Measures of plantar pressure and influences of fatigue on muscle activation in subjects with and without chronic ankle instability

Kathryn A. Webster

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A Dissertation

entitled

Measures of Plantar Pressure and Influences of Fatigue on Muscle Activation in Subjects with and without Chronic Ankle Instability

by

Kathryn A. Webster

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

____________________________________
Dr. Phillip A. Gribble, Committee Chair

____________________________________
Dr. Charles Armstrong, Committee Member

____________________________________
Dr. Brian Pietrosimone, Committee Member

____________________________________
Dr. Jason Levine, Committee Member

____________________________________
Dr. Patricia Komuniecki, Dean
College of Graduate Studies

The University of Toledo

May 2010
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An Abstract of

Measures of Plantar Pressure and Influences of Fatigue on Muscle Activation in Subjects with and without Chronic Ankle Instability

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Kathryn A. Webster

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Although much research has been conducted on those with chronic ankle instability (CAI), more research is necessary in understanding how activation of both proximal and distal lower extremity muscles influence the positioning of the ankle during a functional task. This study measured peak pressures on the plantar foot and the influences of fatigue on four lower extremity muscles during a lateral hop in those with and without CAI. The results revealed no significant differences in peak pressure between groups for the plantar pressure areas. The muscle measurements demonstrated higher peroneus longus and gluteus maximus activity just prior to landing the lateral hop. There were no statistically significant outcomes for fatigue. Both the muscle activation and the plantar pressure results suggest a pre programmed, feed-forward mechanism adapted by those with CAI. Altered neuromuscular activity in those with CAI has been documented in previous research. These results continue to support this theory, now demonstrated during a functional task which indicates those with CAI are finding methods to land a jump without injury in controlled situations.
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Table of Contents

Abstract iii
Acknowledgements iv
Table of Contents vi
List of Tables vii
List of Figures viii

1 Introduction 1

1.1 Introduction ......................................................................................1
1.2 Statement of the Problem .................................................................2
1.3 Significance of the Study .................................................................2
1.4 Purposes of the Study .....................................................................3
1.5 Hypotheses .....................................................................................3
1.6 Known Limitations .......................................................................4

2 Literature Review 6

2.1 Chronic Ankle Instability .................................................................6
2.2 Chronic Ankle Instability and Foot Pressure .................................11
2.3 Chronic Ankle Instability and Gluteus Muscles .............................13
2.3.1 Gluteus Medius ........................................................................13
2.3.2 Gluteus Maximus ......................................................................15
2.3.3 The Gluteus- Chronic Ankle Instability Connection ..................15
2.4 Fatigue Related Injury ................................................................. 20
2.5 Fatigue and Joint Position Changes ........................................... 21
2.6 Fatigue and Postural Control ...................................................... 22

3 Muscle activation in proximal and distal muscles during a lateral hop before and after fatigue in those with and without chronic ankle instability

3.1 Introduction .............................................................................. 24
3.2 Materials .................................................................................. 27
3.3 Methods .................................................................................... 28
  3.3.1 Subjects .............................................................................. 28
  3.3.2 Procedures ......................................................................... 29
    3.3.2.1 Electromyography ......................................................... 29
    3.3.2.2 Pre Testing ................................................................. 30
    3.3.2.3 Functional Fatigue Protocol ......................................... 31
    3.3.2.4 Post Testing .............................................................. 32
  3.3.3 Data Collection and Processing .......................................... 32
  3.3.4 Statistical Analysis ............................................................... 33
3.4 Results ..................................................................................... 34
  3.4.1 Pre Landing Results (200ms pre IC - IC) ............................... 34
  3.4.2 Post Landing Results (IC - 200ms post IC) ......................... 36
3.5 Discussion ............................................................................... 39
  3.5.1 Foot Positioning ................................................................. 39
  3.5.2 Distal Alterations ............................................................... 40
  3.5.3 Proximal Alterations ......................................................... 42
3.5.4 Fatigue
3.5.5 Post Landing
3.5.6 Limitations
3.5.7 Conclusions
3.5.8 Clinical Applications

4 A comparison of plantar pressure peaks of a lateral hop landing in those with and without chronic ankle instability

4.1 Introduction
4.2 Materials
4.3 Methods
4.3.1 Subjects
4.3.2 Procedures
4.3.3 Data Processing
4.3.4 Statistical Analysis
4.4 Results
4.5 Discussion
4.5.1 Group Comparisons
4.5.2 Area Differences
4.5.3 Limitations
4.5.4 Conclusions

Summary

5.1 Summary of Findings
5.2 Questions Answered
5.3 Questions Generated.................................................................66

5.4 Future Directions.................................................................67

References 68

Appendix A Foot and Ankle Disability Index and Sport 77

Appendix B Physical Activity Readiness Questionnaire 79

Appendix C Tegner Activity Scale 80
List of Tables

3.1 Subject Demographics .................................................................28
3.2 Interaction Results .................................................................35
3.3 Pre Landing for Condition Results ..............................................36
3.4 Pre landing for Fatigue Results .................................................36
3.5 Post Landing Interaction Results .................................................37
3.6 Post Landing for Condition .......................................................38
3.7 Post Landing for Fatigue .........................................................38
4.1 Subject Demographics .............................................................53
4.2 Means and SD for Plantar Pressure Areas (PSI) ............................58
4.3 p Values for Areas of Plantar Pressure ........................................59
List of Figures

