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Hindfoot and forefoot kinematic differences among individuals with and without Functional Ankle Instability

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Hindfoot and forefoot kinematic differences among individuals with and without Functional Ankle Instability

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

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LIST OF ABBREVIATIONS

ADL	=	activity of daily living
APSI	=	anterior-posterior stability index
CAI	=	chronic ankle instability
CAIT	=	Cumberland Ankle Instability Tool
CI	=	confidence interval
COP	=	center of pressure
DPSI	=	dynamic postural stability index
FAAM	=	Foot and Ankle Ability Measure
FADI	=	Foot and Ankle Disability Index
FAI	=	functional ankle instability
FI	=	functional instability
GRF	=	ground reaction force
HS	=	heel strike
IC	=	initial contact
JPS	=	joint position sense
MI	=	mechanical instability
MLSI	=	mediolateral stability index
SEBT	=	Star Excursion Balance Test
SLDJ	=	Single leg drop jump task
TO	=	toe off
TTS	=	time to stabilization
$vGRF_{max}$	=	maximal vertical ground reaction force
WALK	=	walking task

ABSTRACT

HINDFOOT AND FOREFOOT KINEMATIC DIFFERENCES AMONG INDIVIDUALS WITH AND WITHOUT FUNCTIONAL ANKLE INSTABILITY

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

Virginia Commonwealth University, 2011.

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Introduction: Following lateral ankle sprain, many individuals experience recurrent injury and symptoms of giving-way, known as Functional Ankle Instability (FAI). It has been proposed that altered joint kinematics during activity may contribute to instability in these individuals, however research findings have been inconsistent. **Objective:** To capture foot and ankle kinematic data during two common tasks (walking gait and jump landing) among three groups: individuals with FAI, healthy controls and copers. **Design**: 3-group observational cross-sectional study. **Participants**: Participants included 23 individuals with a history of ≥ 1 ankle sprain and at least 2 episodes of giving-way in the past year (FAI: M±SD; age=23.30±3.84years; height=1.71±0.11m, weight=68.66±14.60kg; Cumberland Ankle Instability Tool [CAIT]=20.52±2.94, episodes of giving-way=5.81±8.42 per month), 23 subjects with no history of ankle sprain or instability in their lifetime (Controls: age=23.17±4.01years, height=1.72±0.08m, weight=68.78± 13.26kg, CAIT: 28.78±1.78), and 23 individuals with a history of a single ankle sprain and no subsequent episodes of instability (Copers: age=23.52±3.68years, height=1.72±0.07m, weight=69.57±13.94kg; CAIT: 27.74 ± 1.69). **Interventions**: Ten trials of natural walking gait and 10 single leg drop jumps were recorded using a ViconMX motion monitoring system (OMG, Oxford, UK) and two imbedded force plates (Bertec, Columbus, Ohio, USA). **Main Outcome Measures**: Forefoot and hindfoot sagittal and frontal plane angles were calculated at initial contact (IC) and toe-off (TO) of walking gait, and IC and maximal vertical ground reaction force of jump landing. **Results**: At walking IC, there was a significant group difference in forefoot inversion ($F_{2,66}$=4.68, p=0.013). Post hoc testing revealed that individuals with FAI were significantly more inverted than controls, but copers were not significantly different from the FAI or control groups. At jump landing IC, there were significant group differences in hindfoot motion ($F_{2,66}$=6.12, p=0.004). Specifically, individuals with FAI were significantly more dorsiflexed than the control or coper groups. There were no other significant group differences (all p>0.05). **Conclusions**: Kinematic differences exist between healthy controls, copers and individuals with FAI. Copers and individuals with FAI have both experienced ankle sprain injury, yet copers do not experience subsequent instability. Analysis of coper movement patterns compared to control and FAI groups may provide insight into coping mechanisms.

CHAPTER ONE: INTRODUCTION

STATEMENT OF THE PROBLEM

Occurrence of Ankle Sprains

Ankle sprains are one of the most common injuries experienced by youth and adults involved in physical activity.[1-5] Specifically, ankle sprains account for 3-4% of injuries in the general population.[6, 7] Among ankle injuries reported in the general population, 43-65% of ankle sprains result from physical activity (including sports and play),[6, 8-11] 2-10% from automobile accidents,[8, 11] and 12-16% from work related accidents.[6, 8, 11] Within physically active populations, such as sporting teams, 10-54% of injuries are ankle sprains.[12-20] Furthermore, within these physically active populations, it has been reported that 42-70% of individuals had a history of at least one ankle sprain.[21, 22] This suggests that ankle sprains are not only a common injury but alsooccur in relatively large segments of the population.

Problem of Functional Ankle Instability

The incidence of ankle sprains is concerning because this injury can have long-term implications. Between 32% and 74% of patients complaining of an ankle sprain report having some type of chronic symptoms (e.g. pain, swelling, dysfunction, instability) following injury.[10, 14, 23, 24] In fact, approximately half of ankle injuries are re-injuries,[25-27] and risk for ankle sprain increases substantially in individuals with a history of at least one ankle sprain.[28-30]

Of people suffering from chronic symptoms and dysfunction, Freeman[31-33] identified a subcategory complaining of functional ankle instability (FAI), i.e. the sensation of "giving way". Giving way describes the sensation of ankle instability where it feels as though the ankle joint is about to roll over, lose stability, or re-sprain. FAI has been noted in the presence and absence of clinical laxity of the ankle joint.[34-36] On average, 32% (range = 20.4% – 40.4%) of patients complaining of ankle sprains report having FAI at follow up.[14, 23, 37, 38] Approximately a quarter of all individuals with ankle sprains do not recover fully, and 6% are prevented from returning to their occupation[37] and 13-15% of patients remain occupationally handicapped from at least 9 months to 6.5 years following injury.[37, 39] Additionally, long term health outcomes are associated with FAI, such as osteoarthritis (OA).[40] The etiology of approximately 70% of ankle OA cases is posttraumatic,[40, 41] and of those cases 13.4% were caused by the trauma of an ankle sprain and subsequent instability.[40] OA is associated with a large financial burden and decreased quality of life.[42] Specifically, patients with posttraumatic ankle OA score significantly worse on the Short Form-36 health outcome survey,[42] and lower extremity posttraumatic OA in the U.S. costs $11.8 billion per annum, $3.06 billion of which is direct health care expense.[42]

Biomechanics of Functional Ankle Instability

Based on these reports, it is clear that ankle sprains and FAI in particular are a significant health risk with substantial individual and societal costs. Greater understanding of the underlying mechanisms of FAI may lead to a reduction in these costs through enhanced preventative and/or rehabilitative methods.

Several pathological factors have been associated with FAI,[43] including altered joint mechanics.[44-49] Joint kinematics and kinetics demonstrate the strategies with which an individual attempts to maintain dynamic joint stability during functional activity.[50] As such they may provide insight into the biomechanical mechanism of FAI, which could then be targeted in rehabilitation. Differences in joint motion and joint forces may elucidate how an individual with FAI either copes or fails to cope with pathology to dynamically stabilize their ankle during activity.[46]

Several researchers have hypothesized that differences in joint kinematics or kinetics exist between individuals with FAI and healthy controls.[44-49] These researchers have primarily focused on two tasks: gait and jump landing. These tasks are important because landing from a jump is a common mechanism of ankle inversion injury[30] and individuals with FAI complain of giving way while walking on level and uneven surfaces.[49] Specifically, increased ankle inversion at initial contact (IC) may predispose individuals to ankle inversion injury due to the creation of an inversion moment.[51] Although several researchers have focused on IC of gait or jump landing while the limb is being loaded, instability could also occur when the limb is being unloaded during toe-off (TO). TO occurs as the limb leaves contact with the ground and enters into the swing phase. As with IC, angular error at this transition between weight bearing and non-weight bearing conditions could contribute to instability and giving-way. With jump landing, the forefoot typically makes initial contact prior to the hindfoot. Thus, angular error at the forefoot may be a larger contributor to instability than during gait. Also, error at maximal vertical ground reaction force (vGRF) would be especially dangerous due to the high impact forces. While some researchers have found increased ankle inversion at initial contact in gait and jump landing,[45, 46] others have failed to find such differences.[47, 48] Similarly, sagittal plane differences between groups have not been consistently found.[44-47] Even when group differences are apparent, it can be difficult to interpret whether changes are positive, negative or even benign adaptations.

Subject Selection

Subject selection may be one key to clarifying findings. Typically FAI subjects have been compared to individuals who have never sprained or fractured either ankle.[35, 44, 46, 52, 53] However, several researchers have recently questioned how appropriate the typical comparison group is.[48, 54] Hertel and Kaminski[54] recommended that future study of ankle instability include both "copers" and "noncopers." They operationally define copers as "those who suffer an initial sprain but no subsequent injuries" and noncopers as "those who suffer recurrent sprains and residual symptoms after initial sprain." Rather than compare individuals with FAI to individuals who have never sprained an ankle it may be more appropriate to compare to individuals who have also experienced an ankle sprain but not gone on to develop FAI. It is thought that differences between FAI and coper groups may help interpret the meaning of differences between FAI and healthy groups.

The classification of copers versus noncopers itself is borrowed from research in the anterior cruciate ligament (ACL) deficient population. Facing conflicting reports comparing ACL deficient and healthy individuals, several researchers chose to differentiate ACL deficient individuals by their functional ability, designating them copers or noncopers. This more precise subject designation decreased within group heterogeneity and yielded more consistent results, including electromyographical, kinetic, and kinematic differences between copers and noncopers during weight acceptance.[55-58] The ankle instability literature may benefit from more precise subject categorization as well.

Only a few studies of the ankle have grouped subjects as copers, noncopers, or healthy controls.[48, 59-61] Since copers are thought to be able to dynamically stabilize during activity despite past ankle injury, whereas noncopers can not, meaningful differences between these two groups should be especially evident during kinematic and kinetic analysis. For example, if FAI and control groups are significantly different from each other on 2 kinematic variables, are both variables contributing to instability? Perhaps only 1 of these variables truly contributes to instability, and the other is a benign change post-injury. If so, addition of a coper group should show no difference from controls on the variable contributing to instability, and no difference from the FAI group on the benign changes post-injury. Only Brown et al.[48] have compared the ankle joint kinetics and kinematics between copers and noncopers. They reported increased ankle joint frontal plane displacement during gait, but no differences between the FAI (noncoper) group and coper group for any other variable. This seems to indicate that frontal plane motion is the salient difference between those with and without instability. However they did not include a healthy group to make the 3 way comparison. Thus, it is unknown whether values for copers and noncopers were within the normal healthy range.

Ankle Joint Modeling

A second key to clarifying the findings in kinematic analysis of subjects with FAI may be the use of more reliable and precise biomechanical models. In the FAI literature there is a deficiency in the reporting of the kinematic model used, including marker placement and mathematical modeling assumptions. Of 7 studies reporting kinematic differences between individuals with and without FAI,[44-48, 62, 63] only one study[62] reported or referenced the repeatability of the model used. Four studies partially or fully described modeling assumptions,[48, 62-64] however, the three remaining studies provided no modeling information whatsoever. Especially since the angular differences reported in studies between FAI and healthy subjects tends to be small,[45, 47] the interpretation of results reported in the current literature is difficult without adequate information about the repeatability and precision of biomechanical modeling. Error may either obscure true group differences or create spurious differences if an accurate and precise model is not used.

Furthermore, the majority of these studies utilized a one segment foot model.[44-48, 63] This type of model assumes that the foot is a single rigid segment, despite the numerous articulations within the foot and ankle complex. Thus, although it can provide a picture of the overall motion of the foot and ankle, by definition a single segment foot model cannot capture differences in hindfoot and forefoot motion that can be reliably captured with a multi-segment model such as the Oxford foot model used by Drewes and collegues.[62, 65-67] Because hindfoot, forefoot and hallux motion are not identical during activity,[65] a model able to capture these movements may be essential in accurately representing motion in individuals with FAI. Simpler models may have obscured differences by pooling hindfoot and forefoot motion into a single composite value.

PURPOSE OF RESEARCH

Therefore, the purpose of this study is to capture ankle joint kinematic data using the previously reported multi-segment Oxford foot model during two common tasks (walking gait and jump landing) among three groups of subjects (copers, noncopers, and healthy individuals).

RESEARCH AIMS AND HYPOTHESES

Specific Aim 1:

To determine whether hindfoot and forefoot kinematic differences exist during gait between individuals with FAI, ankle sprain copers, and healthy controls.

Hypothesis 1:

During walking gait, FAI subjects would display significantly different hindfoot and forefoot motion than copers and healthy subjects at initial contact and toe off. Copers and healthy subjects would display highly similar movement patterns.

Specifically, based on pilot data, individuals with FAI would display differences from the other groups in the following variables:

1A. greater hindfoot inversion at initial contact (IC)

1B. greater forefoot inversion at toe-off (TO)

- Importance: Increased inversion could create an inversion moment.[51] At IC the hindfoot is typically the only foot segment in contact with the floor, thus at this event hindfoot position is most likely to contribute to stability (or lack thereof). Similarly, at TO the forefoot is the only foot segment in contact with the floor, thus forefoot position at this event is most likely to contribute to stability (or lack thereof).

Specific Aim 2:

To determine whether hindfoot and forefoot kinematic differences exist during jump landing between individuals with FAI, ankle sprain copers, and healthy controls.

Hypothesis 2:

During jump landing FAI subjects would display significantly different hindfoot and forefoot motion than copers and healthy subjects at IC and maximum vertical ground reaction force (vGRF). Copers and healthy subjects would display highly similar movement patterns.

Specifically, based on pilot data, individuals with FAI would display differences from the other groups in the following variables:

2A. greater forefoot plantarflexion at IC

2B. greater hindfoot inversion at maximal vGRF

2C. greater forefoot inversion at maximal vGRF

- Importance: Increased plantarflexion at IC may place the ankle in a more vulnerable position.[62, 68] Similarly, increased inversion creates an inversion moment,[51] which may be especially dangerous while accepting high forces (such as at maximal vGRF).

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CHAPTER TWO: LITERATURE REVIEW

BACKGROUND

Following an ankle sprain, a substantial number of individuals develop functional ankle instability (FAI).[1-4] FAI is a pathology defined by symptoms of instability and giving-way at the ankle.[5-7] These recurrent symptoms can limit physical activity and activities of daily living for years post-injury,[1] indicating there is no such thing as a simple ankle sprain. Despite decades of research, we have yet to develop a clear understanding of the etiology of FAI. Therefore, the purpose of this section is to review: 1) the problem of ankle sprains and FAI, 2) associated terminology and subject selection issues, and 3) the functional insufficiencies associated with FAI.

Ankle Sprain Epidemiology

Ankle sprains are one of the most common injuries experienced by youth and adults involved in physical activity.[8, 9] Specifically, ankle sprains account for 3-4% of injuries in the general population[10, 11] and 15-44% of injuries in physically active populations.[12-14] Among ankle injuries reported in the general population, 45-59% of ankle sprains result from physical activity (including sports and play), 10% from automobile accidents, and 12% from work related accidents.[15, 16] Furthermore, within physically active populations, it has been reported that 42-70% of individuals had a history of at least one ankle sprain.[17, 18] This suggests that ankle sprains are not only a common injury but occur in relatively large segments of physically active populations.

In youth the incidence rate of first-time ankle sprains alone has been reported as 0.8 per 1000 person-days of exposure.[19] The incidence of ankle sprains is concerning because this injury has both short and long-term implications. The cost of treating an ankle sprain ranges from $663-1,906 per sprain when adjusted for inflation,[20] and 50% of ankles sprains result in 7-30 days absent from physical activity.[20] The U.S. Department of Labor estimates an injury rate of 4.6 per 10,000 full-time workers, or 43,890 cases annually.[21] A median of 5 days lost per injury costs approximately $30.5 million annually in lost wages from work-related injuries alone.[22]

Chronic Symptoms

In addition to the high incidence and costs of ankle sprains, between 32% and 74% of patients complaining of an ankle sprain report having some type of chronic symptoms (e.g. pain, swelling, dysfunction, instability) following injury.[2, 3, 16, 23] Approximately 50% of ankle injuries are re-injuries,[24-26] and risk for ankle sprain increases substantially in individuals with a history of at least one ankle sprain.[27] McKay et al. [28] found that athletes with a history of ankle injury were almost 5 times more likely to sustain another ankle injury than those with no history of ankle injury. Not only are individuals with a history of ankle sprain at increased risk of subsequent sprains and ongoing symptoms, the etiology of 70% of cases of ankle osteoarthritis is post-traumatic,[29] indicating that damage induced by ankle sprains and subsequent instability may increase the risk of developing osteoarthritis.[29, 30] Osteoarthritis is associated with a large financial burden and decreased quality of life.[31]

Of people suffering from chronic symptoms and dysfunction, Freeman[5, 6] identified an additional subcategory complaining of functional instability, i.e. the sensation of “giving way”.

Giving way describes the sensation of ankle instability where it feels as though the ankle joint is about to roll over, lose stability, or re-sprain. On average 32% ± 9% of patients complaining of ankle sprains report having FAI at follow up.[1-4] FAI has been shown to prevent approximately 6% of patients from returning to their occupation and 15% of patients remain occupationally handicapped up to 6.5 years following injury.[1]

Based on these reports, it is clear that ankle sprains and FAI in particular are a significant health risk to the physically active with substantial individual and societal costs. Greater understanding of this pathology may lead to a reduction in these costs through enhanced preventative and/or rehabilitative methods.

CHRONIC, FUNCTIONAL AND MECHANICAL INSTABILITIES

Ankle instability has been described using several terms, including FAI, functional instability (FI), mechanical instability (MI) and chronic ankle instability (CAI). To clarify discourse, it is helpful to define and compare these often overlapping terms. CAI refers to the occurrence of repeated episodes of lateral ankle instability and re-injuries following a lateral ankle sprain.[32, 33] While instability in the weeks immediately following an acute lateral ankle sprain is to be expected, individuals with CAI continue to re-injure their joint and experience episodes of pain, swelling, instability or decreased function for several months and even years after an injury.[1, 23] As it is generally used, CAI can be considered an umbrella term encompassing subjectively reported lateral ankle instability regardless of whether it is causally linked to MI, FI or both.[32]

Tropp et al.[34] defined MI as increased ankle joint laxity due to damage of the ankle ligaments. This definition has been expanded by others to include other structural alterations such as ankle joint arthrokinematic restrictions, degenerative changes and synovial changes.[32, 35] While ankle joint laxity remains the hallmark sign of MI, research into these other causes is ongoing. The hypothesis generally associated with MI is that structural changes following injury, such as increased laxity or restricted range of motion, decrease joint stability and predispose the joint to injury.[35, 36]

The other potential etiology of CAI is FI. The hallmark symptoms of FI is "giving way" of the ankle joint. Freeman et al.[5, 6] observed that many individuals without notable joint laxity still continued to complain of ankle instability, thus, he originally hypothesized that instability was caused by proprioceptive deficits following ankle sprain. More recently 3 additional insufficiencies that may lead to FI have been proposed: impaired neuromuscular control,[37, 38] strength deficits,[39-42] and impaired postural control.[34, 43, 44]

With the preceding understanding of MI and FI, there is no simple distinction between these two proposed etiologies. For example, disruption of the ankle ligaments may damage proprioceptors in and around those ligaments, thus, leading to not only increased joint laxity (MI), but impaired proprioception (FI) as well. Specifically, several authors have found individuals with symptoms of FI and MI simultaneously.[34, 40, 45] However, not all individuals with FI have MI, and not all individuals with MI have FI.[34, 45-48] Despite the potential overlap between FI and MI, it should be noted that some authors have defined inclusion criteria for FI that specifically exclude the presence of laxity.[49-52] It may be that individuals with FI and no laxity experience different mechanisms than individuals with FI and MI simultaneously. Thus, limiting inclusion criteria to include only 1 of these subcategories of FI may eliminate confounding.

There are some divergent uses of the terms CAI, FI and MI. Some authors use the term functional ankle instability (FAI) in a virtually interchangeable manner with CAI,[46] while most use FAI as synonymous with FI.[7, 32, 37, 38, 49, 53] Using FAI interchangeably with CAI may imply a belief that *all* individuals experiencing "giving way" have primarily functional insufficiency. However, some patients have improvement of their symptoms following reconstructive surgery of the lateral ligaments,[54] which is a mechanical rather than a functional correction. It therefore seems more appropriate to use the term CAI to describe symptoms that may occur with either underlying mechanism, and to use the terms FAI or FI interchangeably to indicate a primarily functional mechanism (Figure 1). We have written this manuscript with this understanding, that FAI and FI are interchangeable, and will henceforth use the term FAI exclusively because it is the more common term in related literature.

While it is difficult to completely separate the contributions of MI and FAI in individuals, FAI is, nevertheless, of particular interest because functional mechanisms may be altered with rehabilitation,[55-59] whereas alteration of mechanical laxity likely requires surgery.[54, 60] Ankle surgery is invasive, costly, and does not always successfully resolve symptoms of instability.[54] Avoidance of the risks, costs and limitations of surgery when possible is in the best interest of the patient. Better understanding of the mechanisms (proprioception, neuromuscular control, strength and postural control) associated with FAI may lead to enhanced prevention strategies following a lateral ankle sprain, and enhanced conservative treatment of individuals with lateral ankle instability.

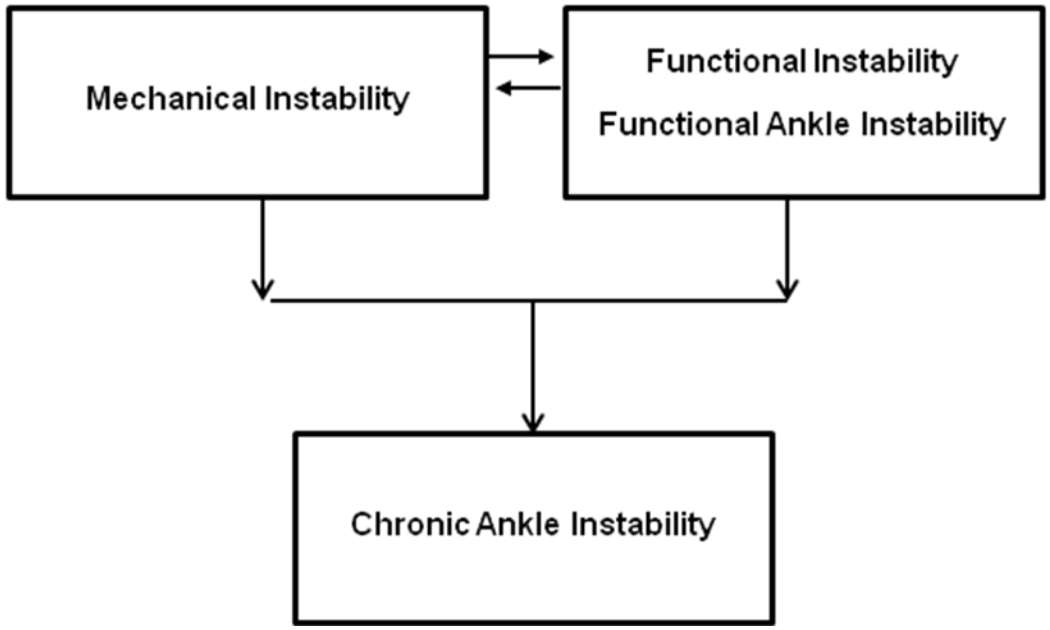

Figure 1. Relationship among ankle instability terms.

SUBJECT SELECTION AND DESCRIPTION

FAI Subject Criteria

As in all research, subject selection is very important. Perhaps due to lack of a standardized definition of precisely what FAI is (and is not), various sets of inclusion and exclusion criteria have been used. A recent meta-analysis of ankle instability and balance impairments by Arnold et al.[43] found highly variable inclusion and exclusion criteria among the 23 included articles. The most common inclusion criteria were history of at least 1 inversion ankle sprain and subsequent episodes of giving way.[43] Additionally, some authors required a specific severity of initial injury. For example Ross et al.[44] required a severe ankle sprain with at least 3 days of immobilization, but there is no consensus on what this severity should be. Some authors also required a specific frequency of sensations of giving way, e.g. at least twice in the past year,[40, 44] but these exclusion parameters are also far from universal.

