an effect size of 0.48.

Additional interactions were noted using only 95% CI to test for differences. In the $\log_e$ SD of ankle plantar flexion, the MAI and FAI groups demonstrated less variability than the comparison group in the drop jump and stop jump (Figure 4), with effect sizes of 0.08-0.36. In the $\log_e$ SD of ankle inversion, the MAI group demonstrated more variability than the FAI group in the step up, but less in the stop jump, and more variability than the comparison group in the step up, run and drop jump (Figure 5). Additionally, the comparison group had less variability than the FAI group in the walk, run, and stop jump (Figure 5). Effect sizes ranged from 0.55-0.98.

No other interactions were noted using p-values or 95% CI in the CV ankle plantar flexion, any of the knee variables, or any anterior-posterior or medial-lateral GRF variable. All main effects noted were supplanted by interactions. While we relied on interactions, the previous two were not significant at the $p<0.05$ level, and using only 95% CI may have inflated the differences between groups in the tasks. Additionally, the low power and small effect sizes indicate these interactions should be interpreted with caution. We included tables (Tables 3-4) of kinematic and kinetic main effects for group on each variable, providing the estimated adjusted means, standard errors, 95% CI, and CLR to aid with interpretation of main effects for group, and because the interactions should be interpreted cautiously.

Several additional analyses were performed to ensure consistency between groups in different measures. A one-way ANOVA was used to test for differences in active range of motion measures recorded during subject screening. Each group was compared on ankle plantar flexion, dorsiflexion, inversion, and eversion on both ankles (Table 5). Using 95% CI, the MAI and FAI estimated marginal mean for left ankle inversion fell beyond the comparison group's upper limit. The MAI group's estimated marginal mean for left ankle eversion also fell beyond the comparison and FAI group's 95% CI upper limit. The MAI group's right ankle estimated marginal mean for eversion also fell beyond the 95% CI upper limit for the FAI and comparison groups. Thus, it appears the unstable ankle groups had greater left ankle inversion versus the comparison group, and the MAI group had increased right and left ankle eversion compared to the FAI and comparison groups. We would expect to see increased range of motion if the subjects were mechanically lax, because they were lacking ligamentous restraints. The FAI group was not clinically positive in laxity in inversion, but they likely had some stretching of the ligament, which appeared as increased range of motion. These differences in active range of motion may influence our results, but we were looking for effects of the injury.

A repeated measures ANOVA was used to determine whether sacral velocity was consistent between groups and met the criteria established in the methods. Because Mauchly's test of sphericity was significant ($p < 0.05$), the Greenhouse-Geiser adjustment was used. No significant group x task interactions were observed ($F_{(5.12, 153.59)} = 0.965$; $p > 0.05$), nor were any main effects for group ($F_{(2, 60)} = 0.795$; $p > 0.05$). Levene's test for equality of variance was checked prior to proceeding with all analyses.

Discussion

The FAI group appeared to be more variable than the comparison group in the $\log_e$ CV ankle inversion, with interactions occurring in the walk, drop jump, and stop jump (Figure 2). Interestingly, these tasks had a range of difficulty and were not just the most demanding. The FAI group may not pay attention to their ankle position or attempt to control it as strictly during tasks with low demand.

Both unstable groups demonstrated greater variability on the vertical ground reaction force when compared to the comparison group, but only on the step up and stop jump tasks, two tasks requiring landing from a height (Figure 3). The unstable groups may have more difficulty controlling their vertical ground reaction force on tasks with higher impact forces. We found differences in ankle plantar flexion angle and sagittal plane displacement in the unstable groups, and this variability in vertical ground reaction force may be accounted for by the differences in ankle motion. If there is less angular displacement at the ankle joint, the vertical ground reaction forces encountered may not be absorbed in a similar manner.

Other interactions noted with 95% CI indicated that the MAI group was less variable in plantar flexion angle than the comparison group on two of the harder tasks (Figure 4). The MAI group may be restricting the ankle in the sagittal plane to limit exposure to potentially injurious situations. By landing in the same manner every time and avoiding plantar flexion, the MAI group may be attempting to avoid injury.[15, 29] This finding fits with the theory of a coping mechanism developed to avoid sprain. Interestingly, the same relationship did not hold for ankle inversion variability. The MAI group was actually more variable than the comparison and FAI groups on a number of tasks, except the stop jump, where the FAI group was more variable (Figure 5). The MAI group may not be receiving proper proprioceptive feedback from the ankle in the frontal plane if the calcaneofibular ligament has been stretched and/or damaged. With increased available active range of motion in that plane and possible changes in proprioception, the MAI group may not have the ability to safely replicate a landing pattern that is normal and avoids lateral ankle sprain.

We know that CAI individuals demonstrate and/or have sensorimotor deficits, but we do not know what pathogentic mechanisms associate these deficits with sustaining an inversion injury when the comparison group is uninjured[30]. During transition from an unloaded to a loaded lower extremity (as during weight acceptance in each of the tasks) a situation occurs in which inversion torques could create a lateral ligament injury. If the unloaded ankle accepts a load while in a mal-aligned, or risky, position, subtalar inversion torque could be generated and cause injury.[30] Konradsen and Voigt (2002) demonstrated that a 10º miscalculation in inversion during the swing phase follow through, with a collision between the between the lateral border of the foot and the ground, resulted in maximal inversion, plantar flexion, an internal rotation of the foot and ankle. Using joint position sense data, they calculated a 7-8º error in inversion foot position could result in injury. As reported in the literature, assuming a CAI subject has 2.6º of joint position sense error, and the error is normally distributed, an error of that magnitude is made more than once every 10,000 steps.[30] If the FAI group is extremely variable in their inversion foot position during the stance phase, this may be an explanation for the mechanism of injury and repeated sprains.

The comparison group displayed decreased $\log_e$ CV vertical GRF compared to the MAI and FAI groups. This difference was small (with small effect sizes) but even a minimal difference in vertical GRF may accumulate over time. The unstable ankle groups appear to be more variable in the amount of vertical GRF they experience across all the tasks. Alterations in movement pattern at the ankle may be responsible for this. As changes in the plantar flexion angle occurred, the ability of the lower extremity to absorb forces may be altered if the subject cannot repeat the task in the same manner. There were no differences between tasks in magnitude of the GRF, so magnitude did not likely influence variability.[15] A previous study assessed the degree of "injury proneness" and task difficulty on joint kinetic variability and reported that in less challenging tasks, healthy subjects had greater variability, while injured subjects had less variability. That relationship reversed when the task became more challenging.[15] The authors hypothesized a relationship between degree of joint kinetic variability and overuse injury proneness, in which healthy subjects subconsciously perceived decreased need for consistency in landing from a low height, preventing overuse injury by changing the stresses on the lower limb. In contrast, when landing from a higher height, the healthy subjects displayed less variability. Unconscious neuromuscular control may have risked overuse injury in order to protect the joints from an acute injury. The increased variability in vertical GRF may increase contact stress at the articular cartilage of the talus, possibly leading to increased joint degeneration in CAI individuals.