3.1 Pre and Post Test Hopping Procedure.......................................................30
3.2 Functional Fatigue Protocol........................................................................31
4.1 Plantar Pressure Template Display..............................................................55
4.2 Placement of Areas of Plantar Pressure to be Analyzed...............................56
4.3 Means and Standard Deviations for the Six Plantar Pressure Areas in CAI and
   Control Subjects...............................................................................................59
Chapter 1

1.1 Introduction

Ankle sprains are some of the most common injuries seen in physical activity with reinjury rate as high as 80%. \(^1\) For those who experience a significant lateral ankle sprain, a common outcome is repeated “giving way” of the ankle during activities. The term chronic ankle instability (CAI) has been given to these individuals and is characterized by residual lateral instability, leading to repetitive ankle sprains.

Altered neuromuscular patterns may be contributing to this recurring injury. \(^2-6\) This may be due to changes in foot positioning not only distal to the ankle, \(^7-9\) but also proximally up the kinetic chain. Because the gluteus maximus and gluteus medius help control the positioning of the lower extremity, \(^10-12\) it is important to consider that dysfunction of these muscles may be contributing to ankle injury. Understanding how both proximal muscles activation and distal foot positioning contribute to CAI may assist in preventing subsequent ankle sprains, therefore, allowing healthy individuals to stay more active.

Another factor that may be contributing to persistent ankle injury is fatigue. It is well documented that fatigue causes neuromuscular changes such as decreased muscular strength and control which may be a contributing factor to injury. \(^13-15\) It may be that as fatigue increases, decreased activity of the proximal muscles at the hip allows improper
positioning of the ankle in those with CAI which may predispose this group to recurrent ankle injury. Better understanding of this relationship can help clinicians implement rehabilitation programs which may help prevent future recurrent injury.

1.2 Statement of the Problem

Although the relationship between gluteus maximus and medius function and ankle injury has been studied,\textsuperscript{16-18} the results have not been conclusive. Much of the research has measured muscle activity of the glutei during open kinetic chain (OKC) activities which may not be directly applicable to a physically active population who incur ankle injury in a closed kinetic chain (CKC) position. More research is necessary to begin to demonstrate consistent outcomes in the functioning of these muscles in CAI patients during CKC activities. Additionally, the effects of functional fatigue on the glutei of those with CAI while performing functional activity have not been examined. Further, the positioning of the foot as measured by foot pressure distribution has not been investigated in a CAI population while performing a lateral hop which may reveal insight into ankle injury, as it is a common mechanism for inversion sprains.

1.3 Significance of the Study

Previous research\textsuperscript{3} has evaluated the effects of fatigue on neuromuscular control in those with CAI but has not focused on the activation of the proximal hip muscles during a functional task. Other studies\textsuperscript{8, 9, 19} have compared foot pressure patterns in those with CAI, but not during a functional frontal plane movement. This study will combine both proximal and distal measures of muscle activity in those with a CAI before and after a fatiguing protocol during a functional task. Having a clearer picture of both the proximal musculature during a fatigued state and distal foot pressure during a
functional task will allow clinicians insight into some of the underlying factors that may be leading to chronic re-injury of the ankle. If we can appreciate some of these changes in those with CAI compared to healthy ankles, we may be able to work to correct insufficiencies and perhaps help prevent future ankle injury. This prevention of injury may lead patients to be more confident when participating in athletic activity as well as remain generally active longer in life, preventing other general health problems.

1.4 Purposes of the Study

1. Examine the Root Mean Square (RMS) activity of the tibialis anterior, prenoeus longus, gluteus medius and maximus during pre-landing (200ms-initial contact) of landing a lateral hop before and after fatigue in those with CAI compared to healthy controls.

2. Examine the activity of the tibialis anterior, prenoeus longus, gluteus medius and maximus at post-landing (initial contact to 200ms) a lateral hop before and after fatigue in those with CAI compared to healthy controls.

3. Examine the peak pressure patterns of foot pressure during a functional activity commonly seen as mechanism of injury in those with CAI compared to healthy controls.

1.5 Hypotheses

1. For gluteus medius, gluteus maximus, tibialis anterior, and peroneus longus activation

   A. At pre-fatigue, pre-landing the CAI group will demonstrate significantly lower muscle activation compared to healthy control group

   B. At pre-fatigue, post-landing, there will be no significant differences in activation between groups.
C. At post-fatigue, pre-landing there will be significantly lower activation in CAI vs. healthy and this difference will be more pronounced than the pre-fatigue comparison.

D. At post-fatigue, post-landing there will be significantly lower activation in CAI vs. healthy

2. For lateral rearfoot, lateral midfoot, and lateral forefoot pressures

A. CAI will demonstrate higher peak pressures on the lateral foot while landing a lateral hop compared to the healthy controls.

1.6 Known Limitations

There are some possible limitations to the study.

1. The subject may give sub-maximal effort on fatigue protocol.

2. The fatigue protocol is not as long as a full practice or game might be, but has been validated to induce the general effects of fatigue.

3. Because the wiring is somewhat cumbersome, we will not have subjects perform the fatigue protocol with the EMG and foot pressure system attached. Although multiple people will be involved and well-practiced, reattaching these instruments will delay the immediate collection of data after the fatigue.