Descriptive Questionnaires

Perhaps because FAI is a symptomatically defined pathology, several authors have used a defined range of scores on an ankle specific questionnaire as inclusion criteria.[61, 62] For example the Cumberland Ankle Instability Tool (CAIT)[63] and Ankle Joint Functional Assessment Tool (AJFAT)[58] both quantify ankle function, pain and stability, and utilize cutoff scores to indicate whether a person is likely to be functionally unstable or not.[63, 64] More common than their use as inclusion criterion, these instruments are used to describe subject characteristics within a given study.[40, 50, 65, 66] These instruments provide a quantitative description of items associated with FAI, such as the severity and frequency of symptoms, or functional impairment. Additional questionnaires commonly seen in the FAI literature include the Ankle Instability Index (AII),[67] Foot and Ankle Ability Measure (FAAM),[68, 69] and the FAAM's predecessor the Foot and Ankle Disability Index (FADI).[70] These scales can provide useful information regarding the severity of

FAI symptoms. They have been used to describe differences between healthy and FAI groups at a single point in time[40, 50] and to describe change pre- and post-intervention.[58, 71]

Choice of Comparison Subjects

Along with adequately defining and describing the FAI subject group, it is also important to consider the characteristics of the comparison group in research. Studies have typically compared FAI subjects with individuals who have never sprained or fractured either ankle.[40, 71, 72] Other inclusion and exclusion criteria have included absence of giving way, pain, instability in their ankles, and/or a history of surgery or fracture to either lower extremity.[44, 53] It is also common to see controls matched by gender, height, weight and injured side.[62, 73] Considering the inability of research to isolate the mechanisms behind the development of FAI despite decades of vigorous research, several researchers have recently questioned the appropriateness of the uninjured comparison group.[50, 74] Hertel and Kaminski[74] recommended that future study of ankle instability include both "copers" and "noncopers." They operationally defined "copers" as "those who suffer an initial sprain but no subsequent injuries" and "noncopers" as "those who suffer recurrent sprains and residual symptoms after initial sprain." Rather than compare individuals with FAI to individuals who have never sprained an ankle, it may be more useful to compare them to individuals who have experienced an ankle sprain but not gone on to develop instability. Differences between these two groups may provide insight into risk factors for the development of FAI,[50] and identify mechanisms by which copers maintain dynamic stability. A limited, but growing, number of ankle instability studies have divided subjects into groups based on these definitions of copers and noncopers.[36, 50, 75-78]

The classification of "copers versus noncopers" is borrowed from research in the anterior cruciate ligament (ACL) deficient population.[79-85] Although there are limitations in borrowing understanding from the ACL literature, due to the different nature of the joint and pathology, it still may be beneficial to review how the ACL literature defines a coper. Individuals are defined as ACL deficient "copers" when they are able to asymptomatically return to all pre-injury activities (including high level sports) without surgery following a confirmed ACL rupture.[79] Similarly, inclusion criteria for ankle sprain copers has required a history of a single ankle sprain (≥12 months prior), no complaints of giving way or instability, and no limitations during physical activity due to their ankle.[36, 50, 75-78] Additionally, Hubbard[36] required copers to have a perfect score on the FADI and FADI Sport functional scales. Other authors have reported similar measures of function or disability to support their subject grouping but not required specific scores.[50, 76]

One obvious difference between looking at copers following an ACL injury versus ankle sprain is that the implications of injury are not identical when it comes to the necessity of surgery, or time out of physical activity. In ACL ruptures, only a minority (~14%) of patients are able to cope with injury without requiring surgery. Whereas, following an ankle sprain the majority of individuals cope (approximately 1/3 fail to cope and develop FAI,[1-4] and only a small portion of these FAI individuals will seek surgical treatment[86]). Another noteable difference is that the ACL literature generally limits the subject population to ACL ruptures confirmed via magnetic resonance imaging (MRI), with a minimum of 3 mm side-to-side difference in laxity.[82] In contrast, because symptoms of ankle instability are not limited to those with grade 3 ruptures of the ankle ligaments, the ankle instability literature has typically studied a range of severities. Furthermore, FAI has been found in those both with and without confirmed laxity,[34, 46] and thus, laxity is only occasionally used as an inclusion/exclusion criterion.[49]

Despite these differences, concepts borrowed from the ACL literature on copers may provide a reasonable starting ground for ankle sprain coper research. For example, ACL coper research has successfully identified predictors of potential copers,[79-81] as well as electromyographical, kinetic and kinematic differences between copers and noncopers.[82-85] The ability to detect likely copers and noncopers following ankle sprain injury could enhance our ability to target treatment to those individuals at the highest risk of developing FAI. The screening evaluation for potential ACL copers consists of both functional tests and questionnaires such as the Knee Outcome Survey Activities of Daily Living score, the unilateral timed hop test, global rating of function, and reported episodes of giving way with daily activities.[79, 80] Interestingly, researchers developing this screening examination found that laxity was not predictive of coping ability.[79] Based on these findings in ACL copers, it seems advisable to include similar measures of function and disability in future attempts to identify potential ankle sprain copers.

Aside from prospective work predicting potential copers following ankle sprain injury, it may provide beneficial to include copers in traditional retrospective case-control designs. In these case-control studies differences have been found in a variety of measures between healthy controls and individuals with FAI. However, there is often difficulty interpreting the meaning of those differences. For example, if individuals with FAI have decreased postural control and decreased strength compared to healthy controls, are both variables contributing to instability? Or perhaps, only 1 of these two deficits truly contributes to instability and the other is a relatively benign change post-injury. If so, when a coper group is measured they should show no difference from controls on the variable contributing to instability, and no difference from the FAI group on the benign changes post-injury. Thus, research that compares individuals with

FAI, copers and healthy controls simultaneously may aid in the interpretation of research findings. To date, six studies have begun this work of comparing individuals with FAI to ankle sprain copers. [36, 50, 75-78]

Understanding of the four main areas of insufficiency associated with FAI—impaired proprioception, impaired neuromuscular control, strength deficits, and impaired postural control—may be illuminated by the addition of a coper group for comparison. This remainder of this review will serve to update the literature in each of these four insufficiencies and highlight areas in need of further research.

PROPRIOCEPTION

One of the factors research commonly links to FAI is impaired proprioception.[7, 32] Proprioceptors in the body include muscle spindles, golgi tendon organs and joint receptors.[87] These afferent proprioceptors contribute to position and movement senses.[87, 88] Proprioception at the ankle joint can be evaluated through measures of joint position sense and force sense.

Joint Position Sense

Joint position sense (JPS) describes an individual's ability to detect the position of his or her joint in space. JPS arises primarily from muscle spindles, which are arranged in parallel with muscle fibers and sense stretching.[87] Awareness of joint position is important for motor programming and for its contribution to muscle reflexes.[89] If an individual senses, for example, that his ankle is doriflexed and everted just prior to heel strike (HS), but it is actually plantarflexed and inverted, he will make ground contact with his ankle in a position susceptible to inversion injury.[90] If he senses correctly that his ankle is in this susceptible position, however, muscles activation can correct his ankle position. Using a cadaveric biomechanical model of the lower leg, Konradsen et al.[90] found that small angular error during the late swing phase of gait could result in inversion torque at the ankle, whereas much larger errors were required to produce an inversion torque at HS due to the compressive forces of weight bearing. This research showed quantitatively how positioning error could directly contribute to destabilizing joint torques.

Evidence for JPS deficits in individuals with FAI compared to healthy controls has often been conflicting.[62, 66, 91, 92] However, a recent meta-analysis by Munn et al.[59] found significantly increased angular error in subjects with FAI for both active JPS (Mean deficit = 0.6°, 95% CI: 0.2-1.0°) and passive JPS (Mean deficit = 0.7°, 95% CI: 0.2-1.2°). This meta-analysis combined results across direction (e.g. inversion, eversion, etc.) and angle (e.g. 5°) of JPS testing. Also, the same study reported differences between limbs in individuals with unilateral FAI (Mean deficit= 0.5°, 95% CI: 0.3-0.7°). Individuals with FAI not only have deficits when compared to healthy controls, but their injured side has JPS deficits when compared to their uninjured side. Side-to-side differences indicate that peripheral adaptations—as opposed to centrally mediated motor control adaptations—are the active component in JPS deficits in individuals with FAI. This is in contrast to postural control deficits, which have been found bilaterally in individuals with FAI and indicate the presence of central adaptations.[71, 93]

Force Sense

Force sense describes an individual's ability to detect muscular force. Eversion force sense is typically measured by having a subject evert his ankle against a load cell using a specific amount of force twice in succession.[65, 66, 94] For the first eversion (i.e. the target) the subject is given visual feedback regarding the accuracy of his force production. During the second eversion the subject is asked to recreate the precise force of the target load without any feedback. The difference between the target and reproduction forces is calculated, and is called the trial error. Docherty and Arnold[94] hypothesized that an impaired ability to accurately detect ankle eversion force—either the effort needed or the actual tension developed—may contribute to instability. Peripherally, force sense arises primarily from the golgi tendon organs located within muscle tissue.[87] Golgi tendon organs are aligned in series with muscle fibers and sense tension whereas muscle spindles, which also play a role, sense length. Eccentric exercise induced damage to these structures causes force sense impairment.[95] Lateral ankle sprains constitute the majority (80%) of all ankle sprains,[3] and concurrent peroneal muscle strain is present in 15% of lateral ankle sprains.[96] This damage is hypothesized to occur as a result of over-stretching during excessive inversion, or as a result of a strong reflexive peroneal muscle contraction following inversion.[97]

Several studies have shown eversion force sense deficits in individuals with FAI, [65, 66, 94] although these findings have not been consistent.[98, 99] Methodological differences may explain the conflicting reports. Specifically, studies which found deficits used lower testing loads than studies which did not detect deficits. A systematic review conducted by Wright and Arnold[100] found that although only a couple of the outcome measures in the 6 included studies reached significance, there were consistent trends toward increased ipsilateral variable error in the injured group. It could be that these studies were underpowered, with too few subjects to detect deficits given the observed effects sizes. Increased variable error indicates that the performance of injured subjects was less precise. At any one point in time an individual with FAI might produce either more or less force than he intends to produce. These miscalculations may explain decreased feelings of stability noted by individuals with FAI. The variability of these errors fits with the sporadic nature of symptoms of giving way at the ankle reported by individuals with FAI.[66] At times, force sense may be adequate to prevent feelings of instability, but the increased variability means that the force sense error may occasionally be great enough to contribute to an episode of giving way of the ankle.

NEUROMUSCULAR CONTROL

In a recent review of the sensorimotor system from a joint stability perspective, Riemann and Lephart[101] defined neuromuscular control as "the unconscious activation of dynamic restraints occurring in preparation for and in response to joint motion and loading for the purpose of maintaining and restoring functional joint stability." This means that neuromuscular control is the interaction between multiple levels of the nervous and muscular systems, working together both to produce desired motion and stop undesired motion. Researchers have hypothesized that impaired neuromuscular control such as delayed reflexes, altered muscle activation patterns or altered feed-forward motor control contribute to the instability noted in individuals with FAI.[102, 103]

Fibularis (Peroneal) Reflexes

The classic mechanism of injury for a lateral ankle sprain is a sudden inversion due to an unexpected perturbation such as landing on an uneven surface.[28] Since the ankle's primary dynamic stabilizers against inversion are the peroneal muscles,[104] several investigators have hypothesized that the mechanism behind FAI is a delayed peroneal reflex. According to this hypothesis, individuals with FAI experience instability because their peroneal muscles activate more slowly than in healthy individuals, and are thus recruited too late to counter the sudden inversion. Although some may attribute impaired peroneal reaction time solely to impaired proprioception around the ankle, the literature does not support this as a singular cause.[105, 106] Specifically, impairing proprioception by injecting lidocaine into the anterior talofibular and calcaneofibular ligaments resulted in no significant differences in peroneal reflex latency or time to maximum amplitude while walking and experiencing an unexpected inversion,[106] indicating that articular deafferentiation is not entirely to blame for differences in peroneal reflexes noted between FAI and healthy ankles. Although anesthetic injection (simulating deafferentiation) had no effect on reflexes, it is interesting to note that anesthetic injection has been shown to decrease postural control.[107]

Researchers have utilized electromyographic (EMG) analysis of muscle response times to unexpected joint perturbation to evaluate the role of reflexes. Research regarding peroneal muscle latency response in indivduals with FAI have had mixed results.[51, 108-113] A review by Delahunt[114] found the evidence inconclusive to either accept or reject the hypothesis that individuals with FAI have delayed peroneal response to unexpected ankle inversion. Delahunt[114] observed that inconsistent results may be due to heterogeneity in subject inclusion criteria as well as research methods (degree of inversion, control of visual and auditory feedback, etc.). Interestingly, in one instance conflicting results were published a year apart by the same research group using virtually identical methods.[111, 112] The authors of these studies offered little explanation of the conflicting results. A recent meta-analysis by Munn et al.[59] reviewed 11 studies of peroneal muscle reaction time to inversion perturbation in individuals with and without FAI and found no significant difference (Mean difference = 7.8ms, 95% CI = -1.4 to 17.1).

One problem with citing delayed peroneal reflexes as a potential cause of FAI, is that the time required for peroneal activation and force development is too long to effectively counteract unexpected inversion forces detected via a feedback loop.[91] For example, while standing on an inverting platform it takes approximately 100 milliseconds (ms) for a healthy ankle to invert to the point of injury, however, it takes between 126-176 ms to generate contractile force to resist inversion, i.e. too long to prevent injury.[97] Hopkins et al.[115] did report that the time it took to fully invert during a walking trial over a suddenly inverting platform was longer and peroneal reflex latencies shorter than when compared to the typical static standing protocol. This may mean that the peroneal muscles have a greater ability to counteract a sudden inversion during activity than previously thought. Using this more functional walking setup, Hopkins et al.[51] did find significantly delayed peroneal response in individuals with FAI. Interestingly the time from onset of inversion to peroneal force generation was still approximately 25 ms longer than the time to maximal inversion, still too slow to prevent injury. However, the standard deviation of measures used to calculate this difference ranged from 15-30 ms, which means for at least some individuals with FAI the peroneal force production delay was approximately the same or less than the time to maximal inversion. Future research should determine whether these differences consistently manifest themselves during functional activities.

Muscle Activation Patterns

Not only does activation of a single muscle group like the peroneals affect joint stability, but the sequence and timing of activation of multiple muscles contributes as well. Van Deun et al.[116] found that muscle activation patterns during the transition from double leg stance to single leg stance differed between subjects with CAI and healthy controls. Testing subjects under two conditions—eyes open and eyes closed—the authors ranked the relative order of muscle recruitment for each subject and classified subjects as first recruiting hip, knee or ankle muscles. They reported that control subjects were more likely than CAI subjects to adapt their muscle recruitment strategy when changing from the easier (eyes open) to harder (eyes closed) task. CAI subjects tended to use the same strategy regardless of the task, and this lack of flexibility in motor program may contribute to instability.[116] Also, in the CAI group the ankle muscles were recruited last in all trials. This indicates reliance on a "hip strategy" of balance,[117] and similar findings have been reported by Beckman and Buchanan.[118] A hip strategy is generally used to make major postural adjustments, whereas ankle strategy is used for fine tuning.[117, 119] In light of this, the use of a hip strategy in individuals with FAI may actually be a cause of poorer balance performance—since the hip strategy causes more gross movement. However, it is unknown whether the use of the hip strategy precipitated injury, or whether it is a strategy switch post-injury to accommodate for other deficits. Horak et al.[119] found that healthy individuals would switch from ankle strategy to a hip strategy under conditions of somatosensory loss. Since individuals with FAI are thought to have somatosensory losses, this may explain why they are more likely to rely on this strategy regardless of condition.

Feedback vs. Feedforward Motor Control

Motor control is a plastic process, undergoing constant revision and modification based on afferent sensory input, efferent motor commands and the resulting movements.[120] As it relates to joint stability, motor control is complex, involving multiple sensory organs and processing levels.[101, 120] Motor control in individuals with FAI may be altered as a result of injury and/or to compensate for decreased post-injury joint stability.[38, 53, 93, 121] Two types of motor control are of particular interest in the FAI population, feedforward and feedback.

Feedforward motor control refers to anticipatory actions or motor programs, whereas feedback control is characterized by corrective responses based on sensory input.[101] Feedback control is therefore highly dependant on proprioceptors and proprioceptive impairments. The peroneal reflex loop is one example of feedback control. Van Deun et al.[116] reported the EMG latency for several thigh, shank and ankle muscle groups during a task transitioning from double limb to single limb stance. Healthy controls actually activated their muscles prior to onset of lateral movement of their center of mass, whereas individuals with CAI activated their muscles after onset of movement.[116] This indicates that the controls were relying on preparatory feedforward motor control, whereas the CAI group relied on reactive feedback control. A similar pattern of reactive versus preparatory control has also been reported by Bullock-Saxton et al. [122] As demonstrated in the preceding section on peroneal reflexes, the time required for a feedback loop limits the ability of feedback control to maintain joint stability. Because of these limitations, recent authors have hypothesized that effective dynamic control of ankle stability relies primarily on feedforward neuromuscular control.[38, 53, 121] A feed-forward program that increases peroneal activation prior to HS, for example, could be a compensatory joint protective strategy, working by increasing eversion force and decreasing the amount of inversion allowed.

Several studies comparing individuals with and without FAI have reported altered EMG activity and/or joint kinematics within the 200 ms window pre- and post-initial contact (IC) during tasks such as jump landing and gait.[38, 53, 121] The short duration of these windows limits the effect of feedback control, and indicates that changes seen during these times are the result of feedforward motor control. Delahunt et al.,[121] for example, reported significantly increased peroneus longus firing during gait in the 40 ms window following HS in subjects with FAI when compared with controls. Since the mean peroneus longus short loop latency is approximately 41 ms,[123] activation prior to that time period indicates the presence of altered feedforward neuromuscular control in subjects with FAI. While these results seem to indicate differences in feedforward control, they are not undisputed. Brown et al.[62] found no difference in muscle activation at 200 ms before jump landing in the tibialis anterior, peroneals, lateral gastrocnemius and soleus muscles. Additionally, the statistical methods used by Delahunt, Caulfield and colleagues[37, 53, 72, 121] include multiple (8-20) t-tests with no reported correction to limit the type I error rate. Their results should be interpreted in light of this increased chance of rejecting a true null hypothesis, in other words, finding a difference when no true differences exist.

The evidence seems to favor alterations in feedforward motor control as an explanation for differences in neuromuscular control between individuals with FAI and healthy controls. It remains unknown, however, whether these changes are factors predisposing to the development of, alternatively, a post-injury adaptation. If they are an adaptation, they may be either positive (stabilizing) or negative (destabilizing). Comparing individuals with FAI to ankle sprain copers may help answer questions regarding the role of motor control. Wikstrom et al.[77, 78] have started answering questions of whether certain postural control adaptations may be stabilizing or destabilizing in recent work on postural stability in copers, noncopers and healthy subjects.

STRENGTH

Strength is a complicated attribute to assess. Researchers must make several methodological choices for every strength assessment: the type of dynamometer, the contraction type (e.g., isometric, concentric or eccentric), the movement direction, and with isokinetic testing the test speed. Psychological variables such as participant motivation to give their maximal effort may also affect results. Several decisions at the analysis stage can also influence results, including whether comparison is made to an external control or to a contralateral uninjured limb, as well as, how the data is normalized. Considering the many different methods to assess and report strength data, it is no wonder that studies yield conflicting results regarding strength deficits in individuals with FAI.

One of the most common hypotheses linking strength to FAI is that individuals with FAI have decreased evertor strength, and that episodes of giving way are directly attributable this weakness. While one study reported eversion strength deficits,[39] several others have found trends towards deficits but no significant differences.[41, 124, 125] A recent meta-analysis by Arnold et al.,[42] however, found that ankles with FAI had significantly decreased concentric eversion strength compared to stable ankles (Standard Difference Means= 0.224, 95% CI: 0.115-0.333). While significant, this difference is small, equivalent to a 1.26 Nm difference between stable and unstable ankles.[42] Nevertheless, the authors point out that 1.26 Nm acting on the short peroneal moment arm translates to approximately 59 N or 13 lbs, which may represent a meaningful weakness.[42] Although potentially meaningful, strength differences of this magnitude are difficult to detect. For example, to have 80% power to detect an effect of this magnitude (0.224) with alpha set at 0.05, 313 participants would be needed per group.[42] This sample size would be prohibitive for most studies.

While eversion deficits may seem the most intuitively likely, deficits in inversion, plantarflexion or dorsiflexion could also contribute to ankle joint instability. Both concentric and eccentric plantarflexion deficits have been reported between FAI and stable groups.[40, 41] Between injured and uninjured ankles Sekir et al.[125] found concentric inversion peak torque deficits. Strength ratios may also be important in explaining FAI. Hubbard et al.[40] assessed the peak torque and average power for all four main ankle joint movements individually, and as a ratio between movements in the same plane. Interestingly, while none of the individual motions captured significant group differences, they found significant group differences in the plantarflexion-to-dorsiflexion peak torque and eversion-to-inversion peak torque. This may indicate that proper strength ratios are more essential to joint stability, than strength in any one direction.

As noted in a recent review by Holmes and Delahunt,[103] strength training is still typically considered an essential part of ankle sprain rehabilitation despite the fact that research has failed to consistently indicate strength deficits in individuals with FAI. Although some evidence exists for increased strength following training,[55, 125] other research reports no strength differences following training.[52] Importantly, strength improvements have not been definitively linked to reduction of FAI symptoms.[55, 125] Thus, although small but significant deficits in strength are evident in individuals with FAI, the role of strength in instability—and specifically the role of strength training in the prevention of instability—are still unclear.

POSTURAL CONTROL

The goal of postural control is to keep the center of mass of an individual within his or her base of support, in order to maintain balance.[126] To do this, postural control strategies must rely on sensory input (e.g. somatosensory, visual and vestibular) and constantly adapt muscle recruitment to compensate for changes in the location of the center of mass. Some speculate, therefore, that postural deficits in individuals with FAI are mostly likely secondary to some combination of impaired neuromuscular control and proprioception.[32, 103]

Researchers have used a number of methods to assess postural control in individuals with FAI.[43] Balance measures in the FAI literature are generally classified as either static or dynamic. Collapsing data across several different types of static and dynamic outcome measures, two recent meta-analyses on postural control both report that FAI is, indeed, associated with impaired balance.[43, 59] Specifically, the meta-analysis by Arnold et al.[43] reported an overall standard difference in means of 0.455 (95% CI = 0.334-0.577), showing a fairly strong group effect. It appears clear that individuals with FAI suffer impaired postural control. Significant differences between outcome measures also make evident that certain outcome measures more efficiently capture these differences.[43]

Static Measures

Static measures assess postural control during quiet standing, in either dual or single limb stance. Visual sensory input is often controlled by having test subjects balance with their eyes closed. Outcome variables during a static balance trial can include linear (e.g. Center of Pressure [COP] excursion), temporal (e.g. time to boundary), area based (e.g. COP area), velocity based (e.g. COP velocity, or medial/lateral sway velocity), or error based (e.g. the number of errors during a trial) measurements. In the meta-analysis by Arnold et al.,[43] the greatest between group differences were found by Hiller et al.,[127] who reported the number of foot lifts during 30sec of single leg stance with eyes closed. Temporal measures also produced relatively large standard difference in means, while measures of area failed to show significant differences between groups.[43] During a common task of quiet standing, this demonstrates how studies that only calculated area measures may have concluded that no intergroup differences were present, whereas studies that included temporal and error based measures would have concluded that intergroup differences were present.

Dynamic Measures

Dynamic measures typically require that a subject stabilize themselves either during or after movement. The two dynamic measures commonly seen in FAI literature are time to stabilization[44, 64] and the Star Excursion Balance Test (SEBT).[71, 128] Time to stabilization is typically the time required after landing from a jump for the anterior/posterior or medial/lateral ground reaction forces (GRF) to return to the same magnitude recorded for normal quiet standing. The SEBT requires a subject to balance on his unstable leg while reaching as far as possible in 1 of 8 reach directions with his opposite leg. The outcome of interest for the SEBT is reach distance, typically normalized to leg length. Between the two, Arnold et al.[43] found that time to stabilization captured greater deficits in the FAI population.

Although Arnold et al.[43] reported a trend toward static measures capturing greater intergroup differences than dynamic measures, dynamic measures capture a more functional situation. Since the mechanism of ankle injury is often running, cutting or landing from a jump,[129, 130] dynamic measures more closely imitate this situation than static measures of quiet single leg stance.

Clinical versus Laboratory Measures

In addition to debate about the relative value of static or dynamic measures, another debate pits clinical against laboratory measures. Clinical measures are those measures that can be done by healthcare practitioners with minimal equipment and limited time and training. Laboratory measures (such as COP velocity) require instrumented force plates and specialized software and training for data processing. Differences between healthy individuals and those with FAI have been found using both clinical and laboratory measures. A recent review of balance impairments in FAI provides a more thorough comparison of these measures.[43]

Interestingly, studies have noted bilateral deficits in postural control following unilateral ankle sprain.[71, 93] This indicates a central impairment in postural control in individuals with FAI, since the non-injured side as well as the injured side is affected. It is also important that postural control deficits in individuals with FAI can be successfully treated with rehabilitation.[58, 71] Not only did Hale et al.[71] find that SEBT reach distance increase with 4 weeks of rehabilitation, but rehabilitation participants also improved their Foot and Ankle Disability Index score by 7-11 points. The authors did not statistically test for correlation between the Foot and Ankle Disability Index and SEBT reach distance improvements, nor did they assess for other potential confounding variables such as increased strength or flexibility, but their findings may indicate a relationship between increased postural control and increased self-reported function.

To date, only 2 articles have compared postural control between noncopers, copers and healthy controls.[77, 78] Using a jump landing task, Wikstrom et al.[78] calculated several stability indices, developed previously by Wikstrom et al.,[131] including the anterior/posterior stability index (APSI), medial/lateral stability index (MLSI) and dynamic postural stability index (DPSI). They found that noncopers were significantly different from copers and controls for both the APSI and DPSI. For the MLSI, copers were significantly different from controls and noncopers, although there was no difference between noncopers and controls. The authors speculate that their results may indicate that copers have adopted a compensation strategy against ankle instability that affects their medial/lateral GRF. Also, since anterior/posterior stability was similarly diminished in both copers and noncopers, the authors speculated that those changes were the result of the initial ankle sprain rather than mechanisms related to stability. Another study by Wikstrom et al.[77] found that COP velocity and COP-center of mass moment arm was increased in individuals with CAI compared to copers. Future studies should confirm and expand this line of research.

JOINT BIOMECHANICS

Another significant line of research related to FAI has been biomechanics of the ankle, knee and hip joints in subjects with and without FAI. Joint kinematics and kinetics demonstrate the strategies that individuals attempt to maintain dynamic joint stability during functional activity.[132] They are composite variables, generated by a dynamic synthesis of several mechanisms that have independently proven significant for understanding ankle joint pathology.