There is limited literature on variability as it related to joint pathology, particularly at the ankle. Most available literature associated increased variability with pathology. For example, a group with patellofemoral pain displayed greater stride length variability during treadmill running at a preferred speed versus a control group.[31] Additionally, older individuals had greater observed variability than younger individuals during stair descent when measuring the minimum clearance between the foot and the stair. Older individuals were at greater risk for contact with the edge of the stair surface, and thus at greater risk for tripping and falling.[32] This matches our results of increased variability in the MAI and FAI groups.

We only observed differences in kinematic variability between groups at the ankle in the sagittal and frontal planes, which are associated with the mechanism of injury for lateral ankle sprains. The other variables were not different between groups, including variables at the knee and the anterior-posterior and medial-lateral GRF variables. It appears that at the knee, the groups are equivalent in variability of motion, and were only affected at the joint that was injured. One might expect that GRF in the plane of injury (medial-lateral) would be different, however, the small magnitude of those forces made differences between groups unlikely. It is also likely the groups were simply not different, as evidenced by the lack of difference in the 95% CI and the small effect sizes.

Only the $\log_e$ SD ankle inversion and knee valgus had CLR greater than 2. All other variables had CLR smaller than 2, and were thus fairly precise and stable.

Limitations

There were a number of potential limitations with this study. The first is the reliance on self-report data of ankle injury history. Although subjects reported repeated episodes of spraining, rolling, and giving way at the ankle, the actual incidence and degree of instability in the MAI and FAI groups was uncertain. Identifying individuals with FAI is difficult, since the population presents with a wide range of symptoms and degree of instability. We made an effort to match subjects between groups as best as possible, but there are inherent differences in length of time with ankle instability, degree of mechanical laxity, and mechanisms that evoke feelings of instability. The FAI group we tested likely encompassed a broad spectrum of recreationally active individuals with varying degrees of instability. The heterogeneous nature of this group may have clouded some results. Additionally, our comparison group of "copers" did not demonstrate mechanical laxity. An ideal comparison group would have consisted of individuals with mechanical laxity who do not suffer episodes of instability, and thus are effectively coping with mechanical laxity of the lateral ligaments. These individuals are difficult to find and there is no history of their use in the CAI literature.

Laxity testing was performed using clinical orthopedic tests and one examiner. Lack of an objective and quantifiable measure of instability is problematic. There is likely some error in the motion capture equipment and processing of data as well. Using SD and CV is a relatively simplistic method of analyzing variability in movement. The complex nature and relationships between the joints in the lower extremity may be better characterized with more advanced methods of variability measurement, such as approximate entropy.[33, 34] Finally, the reported power levels for the interactions and group main effects on the repeated measures ANOVA for both CV and SD variables were typically low. Power was never greater than 0.35 for any of the kinetic variables, and was never higher than 0.71 for the kinematic variables.

The design of the study cannot determine whether or not the differences we observed in variability developed after the injury, or were present prior to developing CAI, and may have contributed to it. The pattern of changes we observed in the MAI and FAI groups may be explained as contributing to further injury, but without a prospective study, it is impossible to determine that.

Conclusions

Our most important finding was greater variability in the ankle motion of the unstable ankle groups versus the comparison group. Greater variability in the frontal plane may place the FAI and MAI groups at greater risk for inversion sprains, and offer an explanation for the pathomechanics of FAI subjects who do not demonstrate mechanical laxity of the lateral ligaments. The unstable group's greater variability in vertical GRF is also important. There may be long-term consequences to this movement pattern, as it could increase joint degeneration over time. Rehabilitation programs should consider these findings and develop appropriate interventions. Specifically, emphasis should be placed on frontal plane motion and encouraging repeatability of ankle position at landing to avoid ankle sprains. Future research is necessary to determine the association of variability of movement patterns with ankle sprains and if there are long term deficits associated with variability of movement patterns.

Based on our results it appears MAI and FAI subjects should be differentiated in future research, and not combined into one CAI group. Mechanical and functional laxity appear to be important factors in variability, and may impact other variables of interest in CAI research, including postural stability, reaction time, electromyography, and others. If CAI subjects are not separated based on lateral ligament laxity, confounding mechanical laxity may cloud the results. Incorporating stricter criteria for defining chronic ankle instability, as well as its subgroups, is necessary. Future research should work to increase sample size and power, and determine if there are long term deficits associated with chronic ankle instability. Future research should also explore up the kinetic chain to see if differences occur proximally.

Table 1. Subject Demographics by Group and Gender

Group	Gender	Age (years)			Height (cm)			Mass (kg)		
		Mean	(SD)	Range (Minimum and Maximum)	Mean	(SD)	Range (Minimum and Maximum)	Mean	(SD)	Range (Minimum and Maximum)
MAI	Male	23.00	5.12	18-33	179.81	10.02	165.00-193.00	76.73	13.80	55.17-101.36
	Female	21.70	3.30	19-28	166.33	5.47	155.00-173.00	65.73	9.75	53.28-86-74
FAI	Male	22.45	4.27	18-31	178.08	6.45	168.00-188.00	77.59	12.00	60.23-93.00
	Female	21.80	3.49	19-29	165.10	7.72	152.00-177.00	67.91	13.01	46.69-89.72
Comparison	Male	21.27	4.17	18-33	182.10	4.16	177.80-191.00	75.38	7.65	63.58-86.90
	Female	22.20	5.69	18-35	167.70	5.48	160.00-178.00	63.92	10.55	48.13-82.21

MAI: Mechanical ankle instability group; FAI: functional ankle instability group; SD: Standard deviation

Table 2. One-Way ANOVA with Tukey Post-Hoc Testing for Subject Matching Between Groups

Measure	**F-value$_{\text{(Degrees of Freedom)}}$**	**P-value**	**Post-Hoc Testing (α = 0.05)**
Age (yrs)	$F_{(2, 60)} = 0.127$	0.881	None
Height (cm)	$F_{(2,60)} = 0.632$	0.535	None
Mass (kg)	$F_{(2,60)} = 0.323$	0.726	None

MAI: Mechanical ankle instability group; FAI: functional ankle instability group; SD: Standard deviation.