4. Because the foot sensors are placed between the sock and the shoe insert and the testing protocol involves a lateral motion, it is possible there may be slipping of the foot sensors. Double-sided tape will be used to help prevent this from occurring.
5. Because the subjects may perspire during the fatigue protocol, it is possible we may get movement of EMG electrodes during the fatigue protocol.

6. Although the foot pressure system being used gives a complete display of the pressures being produced on the plantar surface of the foot, it does not give full picture of foot positioning.
Chapter 2

Literature Review

2.1 Chronic Ankle Instability

Chronic ankle instability is a result of functional ankle instability, mechanical ankle instability, or a combination of the two. Freeman first defined functional ankle instability as a feeling of “giving way”, a description commonly expressed by subjects with recurrent ankle sprains. Functional ankle instability may be caused by proprioceptive and neuromuscular deficits, including deficits in postural control or strength. Mechanical ankle instability was described by Tropp as ankle movement beyond the physiologic limit of the ankle’s range of motion leading to recurrent laxity after ankle injury. To debate if mechanical or functional ankle instability is the cause of repeated ankle injury appears to be a fruitless effort as the continued outcome for either leads to recurrent injury. What seems more reasonable to consider is that those with CAI demonstrate deficits in both areas of functional and mechanical ankle instability when compared to matched healthy ankles. A recent study examined multiple factors associated with mechanical and functional instability to recognize if relationships existed between the two areas. The investigators found aspects of mechanical and functional ankle instability are not completely independent of each other and multiple facets of both should be examined.
When combining aspects of both mechanical and functional ankle instability, one might consider if there exist certain predictive factors to those with CAI. Previous ankle sprains, inversion laxity, anterior laxity, plantar flexion to dorsiflexion peak torque ratio, and postural sway deficits have been demonstrated as predictors of repeated ankle sprains.\textsuperscript{23, 25, 26} Although these multiple risk factors of ankle ligament injury have been proposed, little agreement on one particular clinical symptom as a predictor has surfaced.\textsuperscript{23, 27}

What we are certain of is that CAI is affecting the lifestyles of the physically active. Injury surveillance of US high school athletes in 2005 -2006 school year reported ankle injuries accounting for 22.6\% of all high school-related sports injuries.\textsuperscript{28} Recent injury surveillance of 15 NCAA sports from 1988 -2003 reported ankle injuries the most prevalent injury, accounting for 15\% of all reported injuries.\textsuperscript{29} Specifically sports such as baseball,\textsuperscript{30} men’s basketball,\textsuperscript{31} women’s basketball,\textsuperscript{32} women’s field hockey,\textsuperscript{33} football,\textsuperscript{34} women’s gymnastics,\textsuperscript{35} men’s lacrosse,\textsuperscript{36} women’s lacrosse,\textsuperscript{37} men’s soccer,\textsuperscript{38} women’s soccer,\textsuperscript{39} women’s softball,\textsuperscript{40} and women’s volleyball\textsuperscript{41} all report ankle sprains as the most common injury during practices, games, or both. The athletes who suffer from repeated ankle joint injury often miss both practice and game playing time and the healthcare provider is faced with repeated bouts of treatment and rehabilitation. Additionally, as life progresses, those with CAI may be less likely to continue living a healthy, active lifestyle if they are concerned repeated injury may ensue. This can lead to other general health problems linked to inactivity.

The mechanisms of injury which are most commonly seen with lateral ankle sprains involve everyday activity for the physically active such as gait or landing from a
jump on an externally rotated lower leg combined with excessive supination of the rearfoot.\textsuperscript{42-44} Robbins and Waked\textsuperscript{45} stated that lateral ankle sprains “occur during foot contact on landing or locomotion associated with either unanticipated foot placement on a sloped surface or inappropriate position of the foot in space before contact with a surface.” With this in mind, improper positioning of the foot at contact with the ground could cause the mechanisms described above leading to injury. When landing from a jump, if the center of pressure (COP) at the foot is located, perhaps, medial to the subtalar-joint axis when the foot makes contact with the ground, the vertical ground reaction forces, acting in the opposite direction, cause a greater supination moment which may lead to an inversion ankle sprain.\textsuperscript{46} When considering foot pressures in those with CAI, studies have found in-shoe force pressures while jogging were significantly higher on the lateral foot in those with CAI compared to healthy subjects.\textsuperscript{47} In a cadaveric study,\textsuperscript{48} it was found that as the foot makes contact with the ground, even a misjudgment of approximately 10° of inversion can result in ankle inversion torques which the authors speculate would lead to ligamentous injury of the lateral ankle.\textsuperscript{48} From this information, we can speculate that not only would increased lateral pressures in those with CAI lead to a more inverted position, but also that poor placement of the foot or landing on an unstable surface would change the COP and that both or either of these elements could lead to repeated sprains.

In addition to changes in COP, the ability to control and adjust to changes in movement is critical in the body’s ability to prevent injury. Time to boundary, which estimates the time to reach the limit of COP before falling, has also been shown to be altered in those with CAI.\textsuperscript{49} A lower time to boundary measure signifies less time to
reach the COP boundary, implying greater instability. Those with CAI have a significantly lower time to boundary than those with healthy ankles, indicating they have less ability to maintain postural control when perturbations occur.

Because inversion is the dominant motion involved with a lateral ankle sprain, it would be reasonable to conclude that deficiencies in strength of the evertors in those with CAI may lead to repeated injury. But in fact, multiple authors \(^5, 50-52\) have found no eversion strength deficits in those with CAI compared to those with healthy ankles.