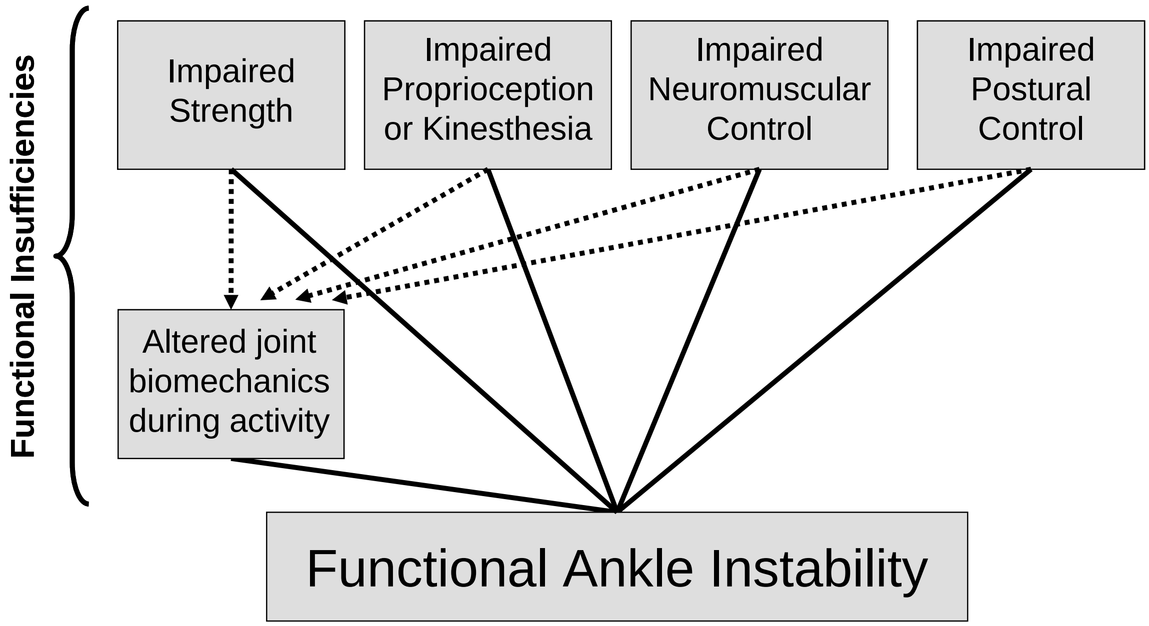

Figure 2. Relationship of functional ankle instability to functional insufficiencies. Solid lines represent established associations, dotted lines represent proposed pathway.

For example, ankle joint frontal plane position can be influenced by strength, proprioception, neuromuscular control and postural control (Figure 2). While a study of any one of these factors in isolation may neglect the influence of the others, joint kinematics and kinetics demonstrate the collective influence during situations where instability might occur. As such they may provide insight into the biomechanical mechanism of FAI, which could then be targeted in rehabilitation. Differences in joint motion and joint forces may elucidate how an individual with FAI either copes or fails to cope with pathology to dynamically stabilize their ankle during activity.[72]

Kinematics

Gait

One common hypothesis is that individuals with FAI make floor contact during gait with greater inversion than individuals with stable ankles. Delahunt et al.[121] demonstrated that FAI subjects had significantly increased ankle joint inversion during gait at 50 ms before HS, at HS, and 50 ms after HS. They found no group differences for hip or knee joint angles at the same time periods, but did find a decreased vertical foot-floor clearance during the terminal swing phase. Similarly, Monaghan et al.[72] found significant increases in inversion angle during walking gait from 100 ms pre-HS to 200 ms post-HS in individuals with CAI by comparison with controls, and altered frontal plane velocity at HS and after HS. They found no significant differences in knee or hip kinematics in the three anatomical planes, nor the ankle joint in the sagittal or transverse planes. These researchers appear to be finding the same thing, but at different time intervals. This lack of consistency detracts from the strength added by multiple reports. Drewes et al.[133] reported that during jogging, individuals with CAI were significantly less dorsiflexed than controls from 9% to 25% of the gait cycle. The authors commented that a loss of dorsiflexion prevents the ankle from obtaining a stable, closed-packed position. Therefore, the observed differences may account for instability in the CAI group.

By contrast, Brown et al.[50] found no differences during walking or jogging gait between a MI, FI and coper group for ankle joint inversion at HS or for the maximum inversion angle during stance. They defined FI as instability in the absence of clinical laxity, MI as instability with laxity, and copers as individuals who had suffered an ankle sprain but experienced no subsequent instability. Both MI and FI groups had more overall ankle frontal plane displacement than a coper group, but there were no significant differences for any other variables in the ankle sagittal plane, nor knee sagittal or frontal plane. The potential for comparisons among these studies is limited since Brown et al.[50] included a coper group but no traditional control group. Overall, there appears to be no evidence to support proximal joint kinematics changes during gait, and limited evidence supporting ankle joint frontal plane alteration.

Jump Landing

Landing from a jump is a common mechanism of ankle inversion injury.[28] Several researchers have studied biomechanics during a jump landing task. Caulfield and Garrett[37] recorded sagittal plane ankle and knee motion during landing from a single leg jump. They found that individuals with FAI had significantly increased dorsiflexion from 10 ms pre-IC to 20 ms post-IC, and increased knee joint flexion from 20 ms pre-IC to 60 ms post-IC. There were no significant differences between groups in the timing of initiation of movement prior to IC. Gribble and Robinson,[134] who also limited their analysis to the sagittal plane, found decreased knee flexion in individuals with FAI compared to controls at IC. They found no differences for hip flexion or ankle plantarflexion. Delahunt et al.[53] evaluated a single leg drop jump using methods similar to those of Caulfield and Garrett,[37] but this time recorded kinematics in all 3 planes. They reported significantly increased ankle joint inversion (200-95 ms pre-IC), decreased ankle joint dorsiflexion (90-200 ms post-IC), decreased hip joint external rotation

(200-55 ms pre-IC) and decreased ankle joint sagittal plane angular velocity (50-125 ms post-IC) for the FAI group.

In contrast to the previously mentioned jump landing studies, Brown et al.[50] found no differences between FI and coper groups for sagittal or frontal plane ankle and knee joint kinematics during drop jump landing. There were, however, significant differences between MI and coper groups. Using a similar landing task but different type of analysis de Noronha et al.[135] also found no correlation between CAIT scores and the ratio of movement in the frontal plane at the hip and ankle joint.

Kinematic Summary and Modeling Limitations

In summary, the research literature is divided regarding whether or not true kinematic alterations exist in individuals with FAI during jump landing. Unlike gait, proximal joint alterations have been found during jump landing, which may reflect the increased difficulty of the task. These studies show a trend (not always significant) toward increased ankle joint frontal plane inversion during gait and jump landing. Evidence for (or against) alterations in proximal joints and the ankle sagittal plane, however, is not conclusive.

One research design flaw that limits interpretation of all these findings is deficiency in the reporting of the kinematic model used, including marker placement and mathematical modeling assumptions. Of 9 studies reporting kinematic differences between individuals with and without FAI,[37, 50, 53, 72, 121, 133-136] only one study[133] reported or referenced the repeatability of the model used. Five studies partially or fully described modeling assumptions;[50, 133-136] the four remaining studies, however, provided anatomical landmarks but no mathematical modeling information whatsoever.[37, 53, 72, 121] Especially since the angular differences reported in studies between FAI and healthy subjects tends to be small,[37, 121] the interpretation of results reported in the current literature is difficult without adequate information about the repeatability and precision of biomechanical modeling. Error may either obscure true group differences or create spurious differences if an accurate and precise model is not used.

Finally, only one of the available studies used a multi-segment foot model.[133] The others used a one segment foot model. This type of model assumes that the foot is a single rigid segment, despite the numerous articulations within the foot and ankle complex. By definition a single segment foot model cannot capture differences in hindfoot and forefoot motion that can be reliably captured with a multi-segment model such as the Oxford foot model[137, 138] used by Drewes et al.[133] Because hindfoot, forefoot and hallux motion are not identical during activity,[137] a model capable to capture these individual movements may be essential in accurately representing motion in individuals with FAI. Simpler models may have obscured differences by pooling hindfoot and forefoot motion into a single composite value.

Kinetics

Kinetic variables include GRFs (e.g. peak anterior/posterior GRF) and the timing of such forces (e.g. time to peak lateral GRF), as well as joint moments and powers. Kinetics is information about the forces and torques that cause motion or result from motion. This information is valuable because the inability to produce or withstand joint torques associated with activity may lead to instability and injury.[139] While several studies have evaluated the magnitude or timing of GRFs in individuals with FAI,[50, 53, 140] less information is available about ankle joint moments and powers.[72] While GRF data provides a view of the cumulative forces resulting from an activity, joint specific kinetics are helpful since they provide a picture of force distribution at each joint. Both types of measures may provide meaningful information about forces experienced during activity.

Comparisons of GRF between individuals with FAI and controls and/or copers have led to some conflicting results. Delahunt et al.[53] found significantly decreased time to peak vertical force and posterior force following drop landing in FAI individuals compared to stable controls. Other research by the same team found the opposite—no differences in timing of vertical and posterior forces, but instead significantly decreased time to peak lateral and anterior forces.[140] Both Caulfield and Garrett[140] and Delahunt et al.[53] reported group averaged GRF during the 150 ms following IC. Both studies also found increased posterior forces and increased vertical forces during part of this period. Brown et al.,[50] however, found no difference in peak or time to peak ground reaction forces in any direction during gait or drop jump landing between their 3 groups. Differences may have been apparent if they had included a healthy control group. Overall, there is little conclusive evidence either for or against significant group differences in GRF during gait or jump landing.

Other measures of kinetics that show promise for detecting group differences and possibly explaining the mechanism of FAI are measures of joint moments and powers calculated using the principles of inverse dynamics. For example, Monaghan et al.[72] reported that individuals with CAI had an ankle eversion moment and concentric power following HS in gait, whereas controls had an inversion moment and eccentric power. The authors speculate that the opposite forces are a result of completely different joint stress patterns occurring between the stable and unstable groups. Alterations in joint stresses can lead to degenerative changes associated with osteoarthritis and may be linked to instability.[29] It is unknown whether these opposing patterns are a positive or negative adaptation following ankle sprain and subsequent instability. Due to limited literature regarding joint kinetics in individuals with FAI it is again helpful to look at the ACL literature. Rudolph et al.[85] have reported altered knee joint kinetics in

ACL-deficient copers and noncopers during walking gait. They noted that group and limb differences were most apparent during the weight acceptance phase, where copers (but not noncopers) decreased stress on their involved limb by decreasing power absorptions. In a later study they also noted differences in the support moment between healthy, ACL coper and ACL noncoper groups.[132] Support moments and joint powers have yet to be studied extensively in the FAI population. More research in this area is needed.

CONCLUSIONS

Characterized by symptoms of giving way and recurrent ankle sprains, FAI is a complex pathology affecting approximately 32%[1-4] of individuals who suffer an acute lateral ankle sprain. FAI has been attributed to four main insufficiencies: impaired proprioception, impaired neuromuscular control, impaired postural control and strength deficits. Additionally, study of joint kinematics and kinetics during movement captures the complex interaction of these factors during a functional task. Despite the observation of insufficiencies in each of these areas, research has isolated no precise mechanism behind the development of FAI. Further research is needed in several areas to clarify inconsistent or incomplete findings. Specifically, the addition of “copers” as a comparison group may help elucidate which differences between individuals with FAI and healthy control are meaningful and should be targeted in prevention and treatment programs.

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CHAPTER THREE: METHODS

Subjects

We included 23 subjects with Functional Ankle Instability (FAI; M±SD, age=23.30±3.84years; height=1.71±0.11m, weight=68.66±14.60kg; Cumberland Ankle Instability Tool [CAIT]=20.52±2.94, episodes of giving-way=5.81±8.42 per month), 23 subjects with a history of an ankle sprain but no instability (Copers; age=23.52±3.68years, height=1.72±0.07m, weight=69.57±13.94kg; CAIT: 27.74 ± 1.69), and 23 subjects with no history of ankle sprain or instability (Controls; age=23.17±4.01years, height=1.72±0.08m, weight=68.78± 13.26kg, CAIT: 28.78±1.78) in this study. Each group had 12 males and 11 females. This study was approved by the Virginia Commonwealth University Institutional Review Board.

Originally, we recruited and initially screened 83 subjects for participation from a large metropolitan area for participation. These subjects reported for a single visit to the Sports Medicine Research Laboratory. After obtaining informed consent, the subject completed an injury history questionnaire and the CAIT to verify inclusion criteria. A customized computer program (Access, Microsoft, Redmond, WA) recorded and scored subject responses for the CAIT. The CAIT has excellent test-retest reliability ($ICC_{2,1}$ = 0.96), and is scored from 0-30 points with higher scores indicating higher stability and better function.[1] The injury history form collected information about the initial ankle sprain injury, symptoms of giving way and re-sprains, as well as history of lower extremity fractures or surgeries, and limb dominance. If the severity of the FAI or coper subject's initial ankle sprain was evaluated and graded by a medical professional, we asked the subject to report the severity of injury. Options presented were Mild (or Grade 1), Moderate (or Grade 2), Severe (or Grade 3), or unknown (subject could not remember). Subjects whose sprain was not evaluated by a medical professional were also marked as unknown severity. Limb dominance was assessed by asking the individual to self-report his or her dominant or preferred limb for activities such as kicking a soccer ball. We measured subject height using a Seca mechanical column scale (Hanover, Maryland). To record weight, the subject stood quietly on a force plate (Bertec, Columbus, Ohio, USA) and we calculated the vertical component of the ground reaction forces.

After reviewing the injury history questionnaire and CAIT scores, 8 participants were excluded for not meeting all study criteria. Another subject was excluded after enrollment because they were unable to follow task instructions. Lastly, 5 subjects could not be matched. We matched copers and healthy controls to FAI subjects by gender, age (±10 years), height (±10cm), and weight (±15kg). This left a final total of 69 matched subjects (23 per group). Based on pilot data we calculated a minimum of 17 subjects per group were necessary to detect group differences in our targeted variables. However since this is lower than the normal sample size in similar literature[2-4] we decided a priori to recruit a minimum of 21 subjects per group. Our final sample size exceeded this minimum by 2 subjects per group.

FAI and coper subjects were required to have a history of an inversion ankle sprain which required protected weight bearing, immobilization, and/or limited activity for ≥24 hours. Additionally, FAI subjects had to report multiple episodes of giving way (at least 2 in the past year),[2] and had to be classified as having FAI using a cutoff score of ≤27 on the Cumberland Ankle Instability Tool (CAIT; Appendix E).[1] Copers had no complaints of ankle instability or repeated episodes of giving way, and had resumed all pre-injury activities without limitation for at least 12 months prior to testing.[2, 5] Similar to previous research,[6, 7] if all other inclusion criteria were met, copers were allowed a single episode of giving-way in their lifetime as long as it occurred at least 12 months prior to study participation. Control subjects had no history of ankle sprain or instability in their lifetime. Additionally, all subjects were required to participate in 1.5 or more hours of moderate to vigorous physical activity per week for inclusion.[2, 5] Subjects self-reported their weekly activity level and intensity using a simple recall. Additionally, potential subjects were excluded if they had a history of surgery or ankle fracture in either lower extremity, any acute symptoms of lower extremity injury on the day of testing, or known systemic disease or condition affecting the musculoskeletal system.[8]

Testing was performed on the involved limb (side of ankle sprain) of the FAI and coper groups, and the matched side of the healthy control group. For FAI individuals with bilateral instability, the subject was asked to subjectively identify their most unstable ankle, and that side was designated as the involved limb. Additionally, each group had equal numbers of left and right limb dominance individuals (2 left, 21 right).

Descriptive Questionnaires

In addition to the CAIT, the subject also filled out the Foot and Ankle Ability Measure (FAAM; Appendix F) to quantify functional limitations. The FAAM has 2 parts, the activities of daily living (ADL) subscale with 21 items and the sports subscale with 8 items, and is scored as a percentage. The reliability for both the ADL and sports subscales is good (ADL $ICC_{2,1} = 0.89$; Sport $ICC_{2,1} = 0.87$).[9] The FAAM (or its predecessor, the Foot and Ankle Disability Instrument) has been used in other ankle instability research including copers, noncopers and healthy controls.[2, 5, 10] A customized computer program (Access, Microsoft, Redmond, WA) recorded and scored subject responses for the FAAM.

Clinical Exam

A single examiner certified in athletic training for 6 years (CJW) performed a clinical exam on the involved limb of each subject. The purpose of this exam was to assess clinical ankle joint laxity, pain on palpation of the lateral ligaments and pain with passive end range of motion (ROM). The examiner was not blinded to subject group.

First, the examiner palpated the anterior talofibular ligament, calcaneofibular ligament and posterior talofibular ligament, and recorded any pain on palpation of these ligaments. Next the examiner passively moved the ankle joint through full ROM in plantarflexion, dorsiflexion, inversion and eversion, and gave firm pressure at end ROM in each direction. Presence or absence of pain at end ROM in each direction was recorded. Lastly, the examiner assessed clinical ankle joint laxity using the anterior drawer test and talar tilt test, performed according to the methods of Ryan et al.[11] In brief, the examiner performed the talar tilt test with the ankle starting in slight plantarflexion, by applying an inversion force to the calcaneus, and observing gapping at the lateral malleolus. The examiner performed the anterior drawer test with the knee flexed and ankle in neutral position, by applying an anterior force to the calcaneus, and palpating anterior displacement. Grading for both tests was on a scale of 1-5, with 1=very hypomobile, 2=slightly to moderately hypomible, 3=normal, 4=slightly to moderately hypermobile and 5=very hypermobile.[11] Good reliability for these tests has been reported using these methods ($ICC_{2,1}$ >0.80, standard error of the measure <0.25).[2]

Motion Capture Preparation

The examiner attached 5 rigid plastic plates of markers to the subject using tape prewrap, and 34 individual 9.5mm reflective markers using double sided adhesive tape at specific anatomical landmarks. Markers placement was according to the Oxford foot model with additional conventional gait model markers on the knee, hip and pelvis.[12, 13] Marker plates were attached to the posterior pelvis at the height of the posterior superior iliac spine, and bilaterally on the distal thigh and shank. Anatomical markers were placed bilaterally on the greater trochanter, anterior superior iliac spine, lateral and medial femoral epicondyles, lateral and medial malleoli, proximal and distal 5th metatarsal, distal second metatarsal, proximal and distal 1st metatarsal, and the lateral, medial and posterior calcaneus.

The subject stood in the capture volume in anatomical position as the a static calibration trial was captured. Following the static trial, we removed the calibration only markers from the subject (i.e. bilateral greater trochanter, lateral and medial femoral epicondlyes, medial malleolus, and the posterior superior calcaneus). For all movement trials, a 12-camera Vicon MX motion monitoring system (Oxford Metrics Group, Oxford, UK) collected the three-dimensional location of reflective markers at 100 Hz, and two Bertec 4060-NC strain-gauge force plates (Columbus, Ohio, USA) captured ground reaction forces at 1000 Hz. Vicon Nexus 1.4 software (Oxford Metrics Group, Oxford, UK) synchronized all data collection.

Range of Motion

The examiner recorded the subject's active ROM for the involved limb. For these movements, the subject sat in a chair with his or her knee flexed to approximately 30-45° for plantarflexion and dorsiflexion ROM movements, and knee flexed to 75-90° and ankle in 0-10° of plantarflexion for inversion and eversion ROM movements. The examiner verified subject positioning and comprehension of the task, then recorded the subject actively moving his or her ankle through its maximal ROM 3 times in each direction (plantarflexion, dorsiflexion, eversion and inversion). We identified maximal active ROM for each direction using a manual event marker. When the subject stated that he or she was at the maximal ROM in a particular direction, and the examiner pushed a trigger synched to the data collection system to manually mark the event. Although each subject recorded 3 trials in each direction, frequently, obscured markers rendered only 2 trials useable. Thus, we chose to average 2 trials in each direction to obtain each subject's average active ROM.

Walking Task

For the walking task (WALK), the examiner instructed the subject to walk in a straight line across the capture space at a comfortable pace. Two embedded force plates in the center of the capture volume recorded ground reaction forces. To promote normal gait, the examiner did not tell the subject that the goal was for initial contact (IC) of each limb to occur on the force plates. Instead subjects were instructed to initiate gait with the same leg each time, and the examiner adjusted their starting location to promote IC occurring on the force plates. Subjects walked at a comfortable, normal pace with their eyes focused straight ahead. The examiner recorded walking trials until 10 clean force plate strikes for each limb occurred. A clean force plate strike was operationally defined as one in which IC and toe off (TO) occur completely on the force plate.

Single Leg Drop Jump

For the single leg drop jump task (SLDJ), the subject stepped off a 40cm box using his or her uninvolved leg, and landed on the force plate on his or her involved leg.[14] After landing, the subject balanced on their involved leg for at least 10 seconds. The examiner first demonstrated the task, then the subject performed a minimum of 3 practice trials to feel comfortable with the task. Ten successful jump landings were recorded, with each trial separated by approximately 30 seconds of rest. An unsuccessful trial included any trial where the subject did not maintain balance for a full 10 seconds, hopped or shifted the involved foot on the force plate, stepped down with the opposite limb, or landed with the involved foot not completely on the force plate.

Data Processing

All kinematic data were processed using Visual3D Professional v4.00.19 (C-Motion Inc., Germantown, Maryland). Kinematic data for the forefoot and hindfoot was calculated using the segment coordinate systems defined by Stebbins et al.[13] Euler angles were calculated for the hindfoot relative to the tibia (hindfoot angle) and forefoot relative to the hindfoot (forefoot angle) using the Grood and Suntay sequence.[15] Dynamic hindfoot and forefoot angles were calculated referenced to standing neutral position (setting all angles equal to zero in standing neutral position), and all kinematic data was filtered at 12 Hz using a zero lag 4th order digital Butterworth filter.[16] These methods are highly reliable for calculating adult forefoot and hindfoot motion (ICC=0.83-0.97).[12]

IC during WALK and SLDJ trials was identified as the onset of vertical ground reaction force (GRF) greater than 10 Newtons.[2] For WALK trials, TO was identified as the first data point after IC where the vertical GRF decreased below 10 Newtons. In SLDJ trials, the point of maximum vertical GRF following IC was identified, and labeled as $vGRF_{max}$. Forefoot and hindfoot position in the sagittal and frontal planes was recorded at IC and TO for WALK trials, and at IC and $vGRF_{max}$ for SLDJ trials. For each subject, data at each time point was averaged across 10 trials.[17] Data collection errors resulted in less than 10 useable trials for 2 subjects (1 coper, 1 FAI) during the SLDJ task and for 1 subject (FAI) during walking gait. Rather than exclude these subjects, and thus unbalance subject matching, we chose to use the average each subject's remaining trials (an average of 7 trials per subject) for analysis.

For active ROM, hindfoot angle at maximum dorsiflexion, plantarflexion, eversion and inversion was extracted and averaged across 2 trials. Gait velocity was calculated and averaged across WALK trials. Gait velocity was defined as the velocity of pelvis segment's center of mass. For SLDJ, jump height was also calculated and averaged across trials. Jump height was defined as the difference in meters between the pelvis height at jump initiation and pelvis height at maximal point of the jump trajectory. Since the task was to perform a drop jump, large jump heights were not expected.

Statistical Analysis

For each task, our primary research aim was to estimate differences among groups at two time points (WALK: IC, TO; SLDJ: IC, $vGRF_{max}$) among 4 dependent variables: hindfoot sagittal plane position, hindfoot frontal plane position, forefoot sagittal plane position and forefoot frontal plane position. Therefore for each dependent variable, we conducted a test for group differences separately at each time point within a mixed-model ANOVA with model effects for group (control, coper, FAI), time and the group by time interaction. These tests compared model effects to address our specific research questions regarding the effect of group at IC, and the effect of group at TO (or $vGRF_{max}$). We chose to conduct these tests within a mixed-model ANOVA (as opposed to independent 1-way ANOVAs) to account for correlations among data at each time point and within groups, thus increasing statistical power and decreasing error due to multiple comparisons. At each time point, if the test for group was significant (alpha = 0.05), we investigated group differences using 3 pairwise comparisons with a Bonferroni adjusted alpha of 0.0167.

In addition to the primary analyses, group differences in CAIT, FAAM-ADL, FAAM-Sport, gait velocity, and jump height were analyzed using one-way ANOVAs. For all one-way ANOVAs, alpha was set at 0.05 and Tukey post hoc test was used for all significant differences. All analyses were completed using SAS 9.2 (SAS Institute Inc., Cary, North Carolina, USA).

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CHAPTER FOUR: RESULTS

Subject demographics

Descriptive data for subject demographics, injury history and questionnaires are reported by group in Table 1. Individuals with FAI averaged 5.81±8.42 episodes of giving way per month. There were significant differences between groups on the CAIT, FAAM-ADL and FAAM-Sport questionnaires (CAIT: $F_{2,66}$=95.377, P<0.001; FAAM-ADL: $F_{2,66}$=18.918, P<0.001; FAAM-Sport: $F_{2,66}$=12.850, P<0.001). Tukey post hoc revealed that for all 3 questionnaires, the FAI group scored significantly lower than the coper and control groups. However, the coper and control groups were not significantly different from each other for any questionnaire. For all questionnaires, lower scores indicated decreased function.

Clinical Exam and Active Range of Motion

Clinical exam findings are reported in Table 2. Active ROM values for the involved hindfoot are reported by group in Table 3. Data collection errors resulted in missing active ROM data for 1 coper subject and 1 healthy subject, thus all descriptive data is for the remaining subjects.