Table 3. Repeated Measures ANOVA Group Main Effects for Kinematic Log_e Transformed Coefficient of Variation and Mean Standard Deviation Measures

Average Variable	Group	Estimated Marginal Mean	Standard Error	F-Value	P-Value	Power Level	95% Confidence Interval		Tukey Post-Hoc*	CLR
							Lower Limit	Upper Limit		
CV Ankle plantarflexion	MAI	2.66	0.11	0.52	0.60	0.13	2.44	2.88	None	1.18
	FAI	2.74					2.52	2.96		1.17
	Comparison	2.82					2.60	3.04		1.17
CV Ankle inversion	MAI	2.49	0.21	1.46	0.24	0.30	2.07	2.91	None	1.41
	FAI	2.87					2.45	3.28		1.34
	Comparison	2.40					1.97	2.81		1.42
CV Knee flexion	MAI	2.67	0.08	0.74	0.48	0.17	2.52	2.82	None	1.12
	FAI	2.55					2.39	2.70		1.13
	Comparison	2.58					2.43	2.73		1.12
CV Knee valgus	MAI	2.65	0.14	0.45	0.64	0.12	2.38	2.92	None	1.23
	FAI	2.74					2.47	3.02		1.22
	Comparison	2.83					2.56	3.10		1.21
SD Ankle plantarflexion	MAI	1.12	0.05	1.17	0.32	0.25	1.01	1.22	None	1.21
	FAI	1.22					1.12	1.33		1.19
	Comparison	1.21					1.11	1.32		1.19
SD Ankle inversion	MAI	0.46	0.06	5.17	0.008	0.81	0.34	0.58	MAI-Comp	1.71
	FAI	0.46					0.34	0.58	FAI-Comp	1.71
	Comparison	0.22					0.10	0.34		3.40
SD Knee flexion	MAI	1.21	0.05	1.48	0.24	0.30	1.11	1.31	None	1.18
	FAI	1.16					1.06	1.25		1.18
	Comparison	1.09					1.00	1.19		1.19
SD Knee valgus	MAI	0.46	0.06	1.99	0.15	0.40	0.34	0.59	None	1.74
	FAI	0.50					0.38	0.62		1.63
	Comparison	0.33					0.21	0.46		2.19

CV Coefficient of Variation; SD Standard Deviation; MAI mechanical ankle instability; FAI functional ankle instability; * Significant at the $p < 0.05$ level. CLR ratio of maximum absolute upper to lower 95% confidence limits. Note: Due to log_e transformation, values are unitless.

Table 4. Repeated Measures ANOVA Group Main Effects for Kinetic Log_e Transformed Coefficient of Variation and Mean Standard Deviation Measures

Average Variable	Group	Estimated Marginal Mean	Standard Error	F-Value	P-Value	Power Level	95% Confidence Interval		Tukey Post-Hoc*	CLR
							Lower Limit	Upper Limit		
CV	MAI	2.46	0.04	1.84	0.17	0.37	2.37	2.55	None	1.08
normalized	FAI	2.44					2.35	2.53		1.08
VGRF	Comparison	2.35					2.26	2.43		1.08
CV	MAI	3.51	0.04	0.63	0.54	0.15	3.43	3.58	None	1.04
normalized	FAI	3.45					3.37	3.52		0.94
APGRF	Comparison	3.46					3.38	3.53		1.04
CV	MAI	3.97	0.14	0.91	0.41	0.20	3.70	4.25	None	1.15
normalized	FAI	3.72					3.44	4.00		1.16
MLGRF	Comparison	3.92					3.64	4.19		1.15
SD	MAI	-2.01	0.04	1.84	0.17	0.37	-2.10	-1.93	None	1.09
normalized	FAI	-2.01					-2.10	-1.93		1.09
VGRF	Comparison	-2.12					-2.20	-2.03		1.08
SD	MAI	-3.01	0.04	0.58	0.56	0.14	-3.09	-2.92	None	1.06
normalized	FAI	-3.00					-3.08	-2.91		1.06
APGRF	Comparison	-3.06					-3.14	-2.97		1.06
SD	MAI	-3.50	0.04	1.46	0.24	0.30	-3.58	-3.42	None	1.05
normalized	FAI	-3.50					-3.58	-3.42		1.05
MLGRF	Comparison	-3.58					-3.66	-3.50		1.05

CV Coefficient of Variation; SD Standard Deviation; MAI mechanical ankle instability; FAI functional ankle instability; * Significant at the $p < 0.05$ level. CLR ratio of maximum absolute upper to lower 95% confidence limits. Note: due to log_e transformation values are unitless.

Table 5. Descriptives and One-Way ANOVA for Range of Motion Measures Between Groups

Average Variable	Group	Group Mean	Standard Deviation	F-Value	P-Value	95% Confidence Interval Upper Limit	95% Confidence Interval Lower Limit	*Tukey Post-Hoc	CLR
R ankle dorsiflexion	MAI	5.30	3.84	1.01	0.37	3.50	7.10	None	2.03
	FAI	6.00	2.96			4.62	7.38		1.60
	Comparison	6.79	2.94			5.37	8.20		1.53
R ankle plantar flexion	MAI	62.60	6.81	0.35	0.71	59.41	65.79	None	1.11
	FAI	62.75	7.65			59.17	66.33		1.12
	Comparison	60.26	14.89			53.09	67.44		1.27
R ankle inversion	MAI	15.00	6.43	0.74	0.48	11.99	18.01	None	1.50
	FAI	13.85	5.81			11.12	16.57		1.49
	Comparison	12.79	4.62			10.56	15.02		1.42
R ankle eversion	MAI	6.85	3.00	1.71	0.19	5.45	8.25	None	1.51
	FAI	5.60	2.37			4.49	6.71		1.49
	Comparison	5.42	2.52			4.20	6.64		1.58
L ankle dorsiflexion	MAI	7.25	3.60	0.37	0.30	5.57	8.93	None	1.60
	FAI	7.40	3.56			5.73	9.07		1.58
	Comparison	8.79	2.90			7.39	10.19		1.38
L ankle plantarflexion	MAI	57.75	6.16	1.22	0.69	54.87	60.63	None	1.10
	FAI	59.60	6.72			56.45	62.75		1.11
	Comparison	58.47	7.67			54.78	62.17		1.13
L ankle inversion	MAI	16.30	6.56	3.24	0.05	13.23	19.37	MAI-Comp	1.46
	FAI	14.35	6.60			11.26	17.44	p=0.04	1.55
	Comparison	11.47	4.31			9.40	13.55		1.44
L ankle eversionn	MAI	6.75	2.38	3.05	0.06	5.64	7.86	MAI-Comp	1.39
	FAI	5.25	2.31			4.17	6.33	P=0.08	1.51
	Comparison	5.11	2.25			4.02	6.19		1.54

R right; L left; MAI mechanical ankle instability; FAI functional ankle instability. *Significant at the $p<0.05$ level. CLR is ratio of maximum absolute upper to lower limit 95% confidence limits.