Another logical conclusion may then be that perhaps there are neuromuscular deficits leading to the repeated inversion. Studies have shown that those with CAI demonstrate altered sensation,\(^2\) decreased kinesthesia,\(^5\) and decreased postural control,\(^3, 4\) all aspects of neuromuscular control.

As neuromuscular changes are examined further, an existing theory proposes that the joint afferents are injured during ankle sprains leading to altered afferent signal. While not participating in activity, studies have shown a decreased sense of foot position in those with functional ankle instability where subjects were unaware of how plantarflexed and everted their foot was positioned.\(^53\) Authors concluded this lack of proprioception may contribute to repeat ankle sprain as this is the common position for injury.\(^53\) During an CKC inversion motion, afferent delays may also lead to delayed reflex responses to changes in range of motion such as inversion.\(^21\) If this delay exists, slowing the efferent muscle response, this may lead to repeated ankle sprains. This theory of articular deafferentation has been challenged as more investigation has been directed at the reaction time of the peroneals. In healthy subjects, it has been shown that inversion velocity sufficient to cause injury to the ligaments occurs at 100 ms, but the
responding peroneal activation to cause eversion happened at median latency of 176 ms.\textsuperscript{54} Therefore, the peroneals cannot act fast enough to reverse the inversion motion and protect the ankle from injury. In addition, when loss of afferent input from the ankle is induced with anesthetic, no change in response time was found.\textsuperscript{55} This leads researchers away from afferent responsibility and to other areas to explain the changes occurring that may be leading to repeated ankle sprains. In a review of current literature on postural control in those with CAI, Riemann\textsuperscript{6} concluded that reduced mechanoreceptor input is not solely responsible for maintaining postural control. This may indicate these subjects seek other neural means to stabilize in response to perturbations.

Understanding the concept of the kinetic chain, some authors have chosen to investigate changes occurring at the proximal joints of those with CAI. This line of thinking has led to multiple studies to find alternations at the hip and knee.\textsuperscript{2, 3, 16, 17, 56} Caufield and Garrett\textsuperscript{56}, proposed that a centrally derived feed-forward motor program may be altered in those with CAI. They studied healthy and CAI patients to note changes in ankle and knee angular displacement just prior to and just after jump landing. Prior to landing, there were significant differences in knee angular displacement, but none in ankle. At landing, those in the injured population landed with greater ankle dorsiflexion and greater knee flexion. The authors suggest this is a result of a feed-forward response to jump landing, perhaps positioning the ankle in more dorsiflexion to avoid the possibility of injury. Increased dorsiflexion causes a closed-pack position with greater bone contact and decreased likelihood of inversion sprain. Other authors\textsuperscript{57} also support the idea of changes in feed-forward motor control being responsible for those with ankle instability. When performing a hopping task where healthy and CAI subjects performed
a lateral hop onto and off of a force platform, those with CAI demonstrated a significantly less everted ankle position and increase in EMG activity of the rectus femoris, tibialis anterior and soleus muscles both pre and post landing compared to the healthy controls. The authors speculated that feed-forward changes appear to be causing those with ankle injury to prepare to land from a jump or lateral hop by use of altered neural patterns compared to healthy subjects.57

These changes in landing affect ground reaction forces (GRF). When comparing those with CAI to healthy subjects, CAI subjects demonstrate significant changes in timing of peak GRF in the anterior and lateral direction as well as incurring greater time-averaged GRF during jump landing.58 These changes may be a result of the changes in positioning of the lower extremity in trying to reduce the impact of the landing. Data from a study by Delahunt59 revealed changes in CAI compared to healthy controls for both ankle kinetics and EMG activity while landing from a jump. Injured subjects demonstrated significant decreases in prelanding peroneus longus EMG activity and a more inverted ankle position just prior to landing. Other results found injured subjects reached their peak vertical GRF earlier than control subjects with forces more medially directed. These results indicate the ankle is in a more lose pack position and is positioned for a greater likelihood of an inversion sprain just prior to landing. As has already been established, a change in foot position as the foot makes contact with the ground greatly encourages injury. The changes in GRF may suggest that the CAI patients are not able to disapate the GRF over time which may also lead to ankle injury.

2.2 Chronic Ankle Instability and Foot Pressure
In continuing the pursuit of how CAI subjects differ in control of the lower extremity, investigations into the distal aspect of the lower extremity have revealed changes in how foot pressures differ in those with CAI compared to healthy subjects. The positioning of the foot is reflected in how the pressures are distributed on the plantar side of the foot.

Nawata et al\textsuperscript{8} studied foot angle and COP relating to pronation-supination in those with functional ankle instability and those with healthy ankles. Walking trials revealed the pathological group had increased inversion at the midsupport phase as well as increased adduction-supination of the foot compared to healthy controls. Confirming this pattern in force distribution, Nyska et al\textsuperscript{9} found a significant increase in forces at the midfoot and lateral forefoot in those with CAI compared to healthy control subjects. There was also a slowing of weight transfer from heel strike to toe off in those with CAI which the authors believe is a protective compensation from the less stable, more loose pack position of plantarflexion. But as these CAI subjects did move into the forefoot, the pressure was significantly higher on the lateral side, causing potential ankle inversion injury.