Table 1. Subject Demographics and Injury History

	Control		Coper		FAI	
Descriptor	**M**	**SD**	**M**	**SD**	**M**	**SD**
Age, years	23.17	4.01	23.52	3.68	23.30	3.84
Height, m	1.72	0.08	1.72	0.07	1.71	0.11
Weight, kg	68.78	13.26	69.57	13.94	68.66	14.60
CAIT, score	28.78	1.78	27.74	1.69	20.52	2.94[a]
FAAM-ADL, %	99.79	0.57	99.54	1.25	96.36	3.39[a]
FAAM-Sport, %	97.83	8.86	98.70	3.68	89.76	6.19[a]
Initial ankle sprain was evaluated by a medical professional	n/a		16 yes 7 no		19 yes 4 no	
Severity of initial ankle sprain	n/a		3 mild 4 moderate 2 severe 14 unknown		2 mild 6 moderate 4 severe 11 unknown	

Abbreviations: FAI = Functional Ankle Instability, CAIT = Cumberland Ankle Instability Tool, FAAM-ADL = Foot and Ankle Ability Measure Activities of Daily Living subscale, FAAM-Sport = Foot and Ankle Ability Measure Sports subscale.

[a] FAI group scored significantly lower than stable and coper groups

Table 2. Clinical Exam Findings

Clinical Test	Control N	Control %	Coper N	Coper %	FAI N	FAI %
Anterior Drawer						
1=Very hypomobile	0	0	0	0	0	0
2=Slight/moderate hypomobile	5	21.7	5	21.7	2	8.7
3=Normal	15	65.2	10	43.5	9	39.1
4=Slight/moderate hypermobile	3	13.0	7	30.4	7	30.4
5=Very hypomobile	0	0	1	4.3	5	21.7
Talar Tilt						
1=Very hypomobile	0	0	0	0	0	0
2=Slight/moderate hypomobile	3	13.0	2	8.7	2	8.7
3=Normal	19	82.6	18	78.3	11	47.8
4=Slight/moderate hypermobile	1	4.3	3	13.0	8	34.8
5=Very hypomobile	0	0	0	0	2	8.7
Anterior talofibular ligament						
Pain	0	0	0	0	4	17.4
No pain	23	100	23	100	19	82.6
Calcaneofibular ligament						
Pain	0	0	0	0	3	13.0
No pain	23	100	23	100	20	87.0
Posterior talofibular ligament						
Pain	0	0	1	4.3	4	17.4
No pain	23	100	22	95.7	19	82.6
Plantarflexion end ROM						
Pain	0	0	0	0	3	13.0
No Pain	23	100	23	100	20	87.0
Dorsiflexion end ROM						
Pain	0	0	0	0	1	4.3
No pain	23	100	23	100	22	95.7
Inversion end ROM						
Pain	0	0	0	0	6	26.1
No pain	23	100	23	100	17	73.9
Eversion end ROM						
Pain	0	0	2	8.7	2	8.7
No pain	23	100	21	91.3	21	91.3

Abbreviations: FAI = Functional Ankle Instability, ROM = range of motion.

Table 3. Active Range of Motion by Group

ROM direction	Control M	Control SD	Coper M	Coper SD	FAI M	FAI SD
Eversion	5.43	8.99	5.65	6.96	3.48	6.74
Inversion	22.27	8.84	25.43	7.40	24.90	9.15
Plantarflexion	28.21	4.64	29.18	5.25	25.63	6.33
Dorsiflexion	11.29	4.30	14.04	5.74	10.99	5.04
Total ROM Inversion/Eversion	27.70	7.18	31.08	7.24	28.38	8.18
Total ROM Dorsiflexion/Plantarflexion	39.50	6.43	43.22	8.16	36.62	7.81

Abbreviations: FAI = Functional Ankle Instability, ROM = Range of Motion.

Walking Gait

There was no significant difference in gait velocity between groups ($F_{2,66}$=0.26, *p*=0.774; Control: 1.11±0.11m/s, Coper: 1.10±0.12m/s, FAI: 1.09±0.10m/s).

Dorsiflexion and Plantarflexion

Descriptive data for walking kinematics are reported by group in Table 4. For the forefoot in the sagittal plane (i.e. dorsiflexion/plantarflexion), there were no significant group differences at IC or TO (IC: $F_{2,66}$=0.16, *p*=0.849; TO: $F_{2,66}$=1.10, *p*=0.338).

For the hindfoot in the sagittal plane, there were no significant group difference at IC or TO (IC: $F_{2,66}$=1.39, *p*=0.256; TO: $F_{2,66}$=3.08, *p*=0.052). However, there was a trend toward increased plantarflexion at TO in the control and coper groups compared to the FAI group (Control vs. FAI: t=-2.06, df=66, *p*=0.043; Coper vs. FAI: t=-2.23, df=66, *p*=0.029; Control vs. coper: t=0.16, df=66, *p*=0.871).

Inversion and Eversion

For the forefoot in the frontal plane (i.e. inversion/eversion), there was a significant group difference at IC ($F_{2,66}$=4.68, *p*=0.013). Post hoc testing at IC, revealed that individuals with FAI were significantly more inverted than controls (t=-3.04, df=66, *p*=0.003). Copers were not significantly different from the FAI or control groups (Coper vs. FAI: t=-1.26, df=66, *p*=0.213; Control vs. Coper: t=-1.78, df=66, *p*=0.079), although the lack of significant difference with the control group was marginal. There was no significant group difference in forefoot frontal plane motion at TO ($F_{2,66}$=1.63, *p*=0.204).

For the hindfoot in the frontal plane, there were no significant group differences at IC or TO (IC: $F_{2,66}$=0.59, *p*=0.556; TO: $F_{2,66}$=0.62, *p*=0.541).

Table 4. Kinematics (degrees) during Walking Task

	Control				Coper				FAI					
			95% CI				95% CI				95% CI			
Kinematics	**M**	**SE**	**Lower**	**Upper**	**M**	**SE**	**Lower**	**Upper**	**M**	**SE**	**Lower**	**Upper**	$F_{2,66}$	***p*-value**
Initial Contact:														
Forefoot														
Sagittal Plane[a]	-1.04	0.59	-2.21	0.13	-1.37	0.59	-2.51	-0.20	-1.50	0.59	-2.67	-0.33	0.16	0.849
Frontal Plane[b]	-2.17[d]	0.66	-3.49	-0.86	-0.51	0.66	-1.83	0.81	0.66[d]	0.66	-0.65	1.98	4.68	0.013[c]
Hindfoot														
Sagittal Plane[a]	-3.23	0.57	-4.37	-2.10	-2.43	0.57	-3.56	-1.30	-1.91	0.57	-3.04	-0.78	1.39	0.256
Frontal Plane[b]	2.40	0.65	1.10	3.70	1.61	0.65	0.31	2.90	2.53	0.65	1.23	3.82	0.59	0.556
Toe-off:														
Forefoot														
Sagittal Plane[a]	-8.62	0.83	-10.27	-6.98	-8.15	0.83	-9.80	-6.51	-6.94	0.83	-8.59	-5.30	1.10	0.338
Frontal Plane[b]	-4.98	0.74	-6.45	-3.50	-3.42	0.74	-4.89	-1.94	-3.27	0.74	-4.75	-1.79	1.63	0.204
Hindfoot														
Sagittal Plane[a]	-11.09	0.86	-12.80	-9.38	-11.28	0.86	-12.99	-9.57	-8.59	0.86	-10.30	-6.88	3.08	0.052
Frontal Plane[b]	7.90	0.96	5.98	9.81	6.64	0.96	4.73	8.55	7.98	0.96	6.07	9.90	0.62	0.541

Abbreviation: FAI = Functional Ankle Instability, CI=Confidence Interval.
[a] Positive angle indicates dorsiflexion, negative angle indicates plantarflexion.
[b] Positive angle indicates inversion, negative angle indicates eversion.
[c] Significant difference between groups
[d] Significant difference between controls and FAI

Single Leg Drop Jump

There was no significant difference in jump height between groups ($F_{2,66}$=1.06, p=0.354; Control: 0.015±0.028m, Coper: 0.013±0.027m, FAI: 0.025±0.031m). The small magnitude of the average jump height indicates that subjects correctly performed the drop jump.

Dorsiflexion and Plantarflexion

Descriptive data for SLDJ kinematics are reported by group in Table 5. For the forefoot in the sagittal plane (i.e. dorsiflexion/plantarflexion), there was a significant group difference at IC ($F_{2,66}$=3.31, p=0.043). Using a Boneforoni adjusted alpha we could not find the differences between groups, however there was a clear trend toward increased dorsiflexion in the coper group compared to the FAI and control groups (Control vs. Coper: t=-2.37, df=66, p=0.021; Coper vs. FAI: t=2.05, df=66, p=0.044; Control vs. FAI: t=-0.31, df=66, p=0.757). There was no significant group difference in forefoot sagittal plane motion at $vGRF_{max}$ ($F_{2,66}$=0.84, p=0.435).

For the hindfoot in the sagittal plane, there was a significant group difference at IC ($F_{2,66}$=6.12, p=0.004). Specifically, post hoc testing at IC revealed that individuals with FAI were significantly more dorsiflexed than the control or coper groups (Control vs. FAI: t=-3.14, df=66, p=0.003; Coper vs. FAI: t=-2.91, df=66, p=0.005). The control and coper groups were not significantly different from each other (t=-0.23, df=66, p=0.822). There were no significant group difference in hindfoot sagittal plane motion at $vGRF_{max}$ ($F_{2,66}$=0.05, p=0.952).

Inversion and Eversion

For the forefoot in the frontal plane (i.e. inversion/eversion), there were no significant group differences at IC or $vGRF_{max}$ (IC: $F_{2,66}$=1.40, p=0.245; $vGRF_{max}$: $F_{2,66}$=1.72, p=0.188).

For the hindfoot in the frontal plane, there were no significant group differences at IC or $vGRF_{max}$ (IC: $F_{2,66}$=0.77, p=0.466; $vGRF_{max}$: $F_{2,66}$=0.52, p=0.596).

Table 5. Kinematics (degrees) during Single Leg Drop Jump task

	Control				Coper				FAI					
			95% CI				95% CI				95% CI			
Kinematics	**M**	**SE**	**Lower**	**Upper**	**M**	**SE**	**Lower**	**Upper**	**M**	**SE**	**Lower**	**Upper**	$F_{2,66}$	***p*-value**
Initial Contact:														
Forefoot														
Sagittal Plane[a]	-10.69	0.82	-12.33	-9.04	-7.94	0.82	-9.58	-6.30	-10.32	0.82	-11.96	-8.68	3.31	0.043[c]
Frontal Plane[b]	-5.79	0.52	-6.84	-4.74	-5.41	0.52	-6.46	-4.36	-4.58	0.52	-5.62	-3.53	1.40	0.245
Hindfoot														
Sagittal Plane[a]	-13.51[d]	0.77	-15.05	-11.96	-13.26[e]	0.77	-14.80	-11.72	-10.08[d,e]	0.77	-11.62	-8.54	4.01	0.004[c]
Frontal Plane[b]	8.54	1.08	6.40	10.69	6.67	1.08	4.52	8.81	7.81	1.08	5.66	9.96	0.77	0.466
Toe-off:														
Forefoot														
Sagittal Plane[a]	5.93	0.62	4.69	7.17	6.47	0.62	5.23	7.71	7.07	0.62	5.83	8.31	0.84	0.435
Frontal Plane[b]	-4.38	0.55	-5.47	-3.29	-3.72	0.55	-4.82	-2.63	-2.95	0.55	-4.04	-1.86	1.72	0.188
Hindfoot														
Sagittal Plane[a]	4.92	0.84	3.25	6.60	5.22	0.84	3.55	6.90	4.88	0.84	3.21	6.56	0.05	0.952
Frontal Plane[b]	-7.70	0.74	-9.17	-6.22	-8.74	0.74	-10.22	-7.26	-8.42	0.74	-9.90	-6.95	0.52	0.596

Abbreviation: FAI = Functional Ankle Instability, CI=Confidence Interval.

[a] Positive angle indicates dorsiflexion, negative angle indicates plantarflexion.

[b] Positive angle indicates inversion, negative angle indicates eversion.

[c] Significant difference between groups

[d] Significant difference between controls and FAI

[e] Significant difference between copers and FAI

CHAPTER FIVE: DISCUSSION

Introduction

The results of this research are discussed in the context of two manuscripts. The first manuscript, "Increased forefoot inversion during walking gait in individuals with Functional Ankle Instability," includes discussion related to the walking gait task. The second manuscript, "Altered hindfoot and forefoot kinematics during drop jump landing in individuals with and without Functional Ankle Instability," discusses the single leg drop jump task. These manuscripts begin on the following page.

Manuscript One: Increased forefoot inversion during walking gait in individuals with Functional Ankle Instability

Abstract

Introduction: Functional ankle instability (FAI), a common sequelae to ankle sprain, can limit physical activity and activities of daily (ADL) living for years post-injury. One ADL that may be affected by instability is walking gait. Different forefoot and hindfoot movement patterns between individuals with and without FAI during gait may partially explain reports of instability. **Objective**: The purpose of this study was to capture ankle and foot kinematic data using a multi-segment foot model during walking gait among three groups: individuals with FAI, individuals with no history of ankle sprain (controls), and individuals with a history of ankle sprain but no instability (copers). **Design**: A 3 group observational cross-sectional design. **Setting**: Sports Medicine Research Laboratory. **Participants**: Participants included 23 individuals with a history of at least 1 ankle sprain and at least 2 episodes of giving-way in the past year (FAI, Cumberland Ankle Instability Tool [CAIT]=20.52±2.94, episodes of giving-way=5.81±8.42 per month), 23 subjects with no history of ankle sprain or instability in their lifetime (Controls, CAIT=28.78±1.78), and 23 individuals with a history of a single ankle sprain and no subsequent episodes of instability (Copers, CAIT=27.74 ± 1.69). Subjects were matched for age, height and weight (M±SD, age=23.3±3.8years, height=1.71±0.09m, weight=69.0±13.7kg). **Interventions**: Ten trials of natural walking gait were recorded using a 12-camera Vicon MX motion monitoring system (Oxford Metrics Group, Oxford, UK) and two Bertec 4060-NC strain-gauge force plates

(Columbus, Ohio, USA). **Main Outcome Measures**: Forefoot and hindfoot sagittal and frontal plane angles at initial contact (IC) and toe-off (TO) of walking gait were calculated using the Oxford foot model. **Results**: For the forefoot in the frontal plane, there was a significant group difference at IC ($F_{2,66}=4.68$, $p=0.013$; Control = -2.17±3.56˚, Coper = -0.51±2.85˚, FAI = 0.66±3.03˚). Post hoc testing at IC, revealed that individuals with FAI were significantly more inverted than controls (mean difference= -2.84˚, SE=0.93, 95% CI= -4.70 to -0.98), but copers were not significantly different from the FAI or control groups (Coper vs. FAI: mean difference= -1.17˚, SE=0.93, 95% CI= -3.04 to 0.69; Control vs. Coper: mean difference= -1.67˚, SE=0.93, 95% CI= -3.53 to 0.20). There were no significant group differences at any other time point for forefoot or hindfoot frontal plane motion, nor forefoot or hindfoot sagittal plane motion (all $p>0.05$). **Conclusions**: We found increased forefoot inversion at IC in individuals with FAI. Previously, increased inversion error in individuals with FAI has been thought to partially explain symptoms of instability. However, we found a similar amount of inversion in copers, despite the fact that they do not suffer from instability. This may indicate that either increased forefoot inversion does not contribute substantially to instability, or that copers are able to mediate instability through some other mechanism.

Introduction

Ankle sprains are one of the most common injuries experienced by individuals involved in physical activity.[1-3] A significant concern following an acute ankle sprain is the possibility of ongoing symptoms and long-term disability.[4] Approximately 32-47% of patients report symptoms of Functional Ankle Instability (FAI) such as sensations of "giving way", subsequent sprains, or instability.[4-6] These symptoms can decrease quality of life[5] and limit physical activity and activities of daily living for years post-injury.[4, 6]

Because of the health risk posed by FAI, the mechanisms of this clinical pathology have been studied extensively.[7-9] Several pathological factors have been associated with FAI,[7] including altered joint mechanics.[10-15] Joint mechanics can demonstrate how an individual maintains dynamic joint stability during functional activity.[16] Differences in joint motion may elucidate how an individual with FAI either a) copes with pathology to dynamically stabilize his or her ankle during activity (by adopting movement strategies to increase stability, such as decreasing available range of motion), or b) fails to cope with pathology (by utilizing movement strategies that decrease stability).[12]

Several researchers have hypothesized that differences in joint kinematics exist between individuals with FAI and healthy controls.[10-15] Walking gait is one task that has received attention, most likely due to its importance in many activities of daily living, and because individuals with FAI often complain of giving way while walking on level and uneven surfaces.[15] During gait, increased ankle inversion at initial contact (IC) may predispose individuals to ankle inversion injury due to the creation of an inversion moment.[17] Although several researchers have focused on IC of gait while the limb is being loaded, instability could also occur when the limb is being unloaded at toe-off (TO). TO occurs as the limb leaves contact with the ground and enters into the swing phase. As with IC, angular error at this transition between weight bearing and non-weight bearing conditions could contribute to instability and giving-way.

While some researchers have found increased ankle inversion at initial contact in gait,[11, 12] others have failed to find such differences.[13, 14] Even when group differences are apparent, it can be difficult to interpret whether changes are positive, negative or even benign adaptations post-injury. Comparing individuals with FAI to "copers" (individuals who have experienced a single ankle sprain but have no instability) may help clarify the current literature. This would allow researchers to see the difference between individuals who sprained but did not develop pathology, and individuals who did develop FAI post-sprain. These differences could clarify previously unclear findings, by indentifying mechanisms by which copers maintain dynamic stability.

A growing number of studies at the ankle have grouped subjects as copers, noncopers, or healthy controls.[14, 18-22] However, Brown et al.[14] is the only group to report ankle joint kinematics during gait between copers and FAI individuals. They reported increased ankle joint frontal plane displacement during gait, but no differences between the FAI group and coper group for any other variable. This seems to indicate that frontal plane motion is the salient difference between those with and without instability. Unfortunately, their report did not include a healthy group to make the 3 way comparison. Thus, it is unknown whether values for copers and FAI subjects were within the normal healthy range.

Additionally, all comparisons of walking gait kinematics between individuals with and without FAI have utilized a single segment foot model to calculated ankle joint motion.[11, 14, 23] Since forefoot and hindfoot motion are not identical during activity,[24] and could both contribute to instability , we felt use of a multi-segment foot model would create a more accurate profile of motion and potentially clarify the currently mixed evidence regarding walking kinematics in individuals with and without FAI.[11, 14, 23]

The primary purpose of this study, therefore, was to capture foot and ankle kinematic data using a multi-segment foot model during walking gait among three groups of subjects (healthy controls, copers, and FAI). We hypothesized that individuals with FAI would be more inverted (a possible risk factor for instability) during gait. We expected to find no difference between our control and coper groups.

Methods

Subjects

We included 23 subjects with FAI (mean episodes of giving-way=5.81 per month, SD=8.42), 23 subjects with a history of an ankle sprain but no instability (Copers), and 23 subjects with no history of ankle sprain or instability (Controls) in this study. There were 12 males and 11 females per group. Subject demographics are reported in Table 1. Prior to commencement, this study was approved by the University Institutional Review Board.

Initially, we recruited and screened 83 subjects from a large metropolitan area for participation. These subjects reported for a single visit to the Sports Medicine Research Laboratory. After obtaining informed consent, the subject completed an injury history questionnaire and the Cumberland Ankle Instability Tool (CAIT) to verify inclusion criteria. A customized computer program (Access, Microsoft, Redmond, WA) recorded and scored subject responses for the CAIT. The CAIT has excellent test-retest reliability ($ICC_{2,1}$ = 0.96), and is scored from 0-30 points with higher scores indicating higher stability.[25] The injury history form collected information about the initial ankle sprain injury, symptoms of giving way and re-sprains, as well as history of lower extremity fractures or surgeries, and limb dominance. Limb dominance was assessed by asking the individual to self-report his or her dominant or preferred limb for activities such as kicking a soccer ball. We measured subject height using a Seca mechanical column scale (Hanover, Maryland). To record weight, the subject stood quietly on a force plate (Bertec,Columbus, Ohio, USA) and we calculated the vertical componenet of the ground reaction forces.

After reviewing the injury history questionnaire and CAIT scores, 8 participants were excluded for not meeting all study criteria. Another subject was excluded after enrollment because they were unable to follow task instructions. Lastly, 5 subjects could not be matched. We matched copers and healthy controls to FAI subjects by gender, age (±10 years), height (±10cm), and weight (±15kg). Additionally, each group had equal numbers of left and right limb dominant individuals (2 left, 21 right). This left a final total of 69 matched subjects (23 per group). Based on pilot data we calculated a minimum of 17 subjects per group were necessary to detect group differences in our targeted variables. However since this is lower than the normal sample size in similar literature[11, 14, 23] we decided *a priori* to recruit a minimum of 21 subjects per group. Our final sample size exceeded this minimum by 2 subjects per group.

FAI and coper subjects were required to have a history of a unilateral inversion ankle sprain which required protected weight bearing, immobilization, and/or limited activity for ≥ 24 hours. Additionally, FAI subjects had to report multiple episodes of giving way (at least 2 in the past year),[14] and had to be classified as having FAI using a cutoff score of ≤ 27 on the CAIT.[25] Copers had no complaints of ankle instability or repeated episodes of giving way, and had resumed all pre-injury activities without limitation for at least 12 months prior to testing.[14, 20]

Similar to previous research,[21, 22] if all other inclusion criteria were met, copers were allowed a single episode of giving-way in their lifetime as long as it occurred at least 12 months prior to study participation. Control subjects had no history of ankle sprain or instability in their lifetime. Additionally, all subjects were required to participate in 1.5 or more hours of moderate to vigorous physical activity per week for inclusion.[14, 20] Subjects self-reported their weekly activity level and intensity using a simple recall. Potential subjects were excluded if they had a history of surgery or ankle fracture in either lower extremity, any acute symptoms of lower extremity injury on the day of testing, or known systemic disease or condition affecting the musculoskeletal system.[26]

Testing was performed on the involved limb (side of ankle sprain) of the FAI and coper groups, and the matched side of the healthy control group. For FAI individuals with bilateral instability, the subject was asked to subjectively identify their most unstable ankle, and that side was designated as the involved limb.

Motion Capture

The examiner attached 5 rigid plastic plates of markers to subjects using tape prewrap, and attaching 34 individual 9.5mm reflective markers using double sided adhesive tape at specific anatomical landmarks. Marker placement was according to the Oxford foot model with additional conventional gait model markers on the knee, hip and pelvis.[27, 28] Marker plates were attached to the posterior pelvis at the height of the posterior superior iliac spine, and bilaterally on the distal thigh and shank. Anatomical markers were placed bilaterally on the greater trochanter, anterior superior iliac spine, lateral and medial femoral epicondyles, lateral and medial malleoli, proximal and distal 5th metatarsal, distal second metatarsal, proximal and distal 1st metatarsal, and the lateral, medial and posterior calcaneus.

The subject then stood in anatomical position while a static calibration trial was captured. Following the static trial, calibration only markers were removed (i.e. bilateral greater trochanter, lateral and medial femoral epicondyles, medial malleolus, and the posterior superior calcaneus). For all movement trials, a 12-camera Vicon MX motion monitoring system (Oxford Metrics Group, Oxford, UK) collected the three-dimensional location of reflective markers at 100 Hz, and two Bertec 4060-NC strain-gauge force plates (Columbus, Ohio, USA) captured ground reaction forces (GRF) at 1000 Hz. Vicon Nexus 1.4 software (Oxford Metrics Group, Oxford, UK) synchronized all data collection.

After calibration, we instructed the subject to walk in a straight line across the capture space at a comfortable pace. To promote normal gait, we did not tell the subject that the goal was for initial contact (IC) of the involved limb to occur on one of the force plates. Instead subjects were instructed to initiate gait with the same leg each time, and the examiner adjusted their starting location to promote IC occurring on a force plate. Subjects walked at a comfortable, normal pace with their eyes focused straight ahead. The examiner recorded walking trials until 10 clean force plate strikes occurred. A clean force plate strike was operationally defined as one in which IC and TO occurred completely on the force plate.

Data Processing

All kinematic data were processed using Visual3D Professional v4.00.19 (C-Motion Inc., Germantown, Maryland). Kinematic data for the forefoot and hindfoot was calculated using the segment coordinate systems defined by Stebbins et al.[28] as part of a revised Oxford foot model. Euler angles were calculated for the hindfoot relative to the tibia (hindfoot angle) and forefoot relative to the hindfoot (forefoot angle) using the Grood and Suntay sequence.[29] Dynamic hindfoot and forefoot angles were calculated for the involved limb referenced to standing neutral position (setting all angles equal to zero in standing neutral position), and all kinematic data was filtered at 12 Hz using a zero lag 4th order digital Butterworth filter.[30] These methods are highly reliable for calculating adult forefoot and hindfoot motion (ICC=0.83-0.97).[27]

IC was identified as the onset of vertical GRF greater than 10 Newtons.[14] TO was identified as the first data point after IC where the vertical GRF decreased below 10 Newtons. Forefoot and hindfoot position in the sagittal and frontal planes was recorded at IC and TO. In addition, kinematic data for the entire stance phase (IC to TO) was time normalized to 100 data points for graphical comparison between groups. For each subject, data was averaged across 10 trials.[23] For 1 subject, data collection errors resulted in less than 10 useable trials. Rather than exclude this subject and unbalance subject matching, we chose to use the average of the subject's 8 available trials for analysis. Additionally, gait velocity, defined as the average velocity of pelvis segment's center of mass, was calculated and averaged across 10 gait trials for each subject.