Figure 1. Subject Set Up

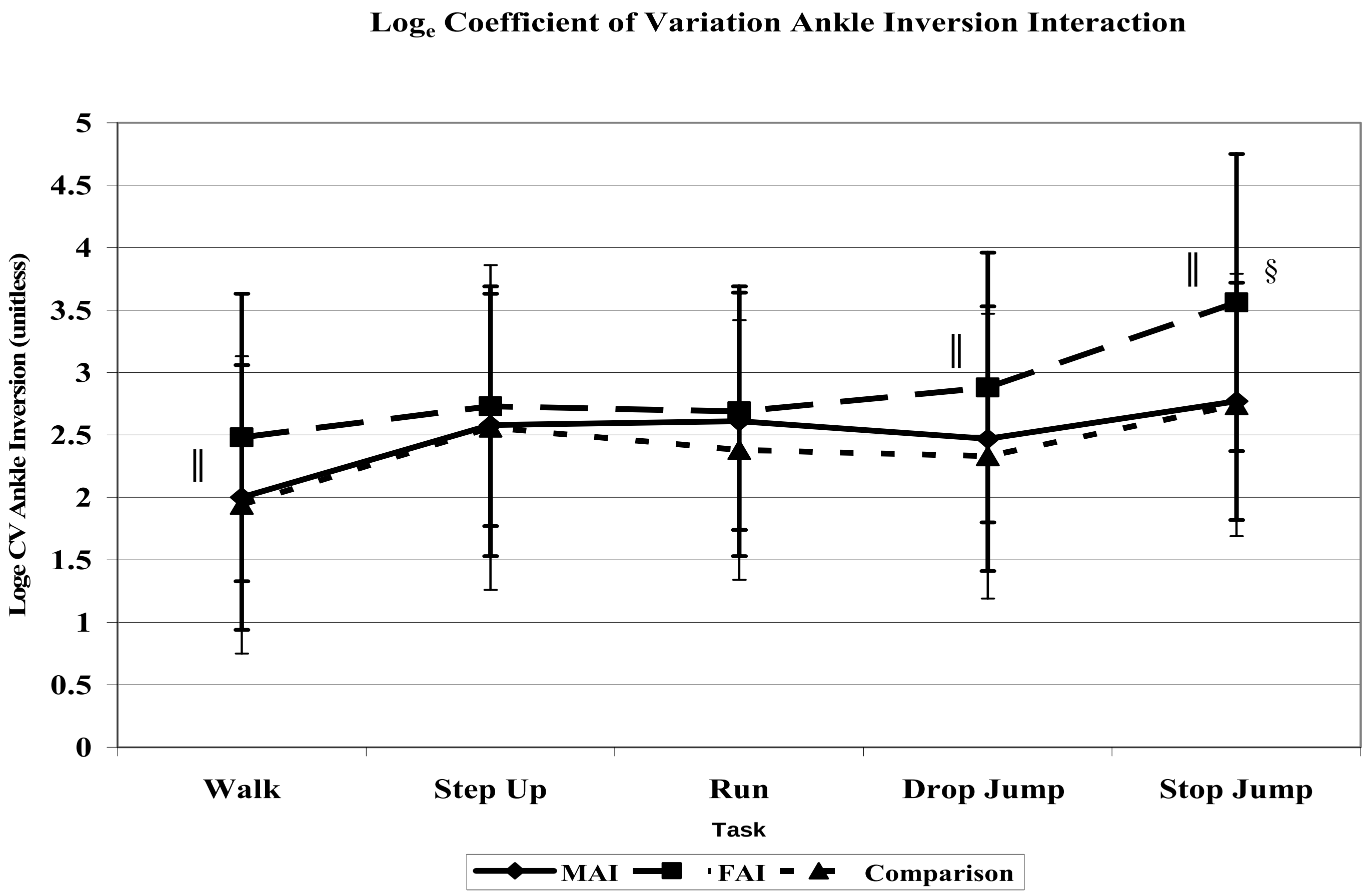

Figure 2. Group x Task Interaction for Log_e Coefficient of Variation Ankle Inversion
$F_{(5.58, 167.43)}=1.57$; $p=0.16$; power=0.57
MAI is mechanical ankle instability; FAI is functional ankle instability. Using p-values: *Significant difference between MAI and FAI ($p<0.05$); †Significant difference between MAI and comparison ($p<0.05$); ‡Significant difference between FAI and comparison ($p<0.05$)
Using 95% Confidence intervals: §Differences between MAI and FAI; ¶Difference between MAI and comparison; ‖Difference between FAI and comparison.

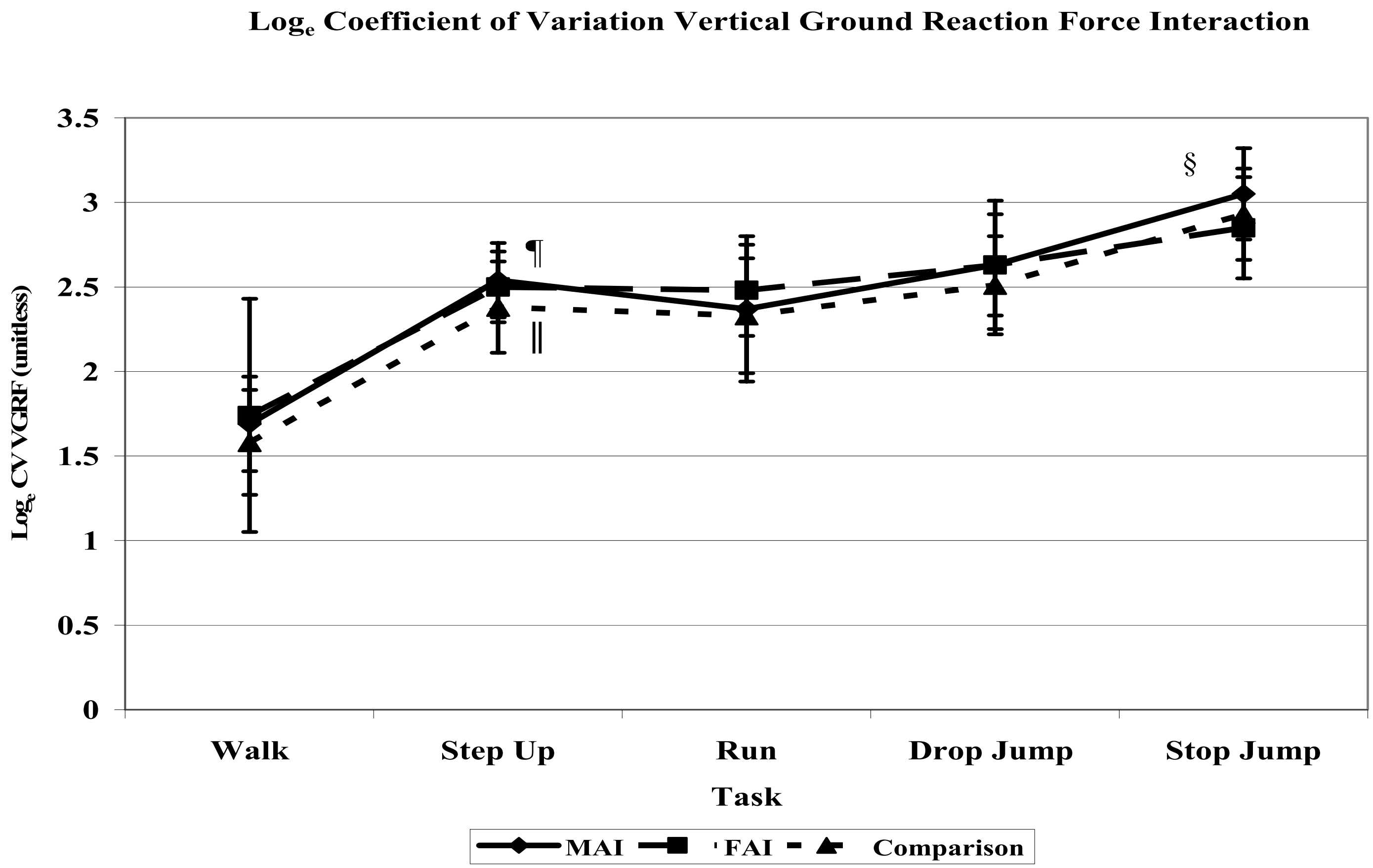

Figure 3. Group x Task Interaction for Log$_e$ Coefficient of Variation Vertical Ground Reaction Force
$F_{(6.67,199.94)}=0.96$; p-value=0.459; power=0.40
MAI is mechanical ankle instability; FAI is functional ankle instability. Using p-values: *Significant difference between MAI and FAI ($p<0.05$); †Significant difference between MAI and comparison ($p<0.05$); ‡Significant difference between FAI and comparison ($p<0.05$)
Using 95% Confidence intervals: §Differences between MAI and FAI; ¶Difference between MAI and comparison; ‖Difference between FAI and comparison.