When studying in-shoe pressures during running gait, results on the lateral midfoot reveal those with CAI display significantly greater maximum pressure, pressure time integral, maximum force, and force time integral compared to healthy subjects. When moving to the forefoot, CAI show significantly greater maximum force, force time integral, and peak pressure compared to healthy subjects.\textsuperscript{19}

Because inverted foot position has been demonstrated in those with CAI and increased lateral loading of the foot in those with CAI, we are led to believe the two are
related and partially explain one another. In connection with altered foot position and altered foot pressure patterns, changes in neural patterns in the proximal segments of the lower extremity may be leading to some of the adjustments in foot positioning. As stated earlier, altered foot positioning can lead to ankle injury. As the foot takes on the weight of the body at contact with the ground, positioning is extremely important in maintaining lower body biomechanics. When looking at the kinetic chain of the lower extremity, it is imperative to understand what muscles may be contributing to foot positioning and possible changes in a feed-forward loop to avoid injury to the ankle. One line of research has begun to look more closely at the glutei muscles and their contributions to lower extremity control.

2.3 Chronic Ankle Instability and Gluteus Muscles

2.3.1 Gluteus Medius

One of the major muscle groups helping to control the positioning of the lower extremity kinetic chain is the gluteus group. The gluteus medius muscle works mainly as a hip abductor in the frontal plane to support the pelvis during single leg stance, preventing the contralateral side from dropping. This muscle also allows for proper foot placement during the heel strike phase of gait and proper control during single leg stance of gait. To gain a better understanding of how the Gmed functions, Soderburg and Dosta used indwelling EMG electrodes and measured muscle activity during seven activities of daily living. Of these, the highest level of gluteus medius activity was shown to be during a single leg stance with a forward lean. Although the article does not describe exact joint positioning, all the activities which showed high levels of gluteus medius activity involved changing trunk flexion and weight acceptance during a dynamic
task. In a separate study of gluteus medius EMG during multiple activities, Ayotte et al.\textsuperscript{10} found, again, high levels of muscle activity during trunk flexion and a change in center of pressure as the movement of the step or squat occurs. In addition, these activities are all performed during a single leg stance, which confirm the findings of the activities in the Soderberg\textsuperscript{60} study. These two studies help to demonstrate a consistent positioning which recruits high activity of the gluteus medius; a position that is similar to a land from a jump or running which is a common mechanism for ankle injury.\textsuperscript{42-44}

In addition to the multiple actions in the sagittal plane as mentioned above, the gluteus medius is a strong contributor to movements in the transverse plane as well. Beyond normal gait, the action of decelerating, rotating the body, and changing direction has been shown to have greater EMG activity than straight-ahead gait.\textsuperscript{61, 62} This cutting or turning movement is essential to athletic activity and is another common mechanism for lower extremity injuries.\textsuperscript{42-44}

Additional EMG investigation of the gluteus medius shows when applying an external rotational force in the transverse plane during a single leg stance, the gluteus medius is highly activated.\textsuperscript{63} Further, when combining abduction forces with a rotational force during a single leg stance, fibers of the gluteus medius are also shown to be highly active.\textsuperscript{64}

These studies indicate the gluteus medius controls frontal plane movement of the pelvis and femur during weight bearing or as the foot prepares to land which effects the lower leg and foot, affecting the positioning of the ankle joint.\textsuperscript{11} Additionally, the studies demonstrate the gluteus medius is essential in controlling frontal and transverse plane movement as well, which would involve cutting. Both jump landing and cutting are
common mechanisms of ankle joint injury. Because the gluteus medius is meant to activate and control movement of the pelvis and femur through three planes of motion, if neuromuscular deficits exist, improper placement of the foot could occur, leading to a greater possibility of ankle injury.

2.3.2 Gluteus Maximus

The gluteus maximus is also essential in controlling the positioning of the lower extremity kinetic chain. It works mainly as a hip extensor as well as controlling rotation of the femur. In activities of daily living, motions such as squatting to sit into a chair, climb a stair, or lunging all show high EMG activity of the gluteus maximus. Much of sporting activity involves changing weight bearing from one leg to another as well as being in a low, squatting position. A single leg squat position has also demonstrated high muscle activity of the gluteus maximus. Weight acceptance during gait to control hip flexion and internal rotation of the femur during midstance is another group of motions where the gluteus maximus is very active. Like the gluteus medius, these motions demonstrating high activity of the gluteus maximus are linked to mechanisms of injury for the ankle. If the femur is not being controlled properly as the foot accepts weight, or as the body changes direction, the effects are seen throughout the lower extremity kinetic chain and ankle injury may result.

2.3.3 The Gluteus-Chronic Ankle Instability Connection

To gain a clearer picture of the relationship between the glutei and the CAI, investigators have studied the hip muscles of those with CAI during various activities. Beckman and Buchanan found changes in hip muscle latency for subjects with
unilateral CAI, utilizing inversion perturbations as an intervention. They found the CAI group recruited the gluteus medius faster than the healthy group in response to inversion ankle motion. This significant difference was found for the injured group on both the left and right sides, regardless of injured side. These differences in bilateral gluteus medius muscle contraction in CAI compared with healthy subjects support the theory that changes are occurring in central patterning as a feed-forward mechanism, rather than reflex control in those with CAI. This would indicate the neural patterns in those with ankle injury are actually different from those with healthy ankles. Whether this is a protective mechanism as a result of ankle injury or if the change in muscle pattern existed before the ankle injury was incurred is unknown. This comparison of healthy to CAI does help in understanding differences in those with CAI compared to healthy populations.