Statistical Analysis

Our primary research aim was to estimate differences among groups at each time point (IC and TO) among 4 dependent variables: hindfoot sagittal plane position, hindfoot frontal plane position, forefoot sagittal plane position and forefoot frontal plane position. Therefore for each dependent variable, we conducted a test for group differences separately at each time point within a mixed-model ANOVA with model effects for group (control, coper, FAI), time (IC, TO) and the group by time interaction. These tests compared model effects to address our specific research questions regarding the effect of group at IC, and the effect of group at TO. We chose to conduct these tests within a mixed-model ANOVA (as opposed to independent 1-way ANOVAs) to account for correlations among data at each time point and within groups, thus increasing statistical power and decreasing error due to multiple comparisons. At each time point, if the test for group was significant (alpha = 0.05), we investigated group differences using 3 pairwise comparisons with a Bonferroni adjusted alpha of 0.0167.

Group differences in CAIT and gait velocity were analyzed using one-way ANOVAs. For all one-way ANOVAs, alpha was set at 0.05 and Tukey post hoc test was used for significant differences. All analyses were completed using SAS 9.2 (SAS Institute Inc., Cary, North Carolina, USA).

Results

Subject demographics

Subject demographics are reported in Table 1. There were significant differences between groups on the CAIT questionnaire ($F_{2,66}$=95.377, p<0.001). Tukey post hoc revealed that the FAI group scored significantly lower than the coper and control groups, which was expected based on inclusion criteria (FAI vs. coper: mean difference= -7.22, SE= 0.65, 95% Confidence Interval [CI]= -8.78 to -5.66; FAI vs. control: mean difference= -8.26, SE=0.65, 95% CI= -9.82 to -6.70). The coper and control groups were not significantly different from each other (control vs. coper: mean difference = 1.04, SE=0.65, 95% CI= -0.52 to 2.61). Lower CAIT scores indicated decreased function.

Walking task

Gait Velocity

There were no significant differences in gait velocity between groups ($F_{2,66}$=0.26, p=0.774; Control: 1.11±0.11m/s, Coper: 1.10±0.12m/s, FAI: 1.09±0.10m/s).

Forefoot motion

Descriptive data for walking kinematics at IC and TO are reported by group in Table 2, and stance phase kinematics are shown in Figure 1. For the forefoot in the sagittal plane (i.e. dorsiflexion/plantarflexion), there were no significant group differences at IC or TO (IC: $F_{2,66}$=0.16, *p*=0.849; TO: $F_{2,66}$=1.10, *p*=0.338).

For the forefoot in the frontal plane (i.e. inversion/eversion), there was a significant group difference at IC ($F_{2,66}$=4.68, *p*=0.013). Post hoc testing at IC, revealed that individuals with FAI were significantly more inverted than controls (t=-3.04, df=66, *p*=0.003, mean difference= -2.84˚, SE=0.93, 95% CI= -4.70 to -0.98). Copers were not significantly different from the FAI or control groups (Coper vs. FAI: t=-1.26, df=66, *p*=0.213, mean difference= -1.17˚, SE=0.93, 95% CI= -3.04 to 0.69; Control vs. Coper: t=-1.78, df=66, *p*=0.079, mean difference= -1.67˚, SE=0.93, 95% CI= -3.53 to 0.20), although the lack of significant difference with the control group was marginal. There were no significant group differences in forefoot frontal plane motion at TO ($F_{2,66}$=1.63, *p*=0.204).

Hindfoot motion

For the hindfoot in the sagittal plane (i.e. dorsiflexion/plantarflexion) there were no significant group difference at IC or TO (IC: $F_{2,66}$=1.39, *p*=0.256; TO: $F_{2,66}$=3.08, *p*=0.052). For the hindfoot in the frontal plane (i.e. inversion/eversion), there were also no significant group differences at IC or TO (IC: $F_{2,66}$=0.59, *p*=0.556; TO: $F_{2,66}$=0.62, *p*=0.541).

Discussion

We hypothesized that individuals with FAI would be more inverted during gait (a possible risk factor for instability). While we did find greater FAI forefoot inversion at IC compared to controls during walking, there were no other differences in hindfoot or forefoot kinematics during gait. Specifically, during normal walking gait, subjects with FAI had 2.84° (SE=0.93, 95% CI= 0.98 to 4.70) greater forefoot inversion than controls at IC. To our knowledge, we are the only group to report walking kinematics using a multi-segment foot model. However, our results at the forefoot are similar to previous research which also reported increased ankle inversion at IC modeling the foot and ankle as a single rigid body.[11, 12] Our average group difference for forefoot inversion was slightly smaller in magnitude than these studies, which recorded group differences of 3.5-6°.[11, 12] It is possible that our values are smaller because motion in our study was split between the hindfoot and forefoot segments. We originally expected to find the difference in hindfoot inversion rather than forefoot inversion, because the hindfoot is the segment in contact with the ground at IC. However, forefoot inversion could still affect ankle lateral stability by contributing to overall positioning error as the foot accepts weight.

The primary reason to include copers was to provide a comparison group that has experienced the same mechanism of injury (lateral ankle sprain) but not developed chronic instability. We expected this to clarify findings from the traditional 2 group model (healthy control vs. FAI) by adding the profile of a previously sprained but currently stable ankle. Theoretically, the coper group would show no difference from controls regarding variables which contribute to instability, and no difference from the FAI group on variables which represent benign post-injury changes. For forefoot inversion at IC, copers were not significantly different from either group; their mean angle was located between the FAI and control group means. This lack of significant difference at IC between copers and individuals with FAI is consistent with the findings of Brown et al.[14] However, in our study, although copers were very similar to individuals with FAI, they showed a trend towards significant difference from controls (*p*=0.079, mean difference=1.67˚, SE=0.93, 95% CI= -0.19 to 3.53). This trend seems to indicate that the increased forefoot inversion seen during walking gait in individuals with FAI is actually not an active contributor towards instability. Or, alternatively, if it is an active contributor to instability, copers have an additional stabilizing mechanism which mediates effect of increased inversion. The methods of our study do not allow us to speculate what this mechanism might be.

The clinical implications of inversion angular error of the magnitude found in this study are not clear. According to the work of Konradsen et al.,[17] who simulated ankle inversion injury at heel strike in cadavers, it would take a substantial degree of mal-alignment (8-10°) before an inversion moment was created. However, the 2.84° difference between control and FAI groups in this study is only the average error. The actual error for any 1 gait cycle varies, and, in fact, previous research has shown that kinematic variability in individuals with FAI is greater than individuals without instability.[18] Thus, it is possible that an episode of giving-way while walking may be precipitated by an abnormally large amount of inversion error during that single gait cycle. Unfortunately, this theory is difficult to test due to the sporadic nature of episodes of giving-way and the low likelihood of one naturally occurring during data capture. Konradsen[31] calculated that given a mean error of 3.4° (only slightly larger than the average error found in this study) and a normal distribution, the statistical probability of experiencing an error sufficient to cause injury (i.e. >8°) was rather frequent, approximately 1 step out of every 1,000. While this estimate is based on theory, it demonstrates how even a seemly small error can translate into clinical significance.

We did not find any group differences in sagittal plane (dorsiflexion/plantarflexion) motion at IC of walking gait, which is consistent with previous reports.[11, 12, 14] Although not significant, there was a trend towards greater hindfoot dorsiflexion at TO in individuals with FAI compared to copers and controls (Control vs. FAI: mean difference= -2.50˚, SE=1.21, 95% CI= -4.92 to -0.08; Coper vs. FAI: mean difference= -2.70˚, SE=1.21, 95% CI= -5.12 to -0.28). What, if any, effect increased hindfoot dorsiflexion at TO would have on ankle stability is unknown. It has been previously hypothesized that increased dorsiflexion may be a stability-enhancing kinematic alteration as it decreases stretch on the lateral ankle ligaments.[13]

Limitations

The 12 bilateral foot and ankle markers necessary for the Oxford foot model[27, 28] made it impossible for our subjects to wear their normal footwear. Thus, the walking trials were completed barefoot. It is possible that kinematics during shod gait differ from barefoot kinematics. Despite this limitation, we believe our group comparisons are still valid since subjects in all groups were tested under the same barefoot condition, and our results are similar to previous studies.[11, 14, 23]

Summary

We found increased forefoot inversion at IC in individuals with FAI. Previously, increased inversion error in individuals with FAI has been thought to partially explain symptoms of instability. However, we found a similar motion pattern in copers despite the fact that they do not suffer from instability. This may indicate that either increased forefoot inversion does not contribute substantially to instability, or that copers are able to mediate instability through some other mechanism.

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Table 1. Subject Demographics

Descriptor	Control		Coper		FAI	
	M	SD	M	SD	M	SD
Age, years	23.17	4.01	23.52	3.68	23.30	3.84
Height, m	1.72	0.08	1.72	0.07	1.71	0.11
Weight, kg	68.78	13.26	69.57	13.94	68.66	14.60
CAIT, score	28.78	1.78	27.74	1.69	20.52	2.94[a]

Abbreviations: FAI = Functional Ankle Instability, CAIT = Cumberland Ankle Instability Tool.

[a] FAI group scored significantly lower than stable and coper groups

Table 2. Kinematics (degrees) during Walking Task

	Control				Coper				FAI					
			95% CI				95% CI				95% CI			
Kinematics	**M**	**SE**	**Lower**	**Upper**	**M**	**SE**	**Lower**	**Upper**	**M**	**SE**	**Lower**	**Upper**	$F_{2,66}$	*p*-value
Initial Contact:														
Forefoot														
Sagittal Plane[a]	-1.04	0.59	-2.21	0.13	-1.37	0.59	-2.51	-0.20	-1.50	0.59	-2.67	-0.33	0.16	0.849
Frontal Plane[b]	-2.17[d]	0.66	-3.49	-0.86	-0.51	0.66	-1.83	0.81	0.66[d]	0.66	-0.65	1.98	4.68	0.013[c]
Hindfoot														
Sagittal Plane[a]	-3.23	0.57	-4.37	-2.10	-2.43	0.57	-3.56	-1.30	-1.91	0.57	-3.04	-0.78	1.39	0.256
Frontal Plane[b]	2.40	0.65	1.10	3.70	1.61	0.65	0.31	2.90	2.53	0.65	1.23	3.82	0.59	0.556
Toe-off:														
Forefoot														
Sagittal Plane[a]	-8.62	0.83	-10.27	-6.98	-8.15	0.83	-9.80	-6.51	-6.94	0.83	-8.59	-5.30	1.10	0.338
Frontal Plane[b]	-4.98	0.74	-6.45	-3.50	-3.42	0.74	-4.89	-1.94	-3.27	0.74	-4.75	-1.79	1.63	0.204
Hindfoot														
Sagittal Plane[a]	-11.09	0.86	-12.80	-9.38	-11.28	0.86	-12.99	-9.57	-8.59	0.86	-10.30	-6.88	3.08	0.052
Frontal Plane[b]	7.90	0.96	5.98	9.81	6.64	0.96	4.73	8.55	7.98	0.96	6.07	9.90	0.62	0.541

Abbreviation: FAI = Functional Ankle Instability.
[a] Positive angle indicates dorsiflexion, negative angle indicates plantarflexion.
[b] Positive angle indicates inversion, negative angle indicates eversion.
[c] Significant difference between groups
[d] Significant difference between controls and FAI

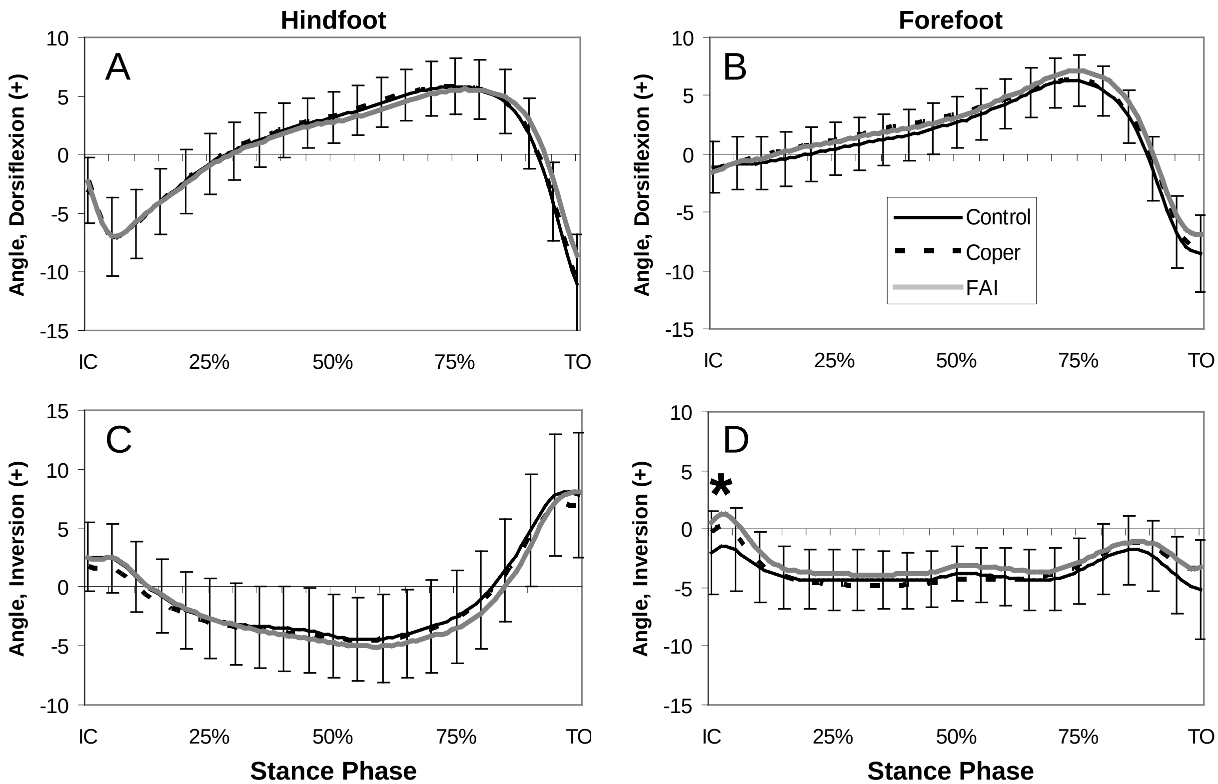

Figure 1. Walking gait mean kinematics from initial contact to toe-off (stance) for hindfoot dorsiflexion/plantarflexion (A), forefoot dorsiflexion/plantarflexion (B), hindfoot inversion/eversion (C), and forefoot inversion/eversion (D). Error bars of ± 1 standard deviation are shown for the control group only. Asterisk denotes significant group difference at IC. Abbreviations: IC = Initial contact, TO = Toe-off, FAI = Functional Ankle Instability.

Manuscript Two: Altered hindfoot and forefoot kinematics during drop jump landing in individuals with and without Functional Ankle Instability

Abstract

Introduction: Following lateral ankle sprain, many individuals experience recurrent injury and symptoms of giving-way, known as Functional Ankle Instability (FAI). It has been proposed that altered joint kinematics during activity, such as jump landing, may partially explain recurrent instability in individuals with FAI. However, when found, differences have been small and difficult to interpret. **Objective**: The purpose of this study was to investigate foot and ankle joint motion during a jump landing task using an established multi-segment foot model, and adding a comparison group of copers (individuals with a history of ankle sprain but no instability), in addition to the traditional healthy control and FAI groups. **Design**: A 3 group observational cross-sectional design. **Setting**: Sports Medicine Research Laboratory **Participants**: Participants included 23 individuals with a history of at least 1 ankle sprain and at least 2 episodes of giving-way in the past year (FAI, Cumberland Ankle Instability Tool [CAIT]=20.52±2.94, giving-way=5.81±8.42 per month), 23 subjects with no history of ankle sprain or instability in their lifetime (Controls, CAIT=28.78±1.78), and 23 individuals with a history of a single ankle sprain and no subsequent episodes of instability (Copers, CAIT=27.74 ± 1.69). Subjects were matched for age, height and weight (M±SD, age=23.3±3.8years, height=1.71±0.09m, weight=69.0±13.7kg). **Interventions**: Ten single leg drop jumps were recorded using a 12-camera Vicon MX motion capture system (Oxford Metrics Group, Oxford, UK) and two Bertec 4060-NC strain-gauge force plates (Columbus, Ohio, USA). **Main Outcome Measures**: Forefoot and hindfoot sagittal and frontal plane angles at jump landing initial contact (IC) and at the point of maximum vertical ground reaction force ($vGRF_{max}$) were calculated using the Oxford foot model. **Results**: For the forefoot and hindfoot in the saggittal plane, there were significant group differences at IC (forefoot: $F_{2,66}=3.31$, $p=0.043$, hindfoot: $F_{2,66}=6.12$, $p=0.004$). Post-hoc testing could not find differences in the forefoot, however, at the hindfoot individuals with FAI were significantly more dorsiflexed than the control and coper groups (Control vs. FAI: mean difference= -3.43˚, SE=1.09, 95% CI= -5.61 to -1.25; Coper vs. FAI: mean difference= -3.18, SE=1.09, 95% CI= -5.36 to -1.00). The control and coper groups were not significantly different from each other (mean difference= -0.25, SE=1.09, 95% CI= -2.43 to 1.93). There were no significant group differences for any measure in the frontal plane, or at $vGRF_{max}$ (all $p>0.05$). **Conclusions**: There were no significant inversion differences during jump landing. Individuals with FAI land with greater hindfoot dorsiflexion, which previous researchers have hypothesized is an adaptation to increase stability. However, individuals with a similar history of ankle sprain but no instability (copers), do not utilize a pattern with greater hindfoot dorsiflexion. Copers may not need this strategy because they are already stable, or it may be that increased dorsiflexion is not actually a positive adaptation as hypothesized after all. Future ankle instability research should continue to use a 3 group model to further investigate dynamic stability mechanisms in individuals with and without FAI.

Introduction

One of the most common injuries experienced by individuals involved in physical activity is a lateral ankle sprain.[1-3] Following an acute ankle sprain, 32-47%of patients report Functional Ankle Instability (FAI), a clinical diagnosis characterized by symptoms of giving-way, instability and re-sprains. FAI can limit physical activity and activities of daily living for years post-injury,[4, 5] and is associated with significant health risks such as post-traumatic osteoarthritis.[6]

Although the mechanisms for this pathology are not clearly understood, several pathological factors have been associated with FAI,[7] including altered joint mechanics during motion.[8-13] Joint mechanics can demonstrate the strategies by which an individual attempts to maintain dynamic joint stability during functional activity.[14] Landing from a jump is one common task in physical activity that requires dynamic stabilization, and is also a common mechanism of ankle inversion injury.[15] As such, the kinematics of jump landing have received considerable attention in the ankle instability literature. [8, 11, 16-19]

Specifically, several authors have hypothesized that kinematic differences exist during jump landing between individuals with FAI and healthy controls.[8, 11, 16-19] However, findings have been inconsistent and methodology varied. At initial contact (IC), Caulfield and Garrett[11] reported significant ankle sagittal plane group differences, whereas others have failed to find such differences.[8, 12, 18] Fewer studies have investigated frontal plane differences, and again only one reported increased ankle inversion in individuals with FAI, and this was prior to, but not at, IC.[8] Two methodological changes may clarify the currently mixed literature. First, the use of a more reliable and precise biomechanical model to capture foot and ankle motion may enhance our ability to detect group differences. In the FAI literature there is a deficiency in the reporting of the kinematic model used, including marker placement and mathematical modeling assumptions. Of 9 studies reporting kinematic differences between individuals with and without FAI,[8-12, 16, 18-20] only one study[20] reported or referenced the repeatability of the model used. Five studies partially or fully described modeling assumptions;[12, 16, 18-20] the four remaining studies, however, provided anatomical landmarks but no mathematical modeling information whatsoever.[8-11] Especially since the angular differences reported in studies between FAI and healthy subjects tends to be small,[9, 11] the interpretation of results reported in the current literature is difficult without adequate information about the repeatability and precision of biomechanical modeling. Error may either obscure true group differences or create spurious differences if an accurate and precise model is not used.

Furthermore, the majority of these studies utilized a one segment foot model.[8-12, 16, 18, 19] This type of model assumes that the foot is a single rigid segment, despite the numerous articulations within the foot and ankle complex. Thus, although it can provide a picture of the overall motion of the foot and ankle, by definition a single segment foot model cannot capture differences in hindfoot and forefoot motion that can be reliably captured with a multi-segment model such as the Oxford foot model[21-23] used by Drewes et al.[20] Because hindfoot, forefoot and hallux motion are not identical during activity,[21] a model able to capture these movements may be essential in accurately representing motion in individuals with FAI. Simpler models may have obscured differences by pooling hindfoot and forefoot motion into a single composite value.

A second methodological change that may help clarify the current literature, is the addition of an alternative comparison group commonly referred to as "copers." Copers are individuals who have experienced a lateral ankle sprain but have not developed instability.[24, 25]

Studying the characteristics of copers compared to individuals with FAI may help further elucidate the mechanism of instability, since copers are able to dynamically stabilize their foot and ankle during activity despite past ankle injury. To our knowledge, only Brown et al.[12] have compared the ankle joint kinematics between copers and individuals with FAI (i.e. noncopers). They found no difference in ankle joint motion at IC between their FAI and coper groups when completing a drop jump. However, they did not include a healthy control group so it is unknown whether the values they reported for copers and individuals with FAI were within or outside of a healthy normal range.

Perhaps due in part to these limitations in biomechanical modeling and subject comparisons, it is still unclear how individuals with and without FAI cope or fail to cope with pathology to dynamically stabilize their ankles during jump landing. Therefore, the purpose of this study is to capture kinematic data using a reliable foot and ankle model during jump landing among three groups of subjects (controls, copers, and FAI). We hypothesized that individuals with FAI would be more plantarflexed at IC and more inverted immediately post-IC at the point of maximal vertical ground reaction forces than copers and controls. It has been shown that both increased inversion and increased plantarflexion can contribute to the creation of a potentially damaging inversion moment at the ankle.[26] Because both copers and controls are dynamically stable, we did not expect to find kinematic differences between these two groups.

Methods

Subjects

We included 23 subjects with FAI (episodes of giving-way=5.81±8.42 per month), 23 subjects with a history of an ankle sprain but no instability (Copers), and 23 subjects with no history of ankle sprain or instability (Controls) in this study. There were 12 males and 11 females per group. Subject demographics are reported in Table 1. This research was part of a larger study investigating coping mechanisms and movement patterns in among individuals with and without instability. Based on our pilot data for the primary variables in this report, we needed a minimum of 16 subjects per group to detect differences with 80% power. However, we chose to recruit a greater number per group to be more consistent with current literature.[8, 11, 12] Prior to commencement, this study was approved by the university's Institutional Review Board. All subjects were recruited from a large metropolitan area.

FAI and coper subjects were required to have a history of a unilateral inversion ankle sprain which required protected weight bearing, immobilization, and/or limited activity for ≥ 24 hours. Additionally, FAI subjects had to report multiple episodes of giving way (at least 2 in the past year),[12] and had to be classified as having FAI using a cutoff score of ≤ 27 on the Cumberland Ankle Instability Tool (CAIT).[27] Copers had no complaints of ankle instability or repeated episodes of giving way, and had resumed all pre-injury activities without limitation for at least 12 months prior to testing.[12, 25] Similar to previous research,[28, 29] if all other inclusion criteria were met, copers were allowed a single episode of giving-way in their lifetime as long as it occurred at least 12 months prior to study participation. Control subjects had no history of ankle sprain or instability in their lifetime. Additionally, all subjects were required to participate in ≥ 1.5 hours of moderate to vigorous physical activity per week for inclusion.[12, 25] Subjects self-reported their weekly activity level and intensity using a simple recall. Potential subjects were excluded if they had a history of surgery or ankle fracture in either lower extremity, any acute symptoms of lower extremity injury on the day of testing, or known systemic disease or condition affecting the musculoskeletal system.[30]

Subjects reported for a single visit to the Sports Medicine Research Laboratory. After obtaining informed consent, the subject completed an injury history questionnaire and the CAIT to verify inclusion criteria. The injury history form collected information about the initial ankle sprain injury, symptoms of giving way and re-sprains, as well as history of lower extremity fractures or surgeries, and limb dominance. A customized computer program (Access, Microsoft, Redmond, WA) recorded and scored subject responses for the CAIT. The CAIT has excellent test-retest reliability ($ICC_{2,1}$ = 0.96), and is scored from 0-30 points with higher scores indicating higher stability.[27] We measured subject height using a Seca mechanical column scale (Hanover, Maryland). To record weight, the subject stood quietly on a force plate (Bertec,Columbus, Ohio, USA) and we calculated the vertical componenet of the ground reaction forces.

We matched copers and healthy controls to FAI subjects by gender, age (±10 years), height (±10cm), and weight (±15kg). Additionally, each group had equal numbers of left and right limb dominant individuals (2 left, 21 right). Limb dominance was assessed by asking the individual to self-report his or her dominant or preferred limb for activities such as kicking a soccer ball. Testing was performed on the involved limb (side of ankle sprain) of the FAI and coper groups, and the matched side of the healthy control group. For FAI individuals with bilateral instability, the subject was asked to subjectively identify their most unstable ankle, and that side was designated as the involved limb.

Motion Capture Preparation

The examiner attached 5 rigid plastic plates of markers to the subject using tape prewrap and attached 34 individual 9.5mm reflective markers using double sided adhesive tape at specific anatomical landmarks. Marker placement was according to the Oxford foot model with additional conventional gait model markers on the knee, hip and pelvis.[22, 23] Marker plates were attached to the posterior pelvis at the height of the posterior superior iliac spine, and bilaterally on the distal thigh and shank. Anatomical markers were placed bilaterally on the greater trochanter, anterior superior iliac spine, lateral and medial femoral epicondyles, lateral and medial malleoli, proximal and distal 5th metatarsal, distal second metatarsal, proximal and distal 1st metatarsal, and the lateral, medial and posterior calcaneus.