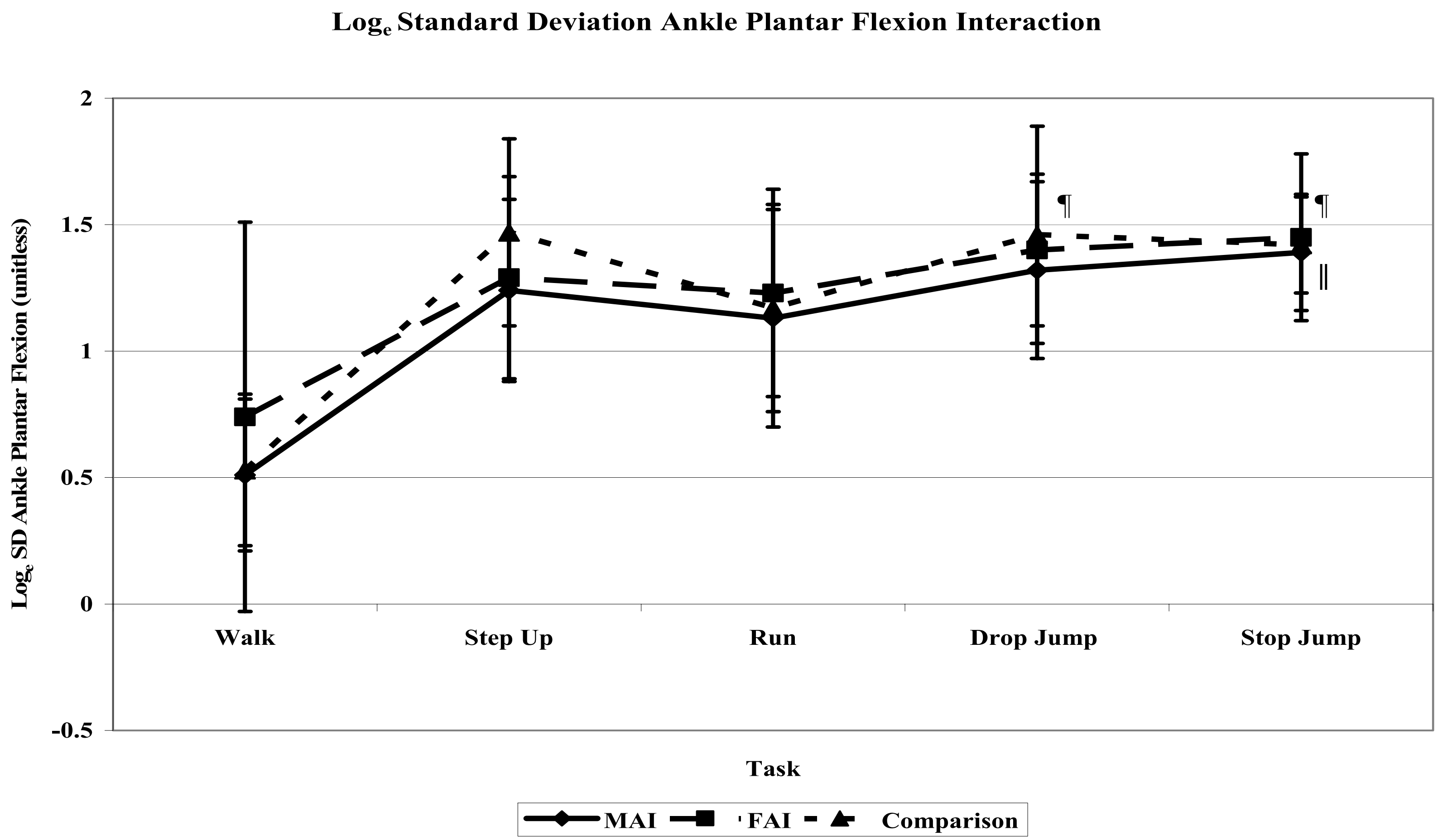

Figure 4. Group x Task Interaction for Log$_e$ Standard Deviation Ankle Plantar Flexion
$F_{(6.27,188.17)}$=1.02; p=0.42; power=0.41
MAI is mechanical ankle instability; FAI is functional ankle instability. Using p-values: *Significant difference between MAI and FAI ($p<0.05$); †Significant difference between MAI and comparison ($p<0.05$); ‡Significant difference between FAI and comparison ($p<0.05$)
Using 95% Confidence intervals: §Differences between MAI and FAI; ¶Difference between MAI and comparison; ‖Difference between FAI and comparison.