The theory of central nervous system changes has also been supported by Bullock-Saxton, et al. In a study utilizing control and CAI subjects, muscle activation patterns of the gluteus maximus, biceps femoris, and erector spinae were studied during prone hip extension. In the control group, hip extension muscle activation pattern was repeatedly consistent between right and left sides, as well as simultaneous muscle activation for the studied muscles. In contrast, the injured group displayed inconsistent muscle activation patterns both within the same side and between sides compared to the control group. In addition, when comparing muscle activation in the injured group, a significant delay was found in gluteus maximus activation of those with CAI compared to healthy subjects. Although the previous study found a faster activation of gluteus medius and this study found a delay in muscle activation of the gluteus maximus, it is
clear changes are occurring in muscle activation of those with CAI. It is unclear why one study would find delays while another would find faster activation. Although the gluteus medius and gluteus maximus share a common origin, the actions of the muscles are different. Another explanation may be that one study chose to look at an open chain, preplanned activity while the other chose a closed chain intervention with an unexpected timing of a collapsing platform. These two motions would require different neuromuscular responses, changing activation of the musculature.

Friel et al performed a study of those with unilateral CAI to further investigate an ankle-hip relationship. These investigators used a hand-held dynamometer to measure strength of hip abductor and hip extensor strength for the injured and uninjured limbs. The results demonstrated significantly lower abductor strength on the injured side compared to the uninjured side but no differences in hip extensor strength. The findings of this study support the view that weakness in gluteus medius may create deviations in motion leading to chronic loss of stability in the kinetic chain which can contribute to multiple ankle sprains.

Friel et al found no significant differences in hip extensor strength. This may be due to a centralization of the neural patterns which can be seen in bilateral gluteus maximus EMG as noted by the previously discussed Bullock-Saxton et al study. Although this study measured hip extension strength and the Bullock-Saxton et al paper looked at EMG activity, if these subjects had been compared to healthy subjects rather than comparing injured and non-injured limbs of the same subjects, results may have been similar to those of Bullock-Saxton et al.
One final study to consider is that of VanDuen et al\textsuperscript{18} who utilized a transition activity from double-leg stance to single-leg stance in those with and without CAI. This procedure was performed with subjects’ eyes open as well as a closed-eye trial. When observing muscle onset patterns, results exhibited CAI subjects had significantly later onsets of peroneus longus, tibialis anterior, gastrocnemius, medial hamstrings, tensor fasciae latae, and gluteus medius during transition from double to single-leg stance. In addition to this finding, the authors also discovered that when comparing the eyes open to the eyes closed trials, those with CAI showed less variability in muscle activation patterns when compared to the healthy group. Therefore, not only are those with CAI exhibiting changes in the proximal muscles of the hip, but they are not able to adjust and utilize the muscles differently when faced with variable situations such as decreased visual input. Once again, the changes in the neural patterns of those with CAI are demonstrated.

In a recent investigation conducted by the author, other neuromuscular changes of the glutei muscles were demonstrated in those with CAI compared to healthy subjects. Subjects were asked to complete four rehabilitative exercises which have shown high activity of the gluteus maximus and medius. These exercises included a hip hike (HH), hip abduction (HA), rotational lunge (RL) and a single-leg rotational squat (RS). These exercises were implemented for multiple reasons. First, they have been documented as demonstrating high gluteus medius and maximus muscle activation.\textsuperscript{10,64} Secondly, they are common exercises that might be performed in the clinical setting for glutei strengthening. Thirdly, functional activity similar to athletic activity was reflected in the exercises. When the EMG activity was analyzed across the entirety of the exercises,
although the CAI demonstrated less gluteus medius activation across all exercises, no significant differences were discovered. However, during the RL exercise, a strong effect size ($d=0.91$) was associated with the differences in gluteus medius activity between the CAI ($0.84±0.33$) and Healthy groups ($0.55±0.29$) and a moderate effect size ($d=0.48$) associated with the differences in gluteus maximus activation between the CAI ($0.75±0.57$) and Healthy groups ($0.54±0.29$). There was a significant difference in both gluteus medius ($F_{3,48}=3.16$, $p=0.033$) and gluteus maximus ($F_{3,48}=15.90$, $p=0.001$) EMG activity across the Exercises, regardless of Group. For the gluteus medius, the RS ($0.82±0.37$) produced the highest activation. For the gluteus maximus, RS ($0.67±0.31$) again had the highest activation level. Additionally, for the gluteus maximus, both RS ($0.67±0.31$) and RL ($0.65±0.45$) produced significantly higher activity than HH ($0.41±0.24$) and HA ($0.30±0.22$) and the HH demonstrated significantly higher activity than HA. Because the RL and RS showed the highest level of muscle activity and were associated with strong effect sizes, the data from these two exercises were analyzed further.