The subject stood in the capture volume in anatomical position as a static calibration trial was captured. Following the static trial, we removed the calibration only markers (i.e. bilateral greater trochanter, lateral and medial femoral epicondyles, medial malleolus, and the posterior superior calcaneus). For all movement trials, a 12-camera Vicon MX motion monitoring system (Oxford Metrics Group, Oxford, UK) collected the three-dimensional location of reflective markers at 100 Hz, and two Bertec 4060-NC strain-gauge force plates (Columbus, Ohio, USA) captured ground reaction forces at 1000 Hz. Vicon Nexus 1.4 software (Oxford Metrics Group, Oxford, UK) synchronized all data collection.

Single Leg Drop Jump

A single leg drop jump was performed by having the subject step off a 40cm box using his or her uninvolved leg, and land on the force plate on his or her involved leg.[11] Upon landing the subject balanced on his or her involved leg for at least 10 seconds. The examiner described and demonstrated the single leg drop jump task, then the subject performed a minimum of 3 practice trials to feel comfortable with the task. Ten successful jump landings were recorded, with each trial separated by approximately 30 seconds of rest. An unsuccessful trial included any trial where the subject did not maintain balance for a full 10 seconds, hopped or shifted the involved foot on the force plate, stepped down with the opposite limb, or landed with the involved foot not completely on the force plate. The number of unsuccessful trials was recorded for each subject. After completing 10 successful trials, subjects were asked to rate how stable their ankle felt while completing the task on a scale of 0-10, with 0 indicating very unstable and ten 10 indicating very stable. The purpose of this rating was to assess each individual's perceived stability during the single leg drop jump task.

Data Processing

All kinematic data were processed using Visual3D Professional v4.00.19 (C-Motion Inc., Germantown, Maryland). Kinematic data for the forefoot and hindfoot was calculated using the segment coordinate systems defined by Stebbins et al.[22] Euler angles were calculated for the hindfoot relative to the tibia (hindfoot angle) and forefoot relative to the hindfoot (forefoot angle) using the Grood and Suntay sequence.[31] Dynamic hindfoot and forefoot angles were calculated for the involved limb referenced to standing neutral position (setting all angles equal to zero in standing neutral position), and all kinematic data was filtered at 12 Hz using a zero lag 4th order digital Butterworth filter.[32] These methods are highly reliable for calculating adult forefoot and hindfoot motion (ICC=0.83-0.97).[23, 23]

We identified 2 events: the onset of vertical ground reaction force greater than 10 Newtons (IC),[12] and maximal vertical ground reaction force ($vGRF_{max}$). Forefoot and hindfoot position in the sagittal and frontal planes was recorded at IC and $vGRF_{max}$ of each jump landing. Data at each event was averaged across 10 trials for each subject.[33] For 2 subjects (1 coper, 1 FAI), data collection errors resulted in less than 10 useable trials. Rather than exclude these subjects and unbalance subject matching, we chose to use the average of each subject's available trials (an average of 7 per subject) for analysis.

Additionally, jump height was calculated and averaged across trials. Jump height was defined as the difference between the pelvis height at jump initiation and pelvis height at maximal point of the jump trajectory. Since the task was to perform a drop jump, large jump heights were not expected.

Statistical Analysis

Our primary research aim was to estimate differences among groups at each time point (IC and $vGRF_{max}$) among 4 dependent variables: hindfoot sagittal plane position, hindfoot frontal plane position, forefoot sagittal plane position and forefoot frontal plane position. Therefore for each dependent variable, we conducted a test for group differences separately at each time point within a mixed-model ANOVA with model effects for group (control, coper, FAI), time (IC, $vGRF_{max}$) and the group by time interaction. These tests compared model effects to address our specific research questions regarding the effect of group at IC, and the effect of group at $vGRF_{max}$. We chose to conduct these tests within a mixed-model ANOVA (as opposed to independent 1-way ANOVAs) to account for correlations among data at each time point and within groups, thus increasing statistical power and decreasing error due to multiple comparisons. At each time point, if the test for group was significant (alpha = 0.05), we investigated group differences using 3 pairwise comparisons with a Bonferroni adjusted alpha of 0.0167.

In addition to the primary analyses, group differences in the CAIT, jump height, failed jump trials and perceived instability were analyzed using one-way ANOVAs. For all one-way ANOVAs, alpha was set at 0.05 and Tukey post hoc test was used for significant differences. All analyses were completed using SAS 9.2 (SAS Institute Inc., Cary, North Carolina, USA).

Results

Subject demographics

Subject demographics are reported in Table 1. There were significant differences between groups on the CAIT ($F_{2,66}$=95.377, p<0.001). Tukey post hoc revealed that the FAI group scored significantly lower than the coper and control groups (FAI vs. coper: mean difference= -7.22, SE= 0.65, 95% Confidence Interval [CI]= -8.78 to -5.66; FAI vs. control: mean difference= -8.26, SE=0.65, 95% CI= -9.82 to -6.70). Lower CAIT scores indicated decreased function. The coper and control groups were not significantly different from each other (control vs. coper: mean difference = 1.04, SE=0.65, 95% CI= -0.52 to 2.61).

Single Leg Drop Jump

Descriptive data for jump landing kinematics are reported by group in Table 2.

Dorsiflexion and Plantarflexion

For the forefoot in the sagittal plane (i.e. dorsiflexion/plantarflexion), there was a significant group difference at IC ($F_{2,66}$=3.31, p=0.043). Using our boneforoni adjusted alpha (p=0.0167) we could not find the differences between groups, however there was a clear trend toward increased dorsiflexion in the coper group compared to the FAI and control groups (Control vs. Coper: t=-2.37, df=66, p=0.021, mean difference= -2.75˚, SE=1.16, 95% CI= -5.07 to -0.43; Coper vs. FAI: t=2.05, df=66, p=0.044, mean difference= 2.39˚, SE=1.16, 95% CI= 0.07 to 4.71; Control vs. FAI: t=-0.31, df=66, p=0.757, mean difference= -0.36˚, SE=1.16, 95% CI= -2.68 to 1.96). There was no significant group difference in forefoot sagittal plane motion at $vGRF_{max}$ ($F_{2,66}$=0.84, p=0.435).

For the hindfoot in the sagittal plane, there was a significant group difference at IC ($F_{2,66}$=6.12, p=0.004). Specifically, post hoc testing at IC revealed that individuals with FAI were significantly more dorsiflexed than the control or coper groups (Control vs. FAI: t=-3.14, df=66, p=0.003, mean difference= -3.43˚, SE=1.09, 95% CI= -5.61 to -1.25; Coper vs. FAI: t=-2.91, df=66, p=0.005, mean difference= -3.18˚, SE=1.09, 95% CI= -5.36 to -1.00). The control and coper groups were not significantly different from each other (t=-0.23, df=66, p=0.822, mean difference= -0.25˚, SE=1.09, 95% CI= -2.43 to 1.93). There were no significant group difference in hindfoot sagittal plane motion at $vGRF_{max}$ ($F_{2,66}$=0.05, p=0.952).

Inversion and Eversion

For both the hindfoot and forefoot in the frontal plane (i.e. inversion/eversion), there were no significant group differences at IC or $vGRF_{max}$ (Hindfoot IC: $F_{2,66}$=0.77, p=0.466; Hindfoot $vGRF_{max}$: $F_{2,66}$=0.52, p=0.596; Forefoot IC: $F_{2,66}$=1.40, p=0.245; Forefoot $vGRF_{max}$: $F_{2,66}$=1.72, p=0.188; Table 2).

Jump height and perceived stability

There was no significant difference in jump height between groups ($F_{2,66}$=1.06, p=0.354; Control: 0.015±0.028m, Coper: 0.013±0.027m, FAI: 0.025±0.031m), indicating that, regardless of group, subjects jumped to similar heights. The small magnitude of the average jump indicates that subjects correctly performed the drop jump. There was no significant difference between groups for the number of unsuccessful jump landing trials ($F_{2,66}$=0.91, p=0.407; Control: 1.30±1.58; Coper: 1.83±1.72; FAI: 1.87±1.42). However, there was a significant difference between groups regarding their perceived instability during the jump landing task ($F_{2,66}$=18.92, p<0.001; Control: 8.35±1.30, Coper: 8.32±1.67; FAI: 5.77±1.80). Tukey's post hoc revealed that individuals with FAI perceived significantly greater instability than controls or copers (Control vs. FAI: mean difference= 2.58˚, SE=0.48, 95% CI=1.43 to 3.72; Coper vs. FAI: mean difference=2.55˚, SE=0.48, 95% CI=1.39 to 3.70). Controls and copers were not significantly different from each other (mean difference=0.03˚, SE=0.48, 95% CI= -1.12 to 1.17).

Discussion

We hypothesized that individuals with FAI would have greater plantarflexion at IC and greater inversion at $vGRF_{max}$. Our hypotheses were only partially supported by our findings. While we did find group differences in sagittal plane motion at IC, in general the direction of this motion was contrary to our expectations, and there were no group differences in hindfoot or forefoot inversion.

Dorsiflexion and Plantarflexion

There are several reports examining jump landing kinematics between individuals with FAI and controls[8, 11, 16-19] and between individuals with FAI and copers.[12] To our knowledge, we are the first to include all 3 groups in a single study. We found significant group differences at IC for both forefoot and hindfoot sagittal plane motion (dorsiflexion/plantarflexion). Specifically, the FAI group had more hindfoot dorsiflexion than either the control or coper groups. Our results agree with the findings of Caulfield and Garrett,[11] who reported increased dorsiflexion in their FAI group compared to controls. They hypothesized that increased dorsiflexion in individuals with FAI may be a protective adaptation, as increased dorsiflexion creates a more stable position for the lateral ankle ligaments and the talocrural joint. If increased dorsiflexion is a positive adaptation to increase stability post-ankle sprain, one might assume that the coper group should also demonstrate this pattern. However, we found that our coper group did not demonstrate increased dorsiflexion. This indicates that increased dorsiflexion is not an adaptation common to all individuals with a history of ankle sprain, but rather, it is specific to individuals who experience instability. Copers in our study maintained dynamic stability without adopting a more dorsiflexed movement pattern.

Contrary to the hypothesis of Caulfield and Garrett,[11] it might be argued that the increased dorsiflexion noted in individuals with FAI is not a positive adaptation, but is perhaps a less stable movement pattern that actually contributes to FAI. One potential explanation for how increased dorsiflexion at IC could contribute to instability is that it decreases the time over which the joint can absorb impact forces. Landing with greater plantarflexion at IC allows a greater ROM for force attenuation. If indeed, increased dorsiflexion is a less stable movement pattern, it may have preceded the development of FAI and served as a contributing mechanism. However, given the retrospective nature of our study design, we cannot establish the temporal relationship between instability and increased dorsiflexion.

Although our finding of increased hindfoot dorsiflexion agrees with the work of Caulfield and Garrett,[11] it should be noted that several other reports found no difference in ankle dorsiflexion at IC of jump landing between individuals with FAI and controls,[8, 17, 18] or between individuals with FAI and copers.[12] Although the studies reporting no difference reported low power, their average sample size (22.5±2.7 per group) was almost identical to ours (n=23 per group). Thus, it does not appear that insufficient subjects was the sole cause for differing results. It could be that slight differences in methods or subject inclusion criteria account for the conflicting results between studies, with the most obvious difference being the use of a single- or multi-segment foot model.

We also found a significant difference between groups for forefoot sagittal plane motion, however post-hoc testing could not find the differences (using an adjusted alpha of 0.0167). Despite the insignificant *p*-value, the mean differences between coper and FAI group (2.39˚, SE=1.16, 95% CI= 0.07 to 4.71), and control and coper group (-2.75˚, SE=1.16, 95% CI= -5.07 to -0.43), appear to be worth further investigation. The meaning of this trend is not clear, but given the coper group's stability, it may be a positive adaptation. Further research is needed before drawing any firm conclusions.

Inversion and Eversion

We did not find frontal plane (i.e. inversion/eversion) group differences at IC or $vGRF_{max}$ at either the hindfoot or forefoot segments. This lack of significant differences at IC is consistent with other reports using a drop jump landing task,[8, 12] although one of these reports did find increased inversion in the interval prior to IC.[8] Delahunt et al.[17] were the only authors to report increased ankle inversion in individuals with FAI specifically at IC, however, rather than a jump landing task they used a lateral hop. Differences in the nature of a lateral hopping task may account for why they found increased inversion at IC, while our study and others[8, 12] found no group differences.

Perceived Stability

Additionally, we tracked participant's perceived stability during task completion, with the primary purposes of assessing whether our task sufficiently challenged dynamic stability in our subjects, and assessing which group of individuals would feel most challenged by the same task. Previous research has used a simple binary question (e.g. "Did you feel unstable while completing this task?") to assess perceived stability during task completion.[25, 34] However, we felt that perceived stability most likely exists in a continuum. Thus, we asked our subjects to report stability on a scale of 0 (very unstable) to 10 (very stable). Our FAI group reported feeling significantly less stable (mean=5.8) than both copers and controls (mean=8.3 and 8.4, respectively). This provides evidence that the task itself was sufficient to challenge stability, especially in FAI subjects.

Limitations

Our subjects completed the jump landing task barefoot, because the multiple anatomical markers attached to each foot prevented them from wearing normal athletic shoes. Several subjects (from all groups) complained that the jump landing was uncomfortable because of the lack of cushioning a shoe would normally provide. No subject was unable to complete the task due to this discomfort. However, it might have modified landing strategy compared to a shod landing. Despite this limitation, we believe our group comparisons are still valid since subjects in all group were tested under the same barefoot condition.

Additionally, we chose to use a drop jump from a 40cm box based on previous research on jump landing kinematics in the FAI population.[8] However, during the course of testing we noticed that using a single box height can create unequal task difficulty for a very short versus very tall individual. Because our subjects were matched on height, we feel that this limitation did not affect our group comparisons. However, we recommend future research normalize box height to a percentage of subject height to create a more equal task between subjects.

Summary

We did not find expected group differences in inversion during task completion. We found increased hindfoot dorsiflexion at IC in individuals with FAI. However, individuals with a similar history of ankle sprain, but no instability (copers), did not utilize a similar pattern of increased hindfoot dorsiflexion. Greater dorsiflexion in individuals with FAI is thought to be an adaption to increase stability.[11] Copers may not need this strategy because they are already stable, or it may be that increased dorsiflexion is not actually a positive adaptation after all—but rather a less stable movement pattern that contributes to FAI. Future ankle instability research should continue to use a similar 3 group model, to further investigate dynamic stability mechanisms in individuals with and without FAI.

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Table 1. Subject Demographics

	Control		Coper		FAI	
Descriptor	**M**	**SD**	**M**	**SD**	**M**	**SD**
Age, years	23.17	4.01	23.52	3.68	23.30	3.84
Height, m	1.72	0.08	1.72	0.07	1.71	0.11
Weight, kg	68.78	13.26	69.57	13.94	68.66	14.60
CAIT, score	28.78	1.78	27.74	1.69	20.52	2.94[a]

Abbreviations: FAI = Functional Ankle Instability, CAIT = Cumberland Ankle Instability Tool.

[a] FAI group scored significantly lower than stable and coper groups

Table 2. Kinematics (degrees) during Single Leg Drop Jump task

	Control				Coper				FAI					
			95% CI				95% CI				95% CI			
Kinematics	**M**	**SE**	**Lower**	**Upper**	**M**	**SE**	**Lower**	**Upper**	**M**	**SE**	**Lower**	**Upper**	$F_{2,66}$	***p*-value**
Initial Contact:														
Forefoot														
Sagittal Plane[a]	-10.69	0.82	-12.33	-9.04	-7.94	0.82	-9.58	-6.30	-10.32	0.82	-11.96	-8.68	3.31	0.043[c]
Frontal Plane[b]	-5.79	0.52	-6.84	-4.74	-5.41	0.52	-6.46	-4.36	-4.58	0.52	-5.62	-3.53	1.40	0.245
Hindfoot														
Sagittal Plane[a]	-13.51[d]	0.77	-15.05	-11.96	-13.26[e]	0.77	-14.80	-11.72	-10.08[d,e]	0.77	-11.62	-8.54	4.01	0.004[c]
Frontal Plane[b]	8.54	1.08	6.40	10.69	6.67	1.08	4.52	8.81	7.81	1.08	5.66	9.96	0.77	0.466
Toe-off:														
Forefoot														
Sagittal Plane[a]	5.93	0.62	4.69	7.17	6.47	0.62	5.23	7.71	7.07	0.62	5.83	8.31	0.84	0.435
Frontal Plane[b]	-4.38	0.55	-5.47	-3.29	-3.72	0.55	-4.82	-2.63	-2.95	0.55	-4.04	-1.86	1.72	0.188
Hindfoot														
Sagittal Plane[a]	4.92	0.84	3.25	6.60	5.22	0.84	3.55	6.90	4.88	0.84	3.21	6.56	0.05	0.952
Frontal Plane[b]	-7.70	0.74	-9.17	-6.22	-8.74	0.74	-10.22	-7.26	-8.42	0.74	-9.90	-6.95	0.52	0.596

Abbreviation: FAI = Functional Ankle Instability, CI=Confidence Interval.
[a] Positive angle indicates dorsiflexion, negative angle indicates plantarflexion.
[b] Positive angle indicates inversion, negative angle indicates eversion.
[c] Significant difference between groups
[d] Significant difference between controls and FAI
[e] Significant difference between copers and FAI

APPENDICES

APPENDIX A:

Additional Methods and Results

Methods

Walking Gait

After completing 10 walking trials, subjects were asked to rate how stable their ankle felt while completing the task on a scale of 0-10, with 0 indicating very unstable and ten 10 indicating very stable.

Single Leg Drop Jump

After completing 10 successful SLDJ trials, subjects were again asked to rate how stable their ankle felt while completing the task on a scale of 0-10, with 0 indicating very unstable and ten 10 indicating very stable. The number of unsuccessful SLDJ trials was also recorded for each subject.

Analyses

In addition to the primary analyses, the number of physical activity per week, unsuccessful jump trials, and perceived instability during task completion were analyzed using one-way ANOVAs. We also used one-way ANOVAs to compare maximal active ROM data in 4 directions (inversion, eversion, plantarflexion, dorsiflexion), and total ROM in 2 planes (sagittal and frontal). For all tests, alpha was set at 0.05 and Tukey post hoc test was used for all significant differences.

Pearson chi-squared tests were used to test for differences between the FAI and coper groups for the categorical variables of injury severity and professional medical care sought. For all other categorical clinical exam variables (i.e. ligamentous laxity, pain at end ROM, pain on palpation) all possible 2 group comparisons (i.e. control vs. coper, control vs. FAI, coper vs. FAI) were tested using Fisher's exact tests. The Fisher's exact test was chosen over the chi-squared due to low expected cell counts. For ligamentous laxity tests, the 5 categories were collapsed into clinical terms of positive tests (score of 4 or 5) or negative tests (score of 1-3). The purpose of these analyses was to further characterize the profile of an individual with FAI compared to an ankle sprain coper or a healthy control.

Results

Subject Demographics

There was no significant difference between the 3 groups for weekly physical activity ($F_{2,66}$=1.21, *p*=0.306; Control: 7.76±4.94, Coper: 5.41±3.12; FAI: 7.07±7.00).

Clinical Exam and Active Range of Motion

The frequency at which the coper and FAI groups sought medical treatment for their initial ankle sprain was not significantly different (Pearson χ^2 =1.08, df=1, *p*=0.300), nor was there a significant difference between the severity of initial injury between these 2 groups (Pearson χ^2 =1.63, df=3, *p*=0.653).

Frequency data as well as 2-sided Fisher's exact test p-values for ligamentous laxity, pain at end ROM, and pain over the lateral ligaments are reported in Table 1. In summary, individuals with FAI were significantly more likely than controls to test positive for anterior drawer and talar tilt laxity. Individuals with FAI were also more likely than copers to test positive for talar tilt laxity. There was no difference between copers and FAI for anterior drawer laxity, or between copers and controls for either talar tilt or anterior drawer laxity. There were no significant differences between groups regarding pain on palpation of the lateral ankle ligaments. Regarding pain on end ROM, in the direction of inversion individuals with FAI were significantly more likely to report pain than either copers or controls. However there were no group differences regarding pain at end ROM in any other direction.

Data collection errors resulted in missing active ROM data for 1 coper subject and 1 healthy subject, thus all analyses were performed on the remaining 67 subjects. There were no significant group differences for eversion, inversion, plantarflexion, dorsiflexion or total inversion/eversion ROM (Table 2). There was a significant group difference for total dorsiflexion/plantarflexion ROM ($F_{2,64}$=4.36, p=0.017). Specifically, individuals with FAI had significantly less active ROM than copers. However, controls were not significantly different from individuals with FAI or copers.

Walking Gait

There was no significant difference between groups regarding their perceived instability during the walking task ($F_{2,66}$=1.73, p=0.185; Control: 9.74±0.62; Coper: 9.96±0.21; 9.74±0.45).

Table 1. Clinical Exam Results

Clinical Test	Control N	Control (%)	Coper N	Coper (%)	FAI N	FAI (%)	Fisher's Exact P-value: Control vs. Coper	Control vs. FAI	Coper vs. FAI
Anterior Drawer									
Negative	20	(87.0)	15	(65.2)	11	(47.8)	0.165	0.011[a]	0.373
Positive	3	(13.0)	8	(34.8)	12	(52.2)			
Talar Tilt									
Negative	22	(95.7)	20	(87.0)	13	(56.5)	0.608	0.004[a]	0.047[a]
Positive	1	(4.3)	3	(13.0)	10	(43.5)			
Anterior talofibular ligament									
Pain	0	(0)	0	(0)	4	(17.4)	--[b]	0.109	0.109
No pain	23	(100)	23	(100)	19	(82.6)			
Calcaneofibular ligament									
Pain	0	(0)	0	(0)	3	(13.0)	--[b]	0.233	0.233
No pain	23	(100)	23	(100)	20	(87.0)			
Posterior talofibular ligament									
Pain	0	(0)	1	(4.3)	4	(17.4)	1.000	0.109	0.346
No pain	23	(100)	22	(95.7)	19	(82.6)			
Plantarflexion end ROM									
Pain	0	(0)	0	(0)	3	(13.0)	--[b]	0.233	0.233
No Pain	23	(100)	23	(100)	20	(87.0)			
Dorsiflexion end ROM									
Pain	0	(0)	0	(0)	1	(4.3)	--[b]	1.000	1.000
No pain	23	(100)	23	(100)	22	(95.7)			
Inversion end ROM									
Pain	0	(0)	0	(0)	6	(26.1)	--[b]	0.022[a]	0.022[a]
No pain	23	(100)	23	(100)	17	(73.9)			
Eversion end ROM									
Pain	0	(0)	2	(8.7)	2	(8.7)	0.489	0.489	1.000
No pain	23	(100)	21	(91.3)	21	(91.3)			

Abbreviations: FAI = Functional Ankle Instability, ROM = range of motion.
[a] Significant difference between groups calculated using 2-sided Fisher's Exact test
[b] Fisher's exact test could not be calculated due to observation of zero in 2 categories.

Table 2. Active Range of Motion by Group with Analysis ($\bar{x}$ ±SD)

ROM direction	Control	Coper	FAI	$F_{2,64}$	P-value
Eversion	5.43±8.99	5.65±6.96	3.48±6.74	0.56	0.575
Inversion	22.27±8.84	25.43±7.40	24.90±9.15	0.87	0.422
Plantarflexion	28.21±4.64	29.18±5.25	25.63±6.33	2.56	0.086
Dorsiflexion	11.29±4.30	14.04±5.74	10.99±5.04	2.44	0.095
Total ROM Inversion/Eversion	27.70±7.18	31.08±7.24	28.38±8.18	1.24	0.297
Total ROM Dorsiflexion/Plantarflexion	39.50±6.43	43.22±8.16 [a]	36.62±7.81[a]	4.36	0.017

Abbreviations: FAI = Functional Ankle Instability, ROM = Range of Motion.
[a] significant difference between FAI and coper groups

Single-Leg Drop Jump

There was no significant difference between groups for the number of unsuccessful SLDJ trials ($F_{2,66}$=0.91, p=0.407; Control: 1.30±1.58; Coper: 1.83±1.72; FAI: 1.87±1.42). There was a significant difference between groups regarding their perceived instability during the SLDJ task ($F_{2,66}$=18.92, p<0.001; Control: 8.35±1.30, Coper: 8.32±1.67; FAI: 5.77±1.80). Tukey's post hoc revealed that individuals with FAI perceived significantly greater instability than controls or copers. Controls and copers were not significantly different from each other.