Log$_e$ Standard Deviation Ankle Inversion Interaction

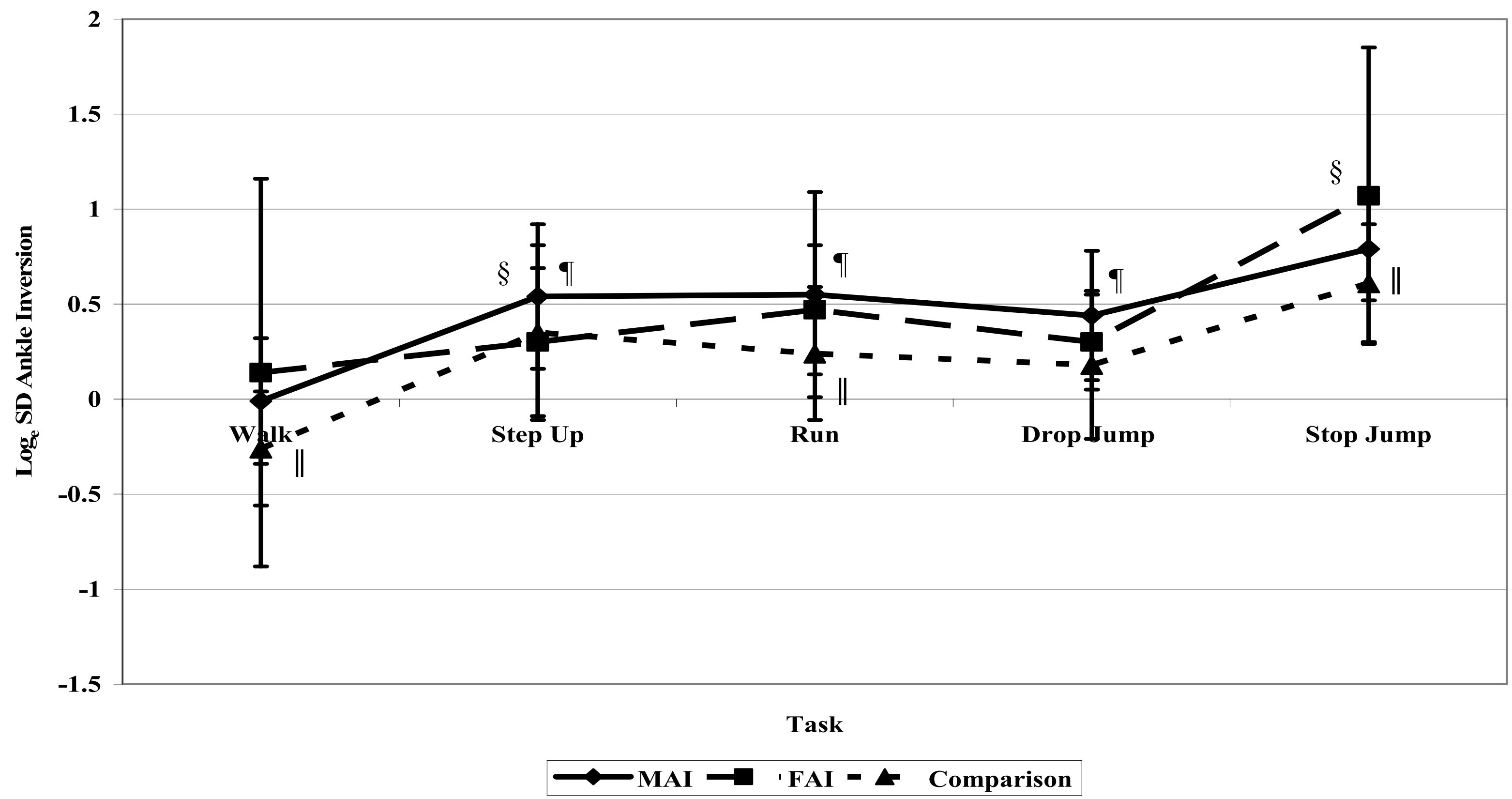

Figure 5. Group x Task Interaction for Log$_e$ Standard Deviation Ankle Inversion
$F_{(6.51,195.34)}=1.77$; $p=0.10$; power=0.69
MAI is mechanical ankle instability; FAI is functional ankle instability. Using p-values: *Significant difference between MAI and FAI ($p<0.05$); †Significant difference between MAI and comparison ($p<0.05$); ‡Significant difference between FAI and comparison ($p<0.05$)
Using 95% Confidence intervals: §Differences between MAI and FAI; ¶Difference between MAI and comparison; ‖Difference between FAI and comparison.

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APPENDIX C

Institutional Review Board and Data Collection Tools

University of North Carolina-Chapel Hill
Consent to Participate in a Research Study
Adult Subjects
Biomedical Form

THIS CONSENT FORM SHOULD BE SIGNED ONLY
BETWEEN 10/10/05 AND 6/20/06
APPROVED BY THE BIOMEDICAL IRB
UNIVERSITY OF NORTH CAROLINA

IRB Study #05-EXSS-343
Consent Form Version Date: October 5, 2005
Title of Study: Factors Contributing to Ankle Instability
Principal Investigator: Cathy Brown MA, ATC
Romer Orada, Lindsey Jordan, Aniel Rao
UNC-Chapel Hill Department: Interdisciplinary Human Movement Science/Exercise and Sport Science
UNC-Chapel Hill Phone number: 919-843-2014
Email Address: browncn@email.unc.edu
Faculty Advisor: Dr. Kevin Guskiewicz
Study Contact telephone number: 919-843-2014
Study Contact email: browncn@email.unc.edu
Funding Source: Smith Graduate Research Grant, UNC-CH

What are some general things you should know about research studies?
You are being asked to take part in a research study. To join the study is voluntary.
You may refuse to join, or you may withdraw your consent to be in the study, for any reason.

Research studies are designed to obtain new knowledge that may help other people in the future. You may not receive any direct benefit from being in the research study. There also may be risks to being in research studies.

Deciding not to be in the study or leaving the study before it is done will not affect your relationship with the researcher, your health care provider, your instructor, or the University of North Carolina-Chapel Hill. If you are a patient with an illness, you do not have to be in the research study in order to receive health care.

Details about this study are discussed below. It is important that you understand this information so that you can make an informed choice about being in this research study. You will be given a copy of this consent form. You should ask the researchers named above, or staff members who may assist them, any questions you have about this study at any time.

What is the purpose of this study?
The purpose of this research study is to learn about which biomechanical factors may cause people to sprain their ankles while performing physical activity. If we can identify factors such as joint angle or muscle activity that increase the risk of ankle sprains, we can develop rehabilitation programs that target those factors and decrease the risk of injury. Ankle sprains are the most common injury in sports, and a large percentage of people suffer repeated sprains and develop chronic instability or "giving way" at the ankle. This can be painful and inconvenient and places them at greater risk for ankle osteoarthritis or joint degeneration.

Currently we do not know why some people develop chronic ankle instability. The aim of the study is to combine several possible factors to obtain a comprehensive biomechanical "snapshot" of how people with and without chronic ankle instability perform sporting and daily activities such as walking, stepping, running, and jump landing. If we can find differences between the groups, it is the first step in developing rehabilitation and prevention programs that help people avoid chronic ankle instability.

You are being asked to be in the study because you are a recreationally active individual between the ages of 18-35. You are also being asked because you reported experiencing previous ankle sprains, or because you did not report previous ankle sprain but are of similar age, height, weight, and gender and can serve as a comparison subject.

Are there any reasons you should not be in this study?

You should not be in this study if you:

1) currently do not participate in recreational physical activity for a total of 90 minutes per week;
2) have had surgery in either leg or a fracture in either ankle;
3) have had a leg injury in the last 3 months, other than an episode of ankle sprain or giving way;
4) have any current signs or symptoms of an ankle injury including pain, swelling, discoloration, or loss of range of motion;
5) have pain with walking, stepping up onto a stair, running, or jump landing;
6) have any knee or hip instability;
7) are currently enrolled in a formal ankle rehabilitation program;
8) are a woman who is knowingly pregnant;
9) have been diagnosed with a vestibular or balance disorder or Charcot-Marie-Tooth or other hereditary nerve disorder.

How many people will take part in this study?

If you decide to be in this study, you will be one of approximately 70 people in this research study.

How long will your part in this study last?

Your involvement will include a test session today if you choose to participate that will last approximately 1.5 hours. If you choose to complete the test session, you will be contacted a few days later to confirm if you would prefer to pick up the check or have it mailed. You will then either pick up the check in person or receive a phone or email notification the check has been mailed. Each contact with the researcher after the test session will take approximately 5 minutes, so your total involvement time will be approximately 1.75 hours.

What will happen if you take part in the study?