The author felt the point at which the subject was furthest from the starting point of the exercise (greatest hip flexion and hip rotation) would be when the stabilizing muscles of the gluteus medius and maximus would be most active. This was designated as the point of maximum excursion. This point was located on the data through video and the 0.2 seconds before and after this point was marked on the EMG signal, averaged, and compared between the two groups. For gluteus maximus activation, there was a statistically significant Group by Exercise interaction ($F_{3,48}=4.84$, $p=0.043$). A Scheffe’s post hoc test revealed that for the RS, the CAI group ($51.1±3.1\%$) had significantly lower
Gluteus maximus activation than the healthy group (78.7±4.4%). In addition, for the healthy group, the Gluteus maximus produced significantly higher activation during RS (78.7±1.3%) compared to the RL (57.8±0.1%). There were no significant Group or Exercise effects on Gluteus medius activation.

The results of these two data sets help confirm there are neuromuscular changes occurring at the gluteus medius and maximus of those with CAI. Further investigation is necessary to confirm these findings of changes during functional activity. More of these changes in neuromuscular activity may be demonstrated in more sport-related situations. It is proposed these changes may be more pronounced when CAI subjects are tested in a muscularly fatigued state and perform a task that represents ankle sprain etiology.

2.4 Fatigue Related to Injury

Aside from injury, impact on the neuromuscular system in general can be affected by how much activity a person has performed. Fatigue has been proposed to desensitize muscle spindles and the afferent pathways to the central nervous system, slowing the response and number of muscle fibers needed to handle perturbations. This impact on the central nervous system increases a predisposition to injury. 68, 69 This fatigued state also leads to changes in positioning of the joints and deficits in postural control.

Miura et al.14 when studying effects of general fatigue, found deficiencies in central processing of proprioceptive signals. The authors suggested that preventing injuries should include not only muscle endurance training, but neuromuscular training, including central motor programming. In essence, proper muscle firing may need to be practiced in a fatigued state to prevent injury. Specific to ACL injury, studies have suggested that fatigue-induced changes in knee mechanics may lead to greater chance of
injury.\textsuperscript{13, 70, 71} Although these particular studies were not focusing on the ankle injuries, it suggests total lower-limb changes which would affect musculature and positioning of hip, knee, and ankle.

In confirmation of the above studies, it has been well recognized that injuries during physical activity occur more commonly when the muscles are in a fatigued state. Injury patterns for sports such as football,\textsuperscript{72} soccer,\textsuperscript{15, 73} rugby,\textsuperscript{74} and skiing,\textsuperscript{75} have all been documented as more frequently sustained in the later parts of the activity.

2.5 Fatigue and Joint Position Changes

Multiple studies have demonstrated changes in joint position as a result of fatigue. At the ankle, decreased dorsiflexion during heel strike of running and increased plantarflexion during the swing phase has been demonstrated, both of which leave the ankle more susceptible to ankle injury.\textsuperscript{76} During a single-leg drop jump landing after fatigue, maximum ankle dorsiflexion increased, perhaps demonstrating difficulty in controlling limb positioning due to gravity while landing.\textsuperscript{77} Another finding at the ankle during a fatigue protocol tested athletes during a cutting maneuver and found increased external rotation\textsuperscript{78} of the ankle at initial contact as the knee moved into internal rotation.

Changes in knee position have also been measured after fatigue. Some of the changes in knee position noted have been increased knee flexion at initial contact and toe-off of running,\textsuperscript{76, 77, 79} and increased knee internal rotation during side-step cutting maneuver,\textsuperscript{78} increased knee abduction and internal rotation during a single limb jump landing,\textsuperscript{80} increased valgus knee position at landing of drop jump,\textsuperscript{81} and increased tibial shear force during a single-leg drop jump.\textsuperscript{13, 77}
Kinematic changes have also been demonstrated at the hip after fatigue. During a single-leg drop jump, post-fatigue data revealed increased hip flexion and decrease in hip abduction for women. Another study measured lower limb kinematics while asking subjects to perform single leg jump-cut after fatigue. Results demonstrated increased hip extension and internal rotation at initial contact. During single-leg drop jump, fatigue caused increased hip flexion and adduction at landing. Small et al. showed reduced hip flexion during sprinting with fatigued subjects. With running, Kellis found hip extension angle increased after fatigue during toe-off. During a cutting maneuver, Sanna and O’Connor noted transverse plane changes at the hip which included increased external rotation. So as the hip moves through its different physiological ranges of motion, changes in these planes of movement are affected by fatigue.

2.6 Fatigue and Postural Control

Overall changes in neuromuscular control have been associated with fatigue as well. Balance testing of fatigued subjects has demonstrated decreases in ability to maintain stability both unilaterally and bilaterally. When implementing a dynamic postural control task such as the Star Excursion Balance Test, those with CAI have shorter reaching distances compared to those with uninjured ankles. When implementing a fatiguing aspect, both healthy subjects and CAI subjects had reductions in reaching distance, indicating fatigue leads to difficulty in maintaining postural control.

Appreciating that fatigue can lead to changes in joint position and postural control, we have better understanding as to why injuries are so commonly sustained at the end of practices and games. With ankle injuries being so common during all different
sporting activities, it is important to investigate the effects of fatigue on those with recurrent injuries to help lead to a better idea of how to prevent future injuries. Because neuromuscular changes in the glutei muscles have been seen those with CAI, perhaps by studying the activity of these muscles in conjunction with force pressures on the foot at landing in those with CAI compared to healthy subjects during a functional task, we may be able to better design intervention programs to prevent this repetitive injury.
Chapter 3

Article 1: Muscle activation in proximal and distal muscles during a lateral hop before and after fatigue in those with and without chronic ankle instability

3.1 Introduction

Ankle sprains are some of the most common injuries seen in physical activity with reinjury rate as high as 80%.\(^1\) For those who experience a significant lateral ankle sprain, a common outcome is repeated “giving way” of the ankle during activities. The term chronic ankle instability (CAI) has been given to these individuals and is characterized by residual lateral instability, leading to repetitive ankle sprains.