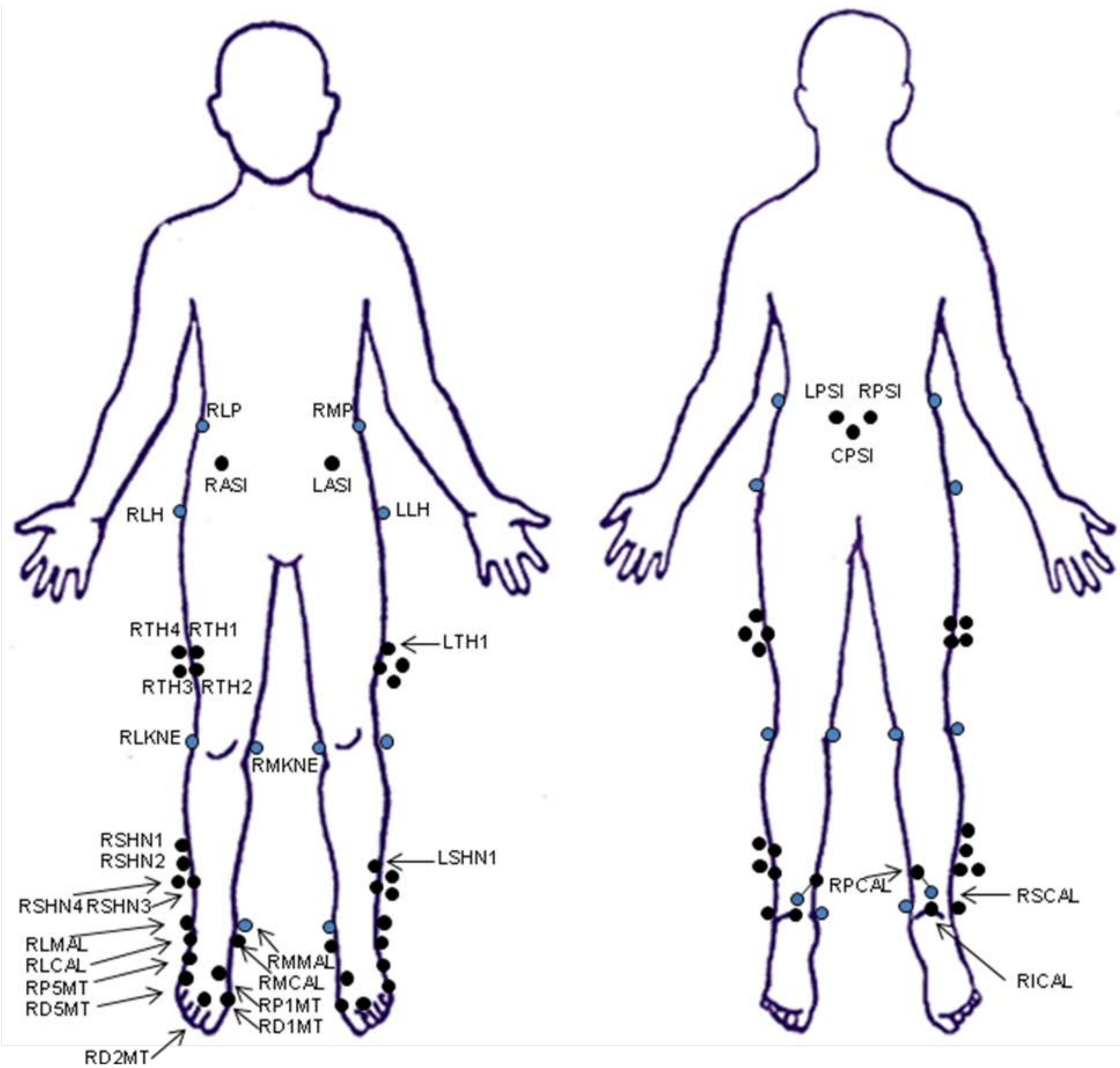
APPENDIX B

Additional Details on Subject Recruitment and Inclusion

	FAI	**COPER**	**Control**
Subject Assigned ID	14m, 14f = 28	14m, 14f = 27	14m, 14f = 28
Didn't meet criteria	1m, 1f = -2	2m, 1f = -3	2m, 1f = -3
Couldn't follow instructions	1m, 0f = -1	0m, 0f = -0	0m, 0f = -0
No match	0m, 2f = -2	0m, 1f = -1	0m, 2f = -2
Final included	12m, 11f = 23	12m, 11f = 23	12m, 11f = 23

APPENDIX C

Marker Placement



APPENDIX D

IRB Consent Form

RESEARCH SUBJECT INFORMATION AND CONSENT FORM

TITLE: Hindfoot and forefoot kinematics during gait and jump landing among individuals with and without Functional Ankle Instability

VCU IRB PROTOCOL NUMBER:

INVESTIGATORS: Brent Arnold, PhD; Scott Ross, PhD; Jessica Ketchum, PhD; Cynthia Wright, MEd

This consent form may contain words that you do not understand. Please ask the study staff to explain any words or information that you do not clearly understand. You may take home an unsigned copy of this consent form to think about or discuss with family or friends before making your decision.

PURPOSE OF THE STUDY

The purpose of this research study is to determine whether different movement patterns exist among 3 types of people: 1) individuals with a history of multiple ankle sprains, 2) individuals with only 1 ankle sprain, 3) individuals who have never had an ankle sprain. Specifically, we want to test whether motion (for example ankle joint angle or ground reaction force) is different while walking and landing from a jump. You are being asked to participate in this study because you are a healthy, physically active adult who we believe fits into 1 of those 3 categories.

DESCRIPTION OF THE STUDY

In this study, you will be asked to fill out a couple questionnaires about your history of lower extremity injury. Next reflective markers will be placed on your torso and lower body using double-sided tape or non-stick pre-wrap tape. Then you will be asked to walk across a platform and jump down off of a box several times each, so that we can record your movement patterns.

Your participation in this study will last up to 1 hour. Approximately 90 subjects will participate in this study.

PROCEDURES
If you decide to be in this research study, you will be asked to sign this consent form after you have had all your questions answered. Participation will include just one visit to the Sports Medicine Research Laboratory. During this session you will complete each of the following activities in the following order:

Step 1.
General demographic information, such as you age, gender, height, weight and history of leg or ankle injury will be recorded. Next you will fill out a couple questionnaires about your foot and ankle function.

Step 2.
An examiner will do a short physical examination of your ankle, testing your ligaments and touching the side of your ankle. Next the same examiner will attach approximately 55 reflective markers to your torso and lower body. Some of these markers will be attached using double sided tape, while 4 rigid plates with markers on them will be attached using non-stick tape pre-wrap. You will be barefoot during this portion of the trial. You will be asked to briefly stand on the platform while a 2-5 second static trial is recorded. You will also be asked to move your ankle in and out, then up and down, in order to test your range of motion.

Step 3.
Next you will be asked to walk in a straight line across the test platform, at a normal walking pace. You will be given time to practice and get comfortable walking with the reflective markers attached. Once you are comfortable you will be asked to walk across the testing platform approximately 10 times.

Step 4.
Once you have completed the walking trials you will move on to a drop jump activity. For this second activity you will step off a 40cm box using one leg, and land on a force plate on your opposite leg. You must balance on your landing leg for at least 10 seconds after landing. The investigator will demonstrate proper technique, give you at least 3 practice trials per leg, and then we will record 20 drop jumps (10 for each leg). Each jump will be separated by at least 30 seconds of rest. And 5 minutes of rest will be given between legs.

RISKS AND DISCOMFORTS
As with any physical activity, you could possibly injure yourself or experience discomfort due to the muscular effort of walking and jumping. Any muscular discomfort should be brief and not associated with any complications. The risk of injury due to tripping or falling is not greater than you normally experience while walking, jogging or engaging in moderate physical activity.

BENEFITS TO YOU AND OTHERS
This is not a treatment study, and you are not expected to receive any direct medical benefits from your participation in the study. The information from this research study may assist the researchers in future research related to musculoskeletal injury.

COSTS

There are no charges for the study visit.

PAYMENT FOR PARTICIPATION
You will be paid $10 for completion of this study.

ALTERNATIVE TREATMENT
This investigation is not a treatment study. Your alternative is not to participate in this study.

CONFIDENTIALITY
Potentially identifiable information about you will consist of your age, gender, history of lower limb injury, anthropometric data (e.g. height, weight), lower body kinematics (e.g. joint angle) and kinetics (e.g. ground reaction forces).

Data is being collected only for research purposes. The information will be identified by an anonymous study number. At the conclusion of the study any link between your name and this code will be destroyed. The data collected will be kept in a locked room and any electronic records are also kept in a password enabled computer in the locked room. The data will only be accessible to investigators. A data and safety monitoring plan is established.

You should know that research data and medical information about you may be reviewed or copied by the sponsor of the research or by Virginia Commonwealth University.

Although results of this research may be presented at meetings or in publications, identifiable personal information pertaining to participants will not be disclosed.

COMPENSATION FOR INJURY
Virginia Commonwealth University and the VCU Health System have no plan for providing long-term care or compensation in the event that you suffer injury as a result of your participation in this research study.

If you are injured or if you become ill as a result of your participation in this study, inform your study staff immediately. Your study staff will arrange for short-term emergency care or referral if it is needed.

Fees for such treatment may be billed to you or to appropriate third party insurance. Your health insurance company may or may not pay for treatment of injuries as a result of your participation in this study.

VOLUNTARY PARTICIPATION AND WITHDRAWAL
Your participation in this study is voluntary. You may decide to not participate in this study. Your decision not to take part will involve no penalty or loss of benefits to which you are otherwise entitled. If you do participate, you may freely withdraw from the study at any time. Your decision to with draw will involve no penalty or loss of benefits to which you are otherwise entitled.

Your participation in this study may be stopped at any time by the staff without your consent. The reasons might include:

- the study staff think it necessary for your health or safety;
- you have not followed study instructions;
- administrative reasons require your withdrawal.

QUESTIONS

In the future, you may have questions about your study participation. You may also have questions about a possible research-related injury. If you have any questions, complaints, or concerns about the research, contact:

Brent L. Arnold, PhD, ATC
PO Box 842020
Richmond, VA 23284-2020
804-828-1948

If you have questions about your rights as a research subject, you may contact:

Office of Research
Virginia Commonwealth University
800 East Leigh Street, Suite 113
PO Box 980568
Richmond, VA 23298
(804) 827-2157

You may also contact this number for general questions, concerns or complaints about the research. Please call this number if you cannot reach the research team or wish to talk to someone else.

Do not sign this consent form unless you have had a chance to ask questions and have received satisfactory answers to all of your questions. Additional information about participation in research studies can be found at http://www.research.vcu.edu/irb/volunteers.htm.

CONSENT

I have been provided with an opportunity to read this consent form carefully. All of the questions that I wish to raise concerning this study have been answered.

By signing this consent form, I have not waived any of the legal rights or benefits, to which I otherwise would be entitled. My signature indicates that I freely consent to participate in this research study. I will receive a copy of the consent form once I have agreed to participate.

____
Subject Name, printed

____ _______________
Subject Signature Date

____

Name of Person Conducting Informed Consent Discussion (Printed)

____ ______________

Signature of Person Conducting Informed Consent Discussion Date

____ ______________

Principal Investigator Signature (if different from above) Date

APPENDIX E:

Cumberland Ankle Instability Tool

Please tick the ONE statement in EACH question that BEST describes your ankles in the last year.

	Left	**Right**
1. I have pain in my ankle		
Never	☐	☐
During sport	☐	☐
Running on uneven surfaces	☐	☐
Running on level surfaces	☐	☐
Walking on uneven surfaces	☐	☐
Walking on level surfaces	☐	☐
2. My ankle feels UNSTABLE		
Never	☐	☐
Sometimes during sport (not every time)	☐	☐
Frequently during sport (every time)	☐	☐
Sometimes during daily activity	☐	☐
Frequently during daily activity	☐	☐
3. When I make SHARP turns, my ankle feels UNSTABLE		
Never	☐	☐
Sometimes when running	☐	☐
Often when running	☐	☐
When walking	☐	☐
4. When going down the stairs, my ankle feels UNSTABLE		
Never	☐	☐
If I go fast	☐	☐
Occasionally	☐	☐
Always	☐	☐
5. My ankle feels UNSTABLE when standing on ONE leg:		
Never	☐	☐
On the ball of my foot	☐	☐
With my foot flat	☐	☐
6. My ankle feels UNSTABLE when:		
Never	☐	☐
I hop from side to side	☐	☐
I hop on the spot	☐	☐
When I jump	☐	☐
7. My ankle feels UNSTABLE when:		
Never	☐	☐
I run on uneven surfaces	☐	☐
I jog on uneven surfaces	☐	☐
I walk on uneven surfaces	☐	☐
I walk on a flat surface	☐	☐

8. TYPICALLY, when I start to roll over (or “twist”) on my ankle, I can stop it:		
Immediately	☐	☐
Often	☐	☐
Sometimes	☐	☐
Never	☐	☐
I have never rolled over on my ankle	☐	☐
9. After a TYPICAL incident of my ankle rolling over, my ankle returns to “normal”:		
Almost immediately	☐	☐
Less than one day	☐	☐
1–2 days	☐	☐
More than 2 days	☐	☐
I have never rolled over on my ankle	☐	☐

APPENDIX F:

Foot and Ankle Ability Measure

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).

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

	No difficulty	Slight difficulty	Moderate difficulty	Extreme difficulty	Unable to do	N/A
Standing	☐	☐	☐	☐	☐	☐
Walking on even ground	☐	☐	☐	☐	☐	☐
Walking on even ground without shoes	☐	☐	☐	☐	☐	☐
Walking up hills	☐	☐	☐	☐	☐	☐
Walking down hills	☐	☐	☐	☐	☐	☐
Going up stairs	☐	☐	☐	☐	☐	☐
Going down stairs	☐	☐	☐	☐	☐	☐
Walking on uneven ground	☐	☐	☐	☐	☐	☐
Stepping up and down curbs	☐	☐	☐	☐	☐	☐
Squatting	☐	☐	☐	☐	☐	☐
Coming up on your toes	☐	☐	☐	☐	☐	☐
Walking initially	☐	☐	☐	☐	☐	☐
Walking 5 minutes or less	☐	☐	☐	☐	☐	☐
Walking approximately 10 minutes	☐	☐	☐	☐	☐	☐
Walking 15 min or greater	☐	☐	☐	☐	☐	☐
Home Responsibilities	☐	☐	☐	☐	☐	☐
Activities of daily living	☐	☐	☐	☐	☐	☐
Personal care	☐	☐	☐	☐	☐	☐
Light to moderate work (standing, walking)	☐	☐	☐	☐	☐	☐

Heavy work (push/pulling, climbing, carrying)	☐	☐	☐	☐	☐	☐
Recreational activities	☐	☐	☐	☐	☐	☐

FAAM Sports Scale

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).

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

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

APPENDIX G:

Injury History Questionnaire

	Left side	**Right side**
1. Have you ever sprained your ankle? If no, skip to question 8	☐ Yes ☐ No	☐ Yes ☐ No
2. Was the sprain evaluated by a medical professional? If no, skip to question 4	☐ Yes ☐ No	☐ Yes ☐ No
3. What was the diagnosed severity of injury?	☐ Mild (Grade 1) ☐ Moderate (Gr. 2) ☐ Severe (Grade 3) ☐ Don't remember	☐ Mild (Grade 1) ☐ Moderate (Gr. 2) ☐ Severe (Grade 3) ☐ Don't remember
4. How long did you have to limit your physical activity after your ankle sprain?	☐ Less 1 day ☐ Between 1-7 days ☐ Greater 1 week	☐ Less 1 day ☐ Between 1-7 days ☐ Greater 1 week
5. Did you have to limit your weight bearing activities (through the use of crutches, an ankle brace, staying off of your feet)?	☐ No not at all. ☐ Yes, for ___ days	☐ No not at all. ☐ Yes, for ___ days
6. After the initial sprain, have you ever re-sprained your ankle?	☐ No, never ☐ Yes, ___ times	☐ No, never ☐ Yes, ___ times
7. After the initial sprain, it may have taken a while to resume physical activity. But in the last 12 months, have you been able to resume all pre-injury physical activities?	☐ Yes ☐ No	☐ Yes ☐ No

8. Does your ankle ever give-way, roll-over or feel unstable? If "yes, multiple times", **how often**?	☐ No, never ☐ Yes, once ☐ Yes, multiple times ___ times a _______	☐ No, never ☐ Yes, once ☐ Yes, multiple times ___ times a _______
9. Have you ever broken or had surgery on your lower leg or ankle?	☐ Yes ☐ No	☐ Yes ☐ No
10. Have you ever broken or had surgery anywhere else on your hip, thigh or knee?	☐ Yes ☐ No	☐ Yes ☐ No
11. Do you currently have any pain, swelling, or decreased movement in your lower	☐ Yes ☐ No	☐ Yes ☐ No

extremity or ankle?		
12. Do you have any other medical conditions that may affect your ability to participate? (e.g. nervous system disorder, recent concussion)	☐ Yes ☐ No	
13. Approximately how many hours per week are you physically active?	____ hours/week	
14. What type of physical activity do you perform regularly? (please describe)		
15. If you were going to kick a ball, which leg would you kick it with?	☐ Left ☐ Right	

APPENDIX H:

Statistical Printout for Specific Aims 1 & 2

```
                     The SAS System          09:00 Tuesday, April 5, 2011
1

                  The Mixed Procedure

                   Model Information

Data Set                     CJW.DISSERTATION_
                             TRIAL11ONLY_STACKED
Dependent Variable           FFwalkX
Covariance Structure         Unstructured
Subject Effect               SubjectID
Estimation Method            REML
Residual Variance Method     None
Fixed Effects SE Method      Kenward-Roger
Degrees of Freedom Method    Kenward-Roger


                Class Level Information

Class        Levels    Values

time              2    1 2
Group             3    1 2 3
SubjectID        69    C01 C02 C03 C04 C05 C06 C07
                       C08 C10 C12 C13 C14 C15 C16
                       C18 C20 C21 C23 C24 C25 C26
                       C27 C28 F01 F02 F03 F04 F05
                       F06 F07 F09 F10 F12 F13 F14
                       F17 F19 F20 F21 F22 F23 F24
                       F25 F26 F27 F28 H01 H02 H04
                       H05 H06 H07 H08 H09 H10 H11
                       H12 H14 H16 H17 H18 H20 H21
                       H22 H23 H25 H26 H27 H28


                      Dimensions

         Covariance Parameters             3
         Columns in X                     12
         Columns in Z                      0
         Subjects                         69
         Max Obs Per Subject               2

                 Number of Observations

     Number of Observations Read            138
     Number of Observations Used            138
     Number of Observations Not Used          0
```

The Mixed Procedure

Iteration History

Iteration	Evaluations	-2 Res Log Like	Criterion
0	1	719.05477653	
1	1	674.36845891	0.00000000

Convergence criteria met.

Estimated R Matrix
for SubjectID C01

Row	Col1	Col2
1	7.8985	7.2952
2	7.2952	15.6752

Estimated R Correlation
Matrix for SubjectID C01

Row	Col1	Col2
1	1.0000	0.6556
2	0.6556	1.0000

Covariance Parameter Estimates

Cov Parm	Subject	Estimate	Standard Error	Z Value	Pr Z
UN(1,1)	SubjectID	7.8985	1.3750	5.74	<.0001
UN(2,1)	SubjectID	7.2952	1.6378	4.45	<.0001
UN(2,2)	SubjectID	15.6752	2.7287	5.74	<.0001

Fit Statistics

-2 Res Log Likelihood	674.4
AIC (smaller is better)	680.4
AICC (smaller is better)	680.6
BIC (smaller is better)	687.1

The Mixed Procedure

Null Model Likelihood Ratio Test

DF	Chi-Square	Pr > ChiSq
2	44.69	<.0001

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
time	1	66	334.78	<.0001
Group	2	66	0.27	0.7650
time*Group	2	66	2.99	0.0569

Estimates

Label	Estimate	Standard Error	DF	t Value	Pr > |t|	Alpha	Lower	Upper
Time 1: G1-G2	0.3302	0.8288	66	0.40	0.6916	0.05	-1.3244	1.9849
Time 1: G1-G3	0.4597	0.8288	66	0.55	0.5809	0.05	-1.1949	2.1144
Time 1: G2-G3	0.1295	0.8288	66	0.16	0.8763	0.05	-1.5252	1.7842
Time 2: G1-G2	-0.4708	1.1675	66	-0.40	0.6881	0.05	-2.8018	1.8602
Time 2: G1-G3	-1.6808	1.1675	66	-1.44	0.1547	0.05	-4.0118	0.6502
Time 2: G2-G3	-1.2101	1.1675	66	-1.04	0.3038	0.05	-3.5411	1.1209

Least Squares Means

Effect	time	Group	Estimate	Standard Error	DF	t Value	Pr > |t|	Alpha	Lower	Upper
time*Group	1	1	-1.0418	0.5860	66	-1.78	0.0800	0.05	-2.2118	0.1282
time*Group	1	2	-1.3721	0.5860	66	-2.34	0.0222	0.05	-2.5421	-0.2020
time*Group	1	3	-1.5016	0.5860	66	-2.56	0.0127	0.05	-2.6716	-0.3315
time*Group	2	1	-8.6244	0.8255	66	-10.45	<.0001	0.05	-10.2726	-6.9761
time*Group	2	2	-8.1536	0.8255	66	-9.88	<.0001	0.05	-9.8019	-6.5053
time*Group	2	3	-6.9435	0.8255	66	-8.41	<.0001	0.05	-8.5918	-5.2953

Tests of Effect Slices

Effect	time	Num DF	Den DF	F Value	Pr > F
time*Group	1	2	66	0.16	0.8494
time*Group	2	2	66	1.10	0.3379

The Mixed Procedure

Model Information

Data Set	CJW.DISSERTATION_ TRIAL11ONLY_STACKED
Dependent Variable	FFwalkY
Covariance Structure	Unstructured
Subject Effect	SubjectID
Estimation Method	REML
Residual Variance Method	None
Fixed Effects SE Method	Kenward-Roger
Degrees of Freedom Method	Kenward-Roger

Class Level Information

Class	Levels	Values
time	2	1 2
Group	3	1 2 3
SubjectID	69	C01 C02 C03 C04 C05 C06 C07 C08 C10 C12 C13 C14 C15 C16 C18 C20 C21 C23 C24 C25 C26 C27 C28 F01 F02 F03 F04 F05 F06 F07 F09 F10 F12 F13 F14 F17 F19 F20 F21 F22 F23 F24 F25 F26 F27 F28 H01 H02 H04 H05 H06 H07 H08 H09 H10 H11 H12 H14 H16 H17 H18 H20 H21 H22 H23 H25 H26 H27 H28

Dimensions

Covariance Parameters	3
Columns in X	12
Columns in Z	0
Subjects	69
Max Obs Per Subject	2

Number of Observations

Number of Observations Read	138
Number of Observations Used	138
Number of Observations Not Used	0

The Mixed Procedure

Iteration History

Iteration	Evaluations	-2 Res Log Like	Criterion
0	1	713.62593009	
1	1	694.02652420	0.00000000

Convergence criteria met.

Estimated R Matrix
for SubjectID C01

Row	Col1	Col2
1	10.0089	5.5838
2	5.5838	12.6150

Estimated R Correlation
Matrix for SubjectID C01

Row	Col1	Col2
1	1.0000	0.4969
2	0.4969	1.0000

Covariance Parameter Estimates

Cov Parm	Subject	Estimate	Standard Error	Z Value	Pr Z
UN(1,1)	SubjectID	10.0089	1.7423	5.74	<.0001
UN(2,1)	SubjectID	5.5838	1.5445	3.62	0.0003
UN(2,2)	SubjectID	12.6150	2.1960	5.74	<.0001

Fit Statistics

-2 Res Log Likelihood	694.0
AIC (smaller is better)	700.0
AICC (smaller is better)	700.2
BIC (smaller is better)	706.7

The Mixed Procedure

Null Model Likelihood Ratio Test

DF	Chi-Square	Pr > ChiSq
2	19.60	<.0001

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
time	1	66	62.20	<.0001
Group	2	66	3.72	0.0294
time*Group	2	66	0.79	0.4600

Estimates

Label	Estimate	Standard Error	DF	t Value	Pr > |t|	Alpha	Lower	Upper
Time 1: G1-G2	-1.6652	0.9329	66	-1.78	0.0789	0.05	-3.5278	0.1974
Time 1: G1-G3	-2.8394	0.9329	66	-3.04	0.0034	0.05	-4.7021	-0.9768
Time 1: G2-G3	-1.1742	0.9329	66	-1.26	0.2126	0.05	-3.0369	0.6884
Time 2: G1-G2	-1.5591	1.0474	66	-1.49	0.1414	0.05	-3.6502	0.5320
Time 2: G1-G3	-1.7067	1.0474	66	-1.63	0.1080	0.05	-3.7979	0.3844
Time 2: G2-G3	-0.1477	1.0474	66	-0.14	0.8883	0.05	-2.2388	1.9434

Least Squares Means

Effect	time	Group	Estimate	Standard Error	DF	t Value	Pr > |t|	Alpha	Lower	Upper
time*Group	1	1	-2.1747	0.6597	66	-3.30	0.0016	0.05	-3.4918	-0.8576
time*Group	1	2	-0.5095	0.6597	66	-0.77	0.4427	0.05	-1.8266	0.8076
time*Group	1	3	0.6648	0.6597	66	1.01	0.3173	0.05	-0.6523	1.9818
time*Group	2	1	-4.9752	0.7406	66	-6.72	<.0001	0.05	-6.4539	-3.4966
time*Group	2	2	-3.4162	0.7406	66	-4.61	<.0001	0.05	-4.8948	-1.9375
time*Group	2	3	-3.2685	0.7406	66	-4.41	<.0001	0.05	-4.7471	-1.7898

Tests of Effect Slices

Effect	time	Num DF	Den DF	F Value	Pr > F
time*Group	1	2	66	4.68	0.0126
time*Group	2	2	66	1.63	0.2036

The Mixed Procedure

Model Information

Data Set	CJW.DISSERTATION_ TRIAL11ONLY_STACKED
Dependent Variable	HFwalkX
Covariance Structure	Unstructured
Subject Effect	SubjectID
Estimation Method	REML
Residual Variance Method	None
Fixed Effects SE Method	Kenward-Roger
Degrees of Freedom Method	Kenward-Roger

Class Level Information

Class	Levels	Values
time	2	1 2
Group	3	1 2 3
SubjectID	69	C01 C02 C03 C04 C05 C06 C07 C08 C10 C12 C13 C14 C15 C16 C18 C20 C21 C23 C24 C25 C26 C27 C28 F01 F02 F03 F04 F05 F06 F07 F09 F10 F12 F13 F14 F17 F19 F20 F21 F22 F23 F24 F25 F26 F27 F28 H01 H02 H04 H05 H06 H07 H08 H09 H10 H11 H12 H14 H16 H17 H18 H20 H21 H22 H23 H25 H26 H27 H28

Dimensions

Covariance Parameters	3
Columns in X	12
Columns in Z	0
Subjects	69
Max Obs Per Subject	2

Number of Observations

Number of Observations Read	138
Number of Observations Used	138
Number of Observations Not Used	0

The Mixed Procedure

Iteration History

Iteration	Evaluations	-2 Res Log Like	Criterion
0	1	722.74930143	
1	1	702.04987487	0.00000000

Convergence criteria met.