After reading this consent form, if you agree to participate, you will go through a two part testing process. The first part will last approximately 15 minutes and will consist of screening procedures to place you into the appropriate group. The second part will be the test procedure when you will be set up on the equipment and go through the different testing tasks. You will be wearing shorts and a t-shirt for the entire testing procedure. During the testing procedures you will be barefoot.

Screening procedure

- You will complete three questionnaires: two regarding your ankle function during physical activities and one asking about your age, ankle injury history, and the type of physical activities in which you prefer to participate.
- You will undergo an ankle orthopedic exam by Cathy Brown MA, ATC, a certified athletic trainer licensed by the state of North Carolina to practice sports medicine. She will measure your ankle joints' range of motion and strength as well as test for ankle joint laxity or looseness. She will also test for your dominant leg by having you perform a stepping, a kicking and a balance recovery task.
- Based on the results of the questionnaires, demographics sheet, and the orthopedic exam you will either be excluded from the study because you do not fit the subject criteria, or you will be placed into one of three groups:
  - A group with mechanical ankle instability or "loose" ankles that sprain often
  - A group with functional ankle instability or ankles that are not loose but still sprain often
  - A group for comparison with ankles that are not loose and do not sprain often

Testing procedure

- Once you are placed into the appropriate group, the testing will start by placing small electrodes on your skin over 5 different areas in your leg. To secure the electrodes to the skin 5 small 1-inch square areas must be shaved over each site, then rubbed with gauze and rubbing alcohol to clean the skin. The electrodes will not shock you; they measure the electrical activity in your muscle when it contracts and send that information to a computer. The electrodes have adhesive stickers on the back. Athletic underwrap will secure the electrodes and tie up the wires so they are not in your way.
- The strength of your muscles at the ankle joint will be tested next with a hand held device. You will be shown the device prior to signing this consent form. Your foot will be positioned at various angles and you will provide a maximum force against the device, contracting each muscle to measure its strength. You will be given 3 practice trials and 3 test trials. Each trial will be 3 seconds long and you will contract against the device with as much force as you can generate. You will be given 30 seconds of rest in between each trial.
- Next five 1-inch square sensors will be attached to your low back, thigh, leg, heel, and foot with double sided tape and athletic tape. A sixth sensor will be moved to point to various bony landmarks around your body to tell the computer where your joints are in space. Those points (6 total) at your knee, ankle, and toes, will be marked with a felt tip pen. The sensors will measure the motion of your leg while you perform the walking, stepping, running, and jump landing tasks. A skeletal model of your leg generated by the computer will provide a visual representation of your motion, but it will not be able to identify you in any way.
- Then you will practice each task before performing the test trials. You will perform walking at 1.2-1.4 m/s, stepping up and over onto a 32 cm high box (slightly higher than typical stair height), running at 2.5-3.5 m/s down a runway, performing a drop jump onto a single leg from a 32 cm high box, and performing a stop jump maneuver. In the stop jump you will run at 2.5-3.5 m/s down a runway, take off of one foot and land with two feet followed immediately by a maximum vertical jump. This is a movement commonly performed in sports such as tennis, volleyball, basketball, and soccer. In each different task you will be asked to land on a wooden forceplate in the ground to measure how hard you land. You will

receive at least 3 practice trials for each task. Once you feel comfortable you will perform 8 test trials, with at least 1 minute of rest in between trials. The researcher will ask you if you are feeling any fatigue, pain or apprehension about performing the tasks. If you are, you should say so and your participation in the study will end. If your foot does not land completely on the forceplate, if you do not move at the right speed, or if you do not perform the task correctly, you will be asked to repeat the trial.

- Next, the sensors will measure how loose your ankle joint is. You will be seated and the researcher will apply a force with her hands to rotate your joint. Then your foot will be strapped to a wedge attached to the floor while the researcher applies a force to your leg. The forces are the same you would experience if a health care provider was examining your ankle joint and should not cause any pain.
- Following completion of your test trials, you will be finished participating in the study. The set up and testing should take approximately 1.5 hours. All of the electrodes and markers will be removed and your skin will be cleaned of any adhesive residue and felt tip pen marks. At this point you will schedule a time to come back and pick up the incentive check or provide an address to which it can be sent. If you choose to pick up the check you will return to the lab in 1-5 business days, or at a time that fits your schedule.

What are the possible benefits from being in this study?

Research is designed to benefit society by gaining new knowledge. There is little chance you will benefit from being in this research study.

What are the possible risks or discomforts involved with being in this study?

There are few possible risks or discomforts involved with being in this study. You may experience slight muscular soreness the following day from the walking, stepping, running, and jump landing trials. You may experience minor skin irritation from the adhesive gel used on the surface electrodes. There is a slight risk of injury as exists when performing any physical activity, however the activities will not be different from those performed in daily life and sporting events such as running, tennis, or basketball. In addition, there may be uncommon or previously unknown risks that might occur. You should report any problems to the researchers.

What are the risks to a pregnancy or to a nursing child?

If you are a woman and know you are pregnant you should not participate in this study because pregnancy can cause some hormones to be released that may affect joint laxity or looseness that may affect the results of this study. There are no risks involved if you are a woman currently nursing a child.

What if we learn about new findings or information during the study?

You will be given any new information gained during the course of the study that might affect your willingness to continue your participation.

How will your privacy be protected?

Your privacy and confidentiality will be protected while participating in this study. An identification number will be assigned to you and used on all documents you complete, instead of your name. A list linking your name with your identification number will be stored in a locked office on a password-protected computer. Only the researchers listed on the first page of this application will have access to that list. All forms you complete will be stored in a locked office. You will not be required to provide any personal information, other than your name, and address if you prefer your incentive check be mailed to you.

No subjects will be identified in any report or publication about this study. Although every effort will be made to keep research records private, there may be times when federal or state law requires the disclosure of such records, including personal information. This is very unlikely, but if disclosure is ever required, UNC-Chapel Hill will take steps allowable by law to protect the privacy of personal information. In some cases, your information in this research study could be reviewed by representatives of the University, research sponsors, or government agencies for purposes such as quality control or safety.

While participating, a computer will generate a skeletal model of your leg based on the length and width of your bones and joints that depicts an animation of your movement. There will be no other video or audio recording made, and no distinguishing features of you will be evident, other than your leg length. This skeleton model will be saved but will not identify you in any way.

What will happen if you are injured by this research?

All research involves a chance that something bad might happen to you. This may include the risk of personal injury. In spite of all safety measures, you might develop a reaction or injury from being in this study. If such problems occur, the researchers will help you get medical care, but any costs for the medical care will be billed to you and/or your insurance company. The University of North Carolina at Chapel Hill has not set aside funds to pay you for any such reactions or injuries, or for the related medical care. However, by signing this form, you do not give up any of your legal rights.

What if you want to stop before your part in the study is complete?

You can withdraw from this study at any time, without penalty. The investigators also have the right to stop your participation at any time. This could be because you have had an unexpected reaction, or have failed to follow instructions, or because the entire study has been stopped.

Will you receive anything for being in this study?