Estimated R Matrix
for SubjectID C01

Row	Col1	Col2
1	7.3777	4.1294
2	4.1294	16.8651

Estimated R Correlation
Matrix for SubjectID C01

Row	Col1	Col2
1	1.0000	0.3702
2	0.3702	1.0000

Covariance Parameter Estimates

Cov Parm	Subject	Estimate	Standard Error	Z Value	Pr Z
UN(1,1)	SubjectID	7.3777	1.2843	5.74	<.0001
UN(2,1)	SubjectID	4.1294	1.4641	2.82	0.0048
UN(2,2)	SubjectID	16.8651	2.9358	5.74	<.0001

Fit Statistics

-2 Res Log Likelihood	702.0
AIC (smaller is better)	708.0
AICC (smaller is better)	708.2
BIC (smaller is better)	714.8

The Mixed Procedure

Null Model Likelihood Ratio Test

DF	Chi-Square	Pr > ChiSq
2	20.70	<.0001

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
time	1	66	262.33	<.0001
Group	2	66	2.99	0.0572
time*Group	2	66	1.71	0.1880

Estimates

Label	Estimate	Standard Error	DF	t Value	Pr > |t|	Alpha	Lower	Upper
Time 1: G1-G2	-0.8077	0.8010	66	-1.01	0.3169	0.05	-2.4069	0.7915
Time 1: G1-G3	-1.3251	0.8010	66	-1.65	0.1028	0.05	-2.9243	0.2741
Time 1: G2-G3	-0.5174	0.8010	66	-0.65	0.5205	0.05	-2.1166	1.0818
Time 2: G1-G2	0.1982	1.2110	66	0.16	0.8705	0.05	-2.2196	2.6161
Time 2: G1-G3	-2.5000	1.2110	66	-2.06	0.0429	0.05	-4.9179	-0.08216
Time 2: G2-G3	-2.6982	1.2110	66	-2.23	0.0293	0.05	-5.1161	-0.2804

Least Squares Means

Effect	time	Group	Estimate	Standard Error	DF	t Value	Pr > |t|	Alpha	Lower	Upper
time*Group	1	1	-3.2343	0.5664	66	-5.71	<.0001	0.05	-4.3651	-2.1036
time*Group	1	2	-2.4266	0.5664	66	-4.28	<.0001	0.05	-3.5574	-1.2959
time*Group	1	3	-1.9092	0.5664	66	-3.37	0.0013	0.05	-3.0400	-0.7785
time*Group	2	1	-11.0861	0.8563	66	-12.95	<.0001	0.05	-12.7958	-9.3764
time*Group	2	2	-11.2843	0.8563	66	-13.18	<.0001	0.05	-12.9940	-9.5746
time*Group	2	3	-8.5861	0.8563	66	-10.03	<.0001	0.05	-10.2958	-6.8764

Tests of Effect Slices

Effect	time	Num DF	Den DF	F Value	Pr > F
time*Group	1	2	66	1.39	0.2562
time*Group	2	2	66	3.08	0.0524

The Mixed Procedure

Model Information

Data Set	CJW.DISSERTATION_ TRIAL11ONLY_STACKED
Dependent Variable	HFwalkY
Covariance Structure	Unstructured
Subject Effect	SubjectID
Estimation Method	REML
Residual Variance Method	None
Fixed Effects SE Method	Kenward-Roger
Degrees of Freedom Method	Kenward-Roger

Class Level Information

Class	Levels	Values
time	2	1 2
Group	3	1 2 3
SubjectID	69	C01 C02 C03 C04 C05 C06 C07 C08 C10 C12 C13 C14 C15 C16 C18 C20 C21 C23 C24 C25 C26 C27 C28 F01 F02 F03 F04 F05 F06 F07 F09 F10 F12 F13 F14 F17 F19 F20 F21 F22 F23 F24 F25 F26 F27 F28 H01 H02 H04 H05 H06 H07 H08 H09 H10 H11 H12 H14 H16 H17 H18 H20 H21 H22 H23 H25 H26 H27 H28

Dimensions

Covariance Parameters	3
Columns in X	12
Columns in Z	0
Subjects	69
Max Obs Per Subject	2

Number of Observations

Number of Observations Read	138
Number of Observations Used	138
Number of Observations Not Used	0

The Mixed Procedure

Iteration History

Iteration	Evaluations	-2 Res Log Like	Criterion
0	1	754.19993973	
1	1	690.33436766	0.00000000

Convergence criteria met.

Estimated R Matrix
for SubjectID C01

Row	Col1	Col2
1	9.6877	10.6903
2	10.6903	21.0774

Estimated R Correlation
Matrix for SubjectID C01

Row	Col1	Col2
1	1.0000	0.7481
2	0.7481	1.0000

Covariance Parameter Estimates

Cov Parm	Subject	Estimate	Standard Error	Z Value	Pr Z
UN(1,1)	SubjectID	9.6877	1.6864	5.74	<.0001
UN(2,1)	SubjectID	10.6903	2.1967	4.87	<.0001
UN(2,2)	SubjectID	21.0774	3.6691	5.74	<.0001

Fit Statistics

-2 Res Log Likelihood	690.3
AIC (smaller is better)	696.3
AICC (smaller is better)	696.5
BIC (smaller is better)	703.0

The Mixed Procedure

Null Model Likelihood Ratio Test

DF	Chi-Square	Pr > ChiSq
2	63.87	<.0001

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
time	1	66	208.69	<.0001
Group	2	66	0.69	0.5042
time*Group	2	66	0.16	0.8505

Estimates

Label	Estimate	Standard Error	DF	t Value	Pr > |t|	Alpha	Lower	Upper
Time 1: G1-G2	0.7945	0.9178	66	0.87	0.3898	0.05	-1.0380	2.6270
Time 1: G1-G3	-0.1281	0.9178	66	-0.14	0.8894	0.05	-1.9607	1.7044
Time 1: G2-G3	-0.9226	0.9178	66	-1.01	0.3185	0.05	-2.7551	0.9099
Time 2: G1-G2	1.2590	1.3538	66	0.93	0.3558	0.05	-1.4439	3.9620
Time 2: G1-G3	-0.08774	1.3538	66	-0.06	0.9485	0.05	-2.7907	2.6152
Time 2: G2-G3	-1.3468	1.3538	66	-0.99	0.3235	0.05	-4.0498	1.3562

Least Squares Means

Effect	time	Group	Estimate	Standard Error	DF	t Value	Pr > |t|	Alpha	Lower	Upper
time*Group	1	1	2.4002	0.6490	66	3.70	0.0004	0.05	1.1044	3.6959
time*Group	1	2	1.6057	0.6490	66	2.47	0.0159	0.05	0.3099	2.9014
time*Group	1	3	2.5283	0.6490	66	3.90	0.0002	0.05	1.2325	3.8241
time*Group	2	1	7.8961	0.9573	66	8.25	<.0001	0.05	5.9848	9.8074
time*Group	2	2	6.6371	0.9573	66	6.93	<.0001	0.05	4.7258	8.5484
time*Group	2	3	7.9838	0.9573	66	8.34	<.0001	0.05	6.0725	9.8951

Tests of Effect Slices

Effect	time	Num DF	Den DF	F Value	Pr > F
time*Group	1	2	66	0.59	0.5555
time*Group	2	2	66	0.62	0.5413

The Mixed Procedure

Model Information

Data Set	CJW.DISSERTATION_ TRIAL11ONLY_STACKED
Dependent Variable	FFJumpX
Covariance Structure	Unstructured
Subject Effect	SubjectID
Estimation Method	REML
Residual Variance Method	None
Fixed Effects SE Method	Kenward-Roger
Degrees of Freedom Method	Kenward-Roger

Class Level Information

Class	Levels	Values
time	2	1 2
Group	3	1 2 3
SubjectID	69	C01 C02 C03 C04 C05 C06 C07 C08 C10 C12 C13 C14 C15 C16 C18 C20 C21 C23 C24 C25 C26 C27 C28 F01 F02 F03 F04 F05 F06 F07 F09 F10 F12 F13 F14 F17 F19 F20 F21 F22 F23 F24 F25 F26 F27 F28 H01 H02 H04 H05 H06 H07 H08 H09 H10 H11 H12 H14 H16 H17 H18 H20 H21 H22 H23 H25 H26 H27 H28

Dimensions

Covariance Parameters	3
Columns in X	12
Columns in Z	0
Subjects	69
Max Obs Per Subject	2

Number of Observations

Number of Observations Read	138
Number of Observations Used	138
Number of Observations Not Used	0

The Mixed Procedure

Iteration History

Iteration	Evaluations	-2 Res Log Like	Criterion
0	1	723.74282977	
1	1	718.69743218	0.00000000

Convergence criteria met.

Estimated R Matrix
for SubjectID C01

Row	Col1	Col2
1	15.5246	-0.1027
2	-0.1027	8.9014

Estimated R Correlation
Matrix for SubjectID C01

Row	Col1	Col2
1	1.0000	-0.00874
2	-0.00874	1.0000

Covariance Parameter Estimates

Cov Parm	Subject	Estimate	Standard Error	Z Value	Pr Z
UN(1,1)	SubjectID	15.5246	2.7025	5.74	<.0001
UN(2,1)	SubjectID	-0.1027	1.4470	-0.07	0.9434
UN(2,2)	SubjectID	8.9014	1.5495	5.74	<.0001

Fit Statistics

-2 Res Log Likelihood	718.7
AIC (smaller is better)	724.7
AICC (smaller is better)	724.9
BIC (smaller is better)	731.4

The Mixed Procedure

Null Model Likelihood Ratio Test

DF	Chi-Square	Pr > ChiSq
2	5.05	0.0802

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
time	1	66	729.60	<.0001
Group	2	66	2.58	0.0833
time*Group	2	66	2.24	0.1146

Estimates

Label	Estimate	Standard Error	DF	t Value	Pr > |t|	Alpha	Lower	Upper
Time 1: G1-G2	-2.7490	1.1619	66	-2.37	0.0209	0.05	-5.0688	-0.4293
Time 1: G1-G3	-0.3617	1.1619	66	-0.31	0.7565	0.05	-2.6815	1.9580
Time 1: G2-G3	2.3873	1.1619	66	2.05	0.0439	0.05	0.06753	4.7071
Time 2: G1-G2	-0.5439	0.8798	66	-0.62	0.5385	0.05	-2.3005	1.2126
Time 2: G1-G3	-1.1428	0.8798	66	-1.30	0.1985	0.05	-2.8994	0.6138
Time 2: G2-G3	-0.5989	0.8798	66	-0.68	0.4985	0.05	-2.3554	1.1577

Least Squares Means

Effect	time	Group	Estimate	Standard Error	DF	t Value	Pr > |t|	Alpha	Lower	Upper
time*Group	1	1	-10.6851	0.8216	66	-13.01	<.0001	0.05	-12.3254	-9.0448
time*Group	1	2	-7.9361	0.8216	66	-9.66	<.0001	0.05	-9.5764	-6.2958
time*Group	1	3	-10.3234	0.8216	66	-12.57	<.0001	0.05	-11.9637	-8.6831
time*Group	2	1	5.9281	0.6221	66	9.53	<.0001	0.05	4.6860	7.1701
time*Group	2	2	6.4720	0.6221	66	10.40	<.0001	0.05	5.2299	7.7141
time*Group	2	3	7.0709	0.6221	66	11.37	<.0001	0.05	5.8288	8.3129

Tests of Effect Slices

Effect	time	Num DF	Den DF	F Value	Pr > F
time*Group	1	2	66	3.31	0.0428
time*Group	2	2	66	0.84	0.4345

The Mixed Procedure

Model Information

Data Set	CJW.DISSERTATION_ TRIAL11ONLY_STACKED
Dependent Variable	FFJumpY
Covariance Structure	Unstructured
Subject Effect	SubjectID
Estimation Method	REML
Residual Variance Method	None
Fixed Effects SE Method	Kenward-Roger
Degrees of Freedom Method	Kenward-Roger

Class Level Information

Class	Levels	Values
time	2	1 2
Group	3	1 2 3
SubjectID	69	C01 C02 C03 C04 C05 C06 C07 C08 C10 C12 C13 C14 C15 C16 C18 C20 C21 C23 C24 C25 C26 C27 C28 F01 F02 F03 F04 F05 F06 F07 F09 F10 F12 F13 F14 F17 F19 F20 F21 F22 F23 F24 F25 F26 F27 F28 H01 H02 H04 H05 H06 H07 H08 H09 H10 H11 H12 H14 H16 H17 H18 H20 H21 H22 H23 H25 H26 H27 H28

Dimensions

Covariance Parameters	3
Columns in X	12
Columns in Z	0
Subjects	69
Max Obs Per Subject	2

Number of Observations

Number of Observations Read	138
Number of Observations Used	138
Number of Observations Not Used	0

The Mixed Procedure

Iteration History

Iteration	Evaluations	-2 Res Log Like	Criterion
0	1	642.73465320	
1	1	634.86918703	0.00000000

Convergence criteria met.

Estimated R Matrix
for SubjectID C01

Row	Col1	Col2
1	6.3356	2.1988
2	2.1988	6.8873

Estimated R Correlation
Matrix for SubjectID C01

Row	Col1	Col2
1	1.0000	0.3329
2	0.3329	1.0000

Covariance Parameter Estimates

Cov Parm	Subject	Estimate	Standard Error	Z Value	Pr Z
UN(1,1)	SubjectID	6.3356	1.1029	5.74	<.0001
UN(2,1)	SubjectID	2.1988	0.8570	2.57	0.0103
UN(2,2)	SubjectID	6.8873	1.1989	5.74	<.0001

Fit Statistics

-2 Res Log Likelihood	634.9
AIC (smaller is better)	640.9
AICC (smaller is better)	641.1
BIC (smaller is better)	647.6

The Mixed Procedure

Null Model Likelihood Ratio Test

DF	Chi-Square	Pr > ChiSq
2	7.87	0.0196

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
time	1	66	19.38	<.0001
Group	2	66	2.32	0.1064
time*Group	2	66	0.06	0.9462

Estimates

Label	Estimate	Standard Error	DF	t Value	Pr > |t|	Alpha	Lower	Upper
Time 1: G1-G2	-0.3804	0.7422	66	-0.51	0.6100	0.05	-1.8623	1.1015
Time 1: G1-G3	-1.2130	0.7422	66	-1.63	0.1070	0.05	-2.6949	0.2690
Time 1: G2-G3	-0.8326	0.7422	66	-1.12	0.2661	0.05	-2.3145	0.6494
Time 2: G1-G2	-0.6566	0.7739	66	-0.85	0.3993	0.05	-2.2017	0.8885
Time 2: G1-G3	-1.4320	0.7739	66	-1.85	0.0687	0.05	-2.9771	0.1131
Time 2: G2-G3	-0.7754	0.7739	66	-1.00	0.3200	0.05	-2.3206	0.7697

Least Squares Means

Effect	time	Group	Estimate	Standard Error	DF	t Value	Pr > |t|	Alpha	Lower	Upper
time*Group	1	1	-5.7892	0.5248	66	-11.03	<.0001	0.05	-6.8371	-4.7413
time*Group	1	2	-5.4088	0.5248	66	-10.31	<.0001	0.05	-6.4567	-4.3610
time*Group	1	3	-4.5763	0.5248	66	-8.72	<.0001	0.05	-5.6242	-3.5284
time*Group	2	1	-4.3800	0.5472	66	-8.00	<.0001	0.05	-5.4726	-3.2874
time*Group	2	2	-3.7234	0.5472	66	-6.80	<.0001	0.05	-4.8160	-2.6309
time*Group	2	3	-2.9480	0.5472	66	-5.39	<.0001	0.05	-4.0405	-1.8554

Tests of Effect Slices

Effect	time	Num DF	Den DF	F Value	Pr > F
time*Group	1	2	66	1.40	0.2545
time*Group	2	2	66	1.72	0.1877

The Mixed Procedure

Model Information

Data Set	CJW.DISSERTATION_ TRIAL11ONLY_STACKED
Dependent Variable	HFJumpX
Covariance Structure	Unstructured
Subject Effect	SubjectID
Estimation Method	REML
Residual Variance Method	None
Fixed Effects SE Method	Kenward-Roger
Degrees of Freedom Method	Kenward-Roger

Class Level Information

Class	Levels	Values
time	2	1 2
Group	3	1 2 3
SubjectID	69	C01 C02 C03 C04 C05 C06 C07 C08 C10 C12 C13 C14 C15 C16 C18 C20 C21 C23 C24 C25 C26 C27 C28 F01 F02 F03 F04 F05 F06 F07 F09 F10 F12 F13 F14 F17 F19 F20 F21 F22 F23 F24 F25 F26 F27 F28 H01 H02 H04 H05 H06 H07 H08 H09 H10 H11 H12 H14 H16 H17 H18 H20 H21 H22 H23 H25 H26 H27 H28

Dimensions

Covariance Parameters	3
Columns in X	12
Columns in Z	0
Subjects	69
Max Obs Per Subject	2

Number of Observations

Number of Observations Read	138
Number of Observations Used	138
Number of Observations Not Used	0

The Mixed Procedure

Iteration History

Iteration	Evaluations	-2 Res Log Like	Criterion
0	1	750.32265690	
1	1	746.03064982	0.00000000

Convergence criteria met.

Estimated R Matrix
for SubjectID C01

Row	Col1	Col2
1	13.7165	3.5437
2	3.5437	16.1582

Estimated R Correlation
Matrix for SubjectID C01

Row	Col1	Col2
1	1.0000	0.2380
2	0.2380	1.0000

Covariance Parameter Estimates

Cov Parm	Subject	Estimate	Standard Error	Z Value	Pr Z
UN(1,1)	SubjectID	13.7165	2.3877	5.74	<.0001
UN(2,1)	SubjectID	3.5437	1.8837	1.88	0.0599
UN(2,2)	SubjectID	16.1582	2.8128	5.74	<.0001

Fit Statistics

-2 Res Log Likelihood	746.0
AIC (smaller is better)	752.0
AICC (smaller is better)	752.2
BIC (smaller is better)	758.7

The Mixed Procedure

Null Model Likelihood Ratio Test

DF	Chi-Square	Pr > ChiSq
2	4.29	0.1170

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
time	1	66	905.33	<.0001
Group	2	66	2.06	0.1362
time*Group	2	66	4.11	0.0208

Estimates

Label	Estimate	Standard Error	DF	t Value	Pr > |t|	Alpha	Lower	Upper
Time 1: G1-G2	-0.2470	1.0921	66	-0.23	0.8218	0.05	-2.4275	1.9335
Time 1: G1-G3	-3.4267	1.0921	66	-3.14	0.0025	0.05	-5.6072	-1.2462
Time 1: G2-G3	-3.1797	1.0921	66	-2.91	0.0049	0.05	-5.3602	-0.9992
Time 2: G1-G2	-0.2977	1.1854	66	-0.25	0.8025	0.05	-2.6643	2.0690
Time 2: G1-G3	0.04202	1.1854	66	0.04	0.9718	0.05	-2.3246	2.4086
Time 2: G2-G3	0.3397	1.1854	66	0.29	0.7753	0.05	-2.0269	2.7063

Least Squares Means

Effect	time	Group	Estimate	Standard Error	DF	t Value	Pr > |t|	Alpha	Lower	Upper
time*Group	1	1	-13.5066	0.7722	66	-17.49	<.0001	0.05	-15.0485	-11.9648
time*Group	1	2	-13.2596	0.7722	66	-17.17	<.0001	0.05	-14.8015	-11.7178
time*Group	1	3	-10.0799	0.7722	66	-13.05	<.0001	0.05	-11.6218	-8.5381
time*Group	2	1	4.9239	0.8382	66	5.87	<.0001	0.05	3.2504	6.5974
time*Group	2	2	5.2216	0.8382	66	6.23	<.0001	0.05	3.5481	6.8950
time*Group	2	3	4.8819	0.8382	66	5.82	<.0001	0.05	3.2084	6.5553

Tests of Effect Slices

Effect	time	Num DF	Den DF	F Value	Pr > F
time*Group	1	2	66	6.12	0.0036
time*Group	2	2	66	0.05	0.9524

The Mixed Procedure

Model Information

Data Set	CJW.DISSERTATION_ TRIAL11ONLY_STACKED
Dependent Variable	HFJumpY
Covariance Structure	Unstructured
Subject Effect	SubjectID
Estimation Method	REML
Residual Variance Method	None
Fixed Effects SE Method	Kenward-Roger
Degrees of Freedom Method	Kenward-Roger

Class Level Information

Class	Levels	Values
time	2	1 2
Group	3	1 2 3
SubjectID	69	C01 C02 C03 C04 C05 C06 C07 C08 C10 C12 C13 C14 C15 C16 C18 C20 C21 C23 C24 C25 C26 C27 C28 F01 F02 F03 F04 F05 F06 F07 F09 F10 F12 F13 F14 F17 F19 F20 F21 F22 F23 F24 F25 F26 F27 F28 H01 H02 H04 H05 H06 H07 H08 H09 H10 H11 H12 H14 H16 H17 H18 H20 H21 H22 H23 H25 H26 H27 H28

Dimensions

Covariance Parameters	3
Columns in X	12
Columns in Z	0
Subjects	69
Max Obs Per Subject	2

Number of Observations

Number of Observations Read	138
Number of Observations Used	138
Number of Observations Not Used	0

The Mixed Procedure

Iteration History

Iteration	Evaluations	-2 Res Log Like	Criterion
0	1	786.07160645	
1	1	750.69215213	0.00000000

Convergence criteria met.

Estimated R Matrix
for SubjectID C01

Row	Col1	Col2
1	26.5830	10.4950
2	10.4950	12.5840

Estimated R Correlation
Matrix for SubjectID C01

Row	Col1	Col2
1	1.0000	0.5738
2	0.5738	1.0000

Covariance Parameter Estimates

Cov Parm	Subject	Estimate	Standard Error	Z Value	Pr Z
UN(1,1)	SubjectID	26.5830	4.6275	5.74	<.0001
UN(2,1)	SubjectID	10.4950	2.5956	4.04	<.0001
UN(2,2)	SubjectID	12.5840	2.1906	5.74	<.0001

Fit Statistics

-2 Res Log Likelihood	750.7
AIC (smaller is better)	756.7
AICC (smaller is better)	756.9
BIC (smaller is better)	763.4

The Mixed Procedure

Null Model Likelihood Ratio Test

DF	Chi-Square	Pr > ChiSq
2	35.38	<.0001

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
time	1	66	966.82	<.0001
Group	2	66	0.81	0.4476
time*Group	2	66	0.29	0.7482

Estimates

Label	Estimate	Standard Error	DF	t Value	Pr > |t|	Alpha	Lower	Upper
Time 1: G1-G2	1.8752	1.5204	66	1.23	0.2218	0.05	-1.1604	4.9107
Time 1: G1-G3	0.7302	1.5204	66	0.48	0.6326	0.05	-2.3053	3.7658
Time 1: G2-G3	-1.1449	1.5204	66	-0.75	0.4541	0.05	-4.1805	1.8906
Time 2: G1-G2	1.0425	1.0461	66	1.00	0.3226	0.05	-1.0460	3.1311
Time 2: G1-G3	0.7272	1.0461	66	0.70	0.4894	0.05	-1.3613	2.8158
Time 2: G2-G3	-0.3153	1.0461	66	-0.30	0.7641	0.05	-2.4038	1.7733

Least Squares Means

Effect	time	Group	Estimate	Standard Error	DF	t Value	Pr > |t|	Alpha	Lower	Upper
time*Group	1	1	8.5415	1.0751	66	7.95	<.0001	0.05	6.3950	10.6879
time*Group	1	2	6.6663	1.0751	66	6.20	<.0001	0.05	4.5199	8.8128
time*Group	1	3	7.8113	1.0751	66	7.27	<.0001	0.05	5.6648	9.9577
time*Group	2	1	-7.6962	0.7397	66	-10.40	<.0001	0.05	-9.1730	-6.2194
time*Group	2	2	-8.7387	0.7397	66	-11.81	<.0001	0.05	-10.2155	-7.2619
time*Group	2	3	-8.4234	0.7397	66	-11.39	<.0001	0.05	-9.9002	-6.9466

Tests of Effect Slices

Effect	time	Num DF	Den DF	F Value	Pr > F
time*Group	1	2	66	0.77	0.4658
time*Group	2	2	66	0.52	0.5955

VITA

Cynthia Joy Wright was born on March 24, 1983, in Renton, Washington, and is an American citizen. She received her Bachelor of Arts in Athletic Training (minor in Spanish) from Whitworth University in May 2005. She worked as a graduate assistant athletic trainer for Texas State University while pursuing a Master of Education in Physical Education (emphasis in Exercise Science) from the same university, completing the degree in December 2006.