You will be receiving a check for $10 for taking part in this study. The check will be mailed to you or you may pick it up a few days (1-5) following completion of the study. The incentive will not be prorated if you do not finish the study. There will be no reimbursement for parking, transportation, or child care.

Will it cost you anything to be in this study?

It will not cost you anything to participate in this study.

What if you are a UNC student?

You may choose not to be in the study or to stop being in the study before it is over at any time. This will not affect your class standing or grades at UNC-Chapel Hill. You will not be offered or receive any special consideration, including course credit, if you take part in this research.

What if you are a UNC employee?

Taking part in this research is not a part of your University duties, and refusing will not affect your job. You will not be offered or receive any special job-related consideration if you take part in this research.

Who is sponsoring this study?
This research is funded by the Graduate School at the University of North Carolina at Chapel Hill. This means that the supplies required for the research team as well as subject incentives are being paid for by the sponsor. The researchers do not, however, have a direct financial interest with the sponsor or in the final results of the study, nor are they being paid.

What if you have questions about this study?
You have the right to ask, and have answered, any questions you may have about this research. If you have questions, or if a research-related injury occurs, you should contact the researchers listed on the first page of this form.

What if you have questions about your rights as a research subject?
All research on human volunteers is reviewed by a committee that works to protect your rights and welfare. If you have questions or concerns about your rights as a research subject you may contact, anonymously if you wish, the Biomedical Institutional Review Board at 919-966-1344 or biomed_irb@unc.edu.

- -

Subject's Agreement:

I have read the information provided above. I have asked all the questions I have at this time. I voluntarily agree to participate in this research study.

_______________________________ _______________
Signature of Research Subject Date

____
Printed Name of Research Subject

_______________________________ _______________
Signature of Person Obtaining Consent Date

____
Printed Name of Person Obtaining Consent

Demographics, Activity, and Ankle Sprain Interview Information
Biomedical IRB 05-EXSS-343 June 23, 2005

Do not fill in this box:

ID ____________________

Date __________ Gender _____ Dominant Leg ____

Height ________ Weight _____ +Talar tilt___ +Ant drawer ___

Age __________ ROM R pf____ df _____ inv _____ ev___

L pf____ df _____ inv _____ ev___

Strength R pf____ df _____ inv _____ ev___

L pf____ df _____ inv _____ ev___

Please Print

1. Does one or more of your ankles "give way" with activity or sprain often?

   Yes _____ No _____

2. Have you had 2 or more sprains in either ankle in the last year? If yes, please circle which one. A sprain is considered to occur when pain, swelling, redness, heat, or loss of function was noted in the ankle.

   Yes _____ No_____ R or L or Both

3. How many total times have you sprained each of your ankles? A sprain is considered to occur when pain, swelling, redness, heat, or loss of function was noted in the ankle.

   R _____ L _____

4. When was the last time you sprained your ankle (day, month and year if you remember)?

   R _____ L _____

5. Do you perform some recreational/physical activity for at least 1.5 hours per week?

   Yes _____ No _____

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6. How many hours per week do you spend performing physical activity, e.g. running, playing a sport, lifting weights, etc?

7. List what types of physical activity you engage in.

8. Do you play a club sport?

   Yes ____ No _____

9. If yes, list which one and the number of hours you practice per week.

Biomedical IRB #05-EXSS-343 **June 23, 2005**

Ankle Stability Questionnaire

The following questions are meant to determine in which situations you feel that your ankle may or may not be unstable or "give way." Using a scale of 0-10, please answer the following questions. "0" means you have no confidence of stability; in other words you know your ankle will "give way." "10" means that you are very confident your ankle will be stable and not "give way."

REPEAT FOR EACH ACTIVITY: **How confident/sure are you that your ankle would be stable and not "give way" when you:**

	No confidence										Absolutely confident
Walk around your house or apartment	0	1	2	3	4	5	6	7	8	9	10
Stand on one leg	0	1	2	3	4	5	6	7	8	9	10
Step up on a curb	0	1	2	3	4	5	6	7	8	9	10
When you are walking around on a trail	0	1	2	3	4	5	6	7	8	9	10
When you are going up or down stairs	0	1	2	3	4	5	6	7	8	9	10
Landing from a jump	0	1	2	3	4	5	6	7	8	9	10
When you jog or run on a level paved surface	0	1	2	3	4	5	6	7	8	9	10
When you jog or run on an unlevel surface such as a trail	0	1	2	3	4	5	6	7	8	9	10
When you need to cut or change directions while running	0	1	2	3	4	5	6	7	8	9	10
When you engage in recreational activity such as tennis, basketball, baseball, raquetball, etc.	0	1	2	3	4	5	6	7	8	9	10

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Foot and Ankle Disability Index (FADI)

Please answer **every question** with one response that most closely describes to 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).

	No difficulty at all	Slight difficulty	Moderate difficulty	Extreme difficulty	Unable to do	N/A
Standing	O	O	O	O	O	O
Walking on even ground	O	O	O	O	O	O
Walking on even ground witout shoes	O	O	O	O	O	O
Walking up hills	O	O	O	O	O	O
Walking down hills	O	O	O	O	O	O
Going up stairs	O	O	O	O	O	O
Going down stairs	O	O	O	O	O	O
Walking on uneven ground	O	O	O	O	O	O
Stepping up and down curbs	O	O	O	O	O	O
Squatting	O	O	O	O	O	O
Sleeping	O	O	O	O	O	O
Coming up on your toes	O	O	O	O	O	O
Walking initially	O	O	O	O	O	O
Walking 5 minutes or less	O	O	O	O	O	O
Walking approximately 10 minutes	O	O	O	O	O	O
Walking 15 minutes or greater	O	O	O	O	O	O

1999 FADI Interim 1/2

Biomedical IRB #05-EXSS-343 June 23, 2005

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

	No difficulty at all	Slight difficulty	Moderate difficulty	Extreme difficulty	Unable to do	N/A
Home resposibilities	O	O	O	O	O	O
Activities of daily living	O	O	O	O	O	O
Personal care	O	O	O	O	O	O
Light to moderate work (standing, walking)	O	O	O	O	O	O
Heavy work (push/pulling, climbing, carrying)	O	O	O	O	O	O
Recreational Activities	O	O	O	O	O	O

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

	None	Mild	Moderate	Severe	Unbearable
General level of pain	O	O	O	O	O
At rest	O	O	O	O	O
During your normal activity	O	O	O	O	O
First thing in the morning	O	O	O	O	O

FADI Sports Scale

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

	No difficulty at all	Slight difficulty	Moderate difficulty	Extreme difficulty	Unable to do	N/A
Running	O	O	O	O	O	O
Jumping	O	O	O	O	O	O
Landing	O	O	O	O	O	O
Starting and stopping quickly	O	O	O	O	O	O
Cutting/lateral movements	O	O	O	O	O	O
Low impact activities	O	O	O	O	O	O
Ability to perform activity with your normal technique	O	O	O	O	O	O
Ability to participate in your desired sport as long as you would like	O	O	O	O	O	O

1999 FADI Interim 2/2

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