Altered neuromuscular patterns may be contributing to this recurring injury.\(^2-6\) This may be due to changes in foot positioning not only at the ankle, but also proximally up the kinetic chain. Because the gluteus maximus (Gmax) and gluteus medius (Gmed) help control the positioning of the lower extremity,\(^10-12\) it is important to consider that in addition to the muscles surrounding the ankle joint, these proximal muscles may be contributing to the injury as well, or may also be helping to prevent sprains from
occurring more regularly. Some researchers have proposed that those with CAI have implemented a pre-programmed, feed-forward mechanism to help prevent injury during dynamic tasks. These patterns may be more clearly demonstrated by simultaneously observing muscle activity at the proximal and distal portions of the kinetic chain. Understanding how together, the proximal and distal muscles both prepare for and stabilize at landing in subjects with CAI compared to healthy controls may help researchers and clinicians in their goal of preventing subsequent ankle sprains, consequently, allowing these individuals to stay more active.

Another factor that may be contributing to persistent ankle injury is fatigue. It is well documented that fatigue causes neuromuscular changes such as decreased muscular strength and control which may be a contributing factor to injury. Potentially, as fatigue increases, these neuromuscular control changes affect the proximal muscles at the hip and distal muscles at the ankle, allowing improper positioning of the ankle in those with CAI which may predispose this group to recurrent ankle injury. Introducing a fatigue element in patients with CAI which involves functional activity may allow pre-programmed, feed-forward mechanisms to be more clearly demonstrated. Better understanding of this relationship of fatigue on the neuromuscular system and how it prepares for and controls a lateral hop landing can help clinicians implement rehabilitation programs which may help prevent future recurrent injury. Examining the proximal muscles of the Gmed and Gmax together with the tibialis anterior (TA) and peroneus longus (PL), which prevent inversion ankle sprains, may help in further explaining how those with CAI maneuver to complete a lateral hop landing. Previous projects have studied the effects of fatigue on electromyographic (EMG) activity in
individuals with CAI but have not focused on the activation of both proximal hip muscles during a functional task. This will be the first study to combine both proximal and distal measures of muscle activity in those with CAI before and after a fatiguing protocol during a functional task. Specifically, the purpose of this study was to examine the EMG activity of the tibialis anterior, peroneus longus, gluteus medius and gluteus maximus just prior to and while landing a lateral hop before and after fatigue in subjects with CAI compared to healthy controls.
3.2 Materials

A Bertec NC-4060 force platform (Bertec, Corp., Columbus, OH) was integrated with Motion Monitor™ software (Innovative Sports Training, Inc; Chicago, IL) to indicate initial contact (IC) during the hopping task. The EMG signal was collected using Noraxon Telemyo 2000 System (Noraxon USA, Inc, Scottsdale, AZ), including receiver, transmitter, and USB A/D converter which was then recorded through Motion Monitor™. Dual circular Ag/AgCl disposable electrodes were utilized for surface electromyography with adhesive area measuring 4 cm x 2.2 cm, conductive area 1 cm, and inter-electrode distance measured at 2 cm (Noraxon USA, Inc., Scottsdale, AZ). Files were exported to Microsoft Office Excel for data reduction and preparation for analysis.
3.3 Methods

A case control, repeated measures design was used to examine EMG muscle activation during a lateral hop before after fatigue in those with and without CAI.

3.3.1 Subjects

Thirty-two subjects volunteered for the study. Sixteen CAI subjects (8M, 8F, 172.25 ±10.87cm, 69.13±13.31kg, 20.50±2.00yrs) were matched to sixteen healthy subjects (8M, 8F 170.50 ±9.94cm, 69.63±14.82kg, 22.00±3.30yrs) by height, weight, mass, sex, and side.

<table>
<thead>
<tr>
<th>Table 3.1: Subjects' Demographics</th>
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</thead>
<tbody>
<tr>
<td>Age (years)</td>
</tr>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>CAI</td>
</tr>
<tr>
<td>Control</td>
</tr>
</tbody>
</table>

Subjects reported in athletic clothing to the Motion Analysis Laboratory for the data collection session. Subjects read and signed the university-approved informed consent then were assigned a subject number. Demographic information and leg dominance were also collected. When asked which leg he or she would use to kick a ball, all subjects reported using the right leg.

For the CAI group, 16 subjects were recruited with previous history of ankle injury which caused limping or pain for at least 24 hours. Since the time of the initial injury, subjects in the CAI group reported having at least two episodes of the ankle “giving way”, and at least one in six months preceding testing. At the time of testing,
patients were able to perform normal activity with no pain and scored 90% or lower on the Foot and Ankle Disability Index (FADI) and/or 80% or lower on the FADI-Sport (See Appendix A). Sixteen subjects were recruited in the healthy control group matched by side, age, height, mass, and sex to a member of the CAI group. Those in the healthy control group were free from previous ankle sprain. Both groups were free from any previous lower extremity fracture or surgery and any vestibular changes including concussions within the last six months. All participants reported being “physically active” which was defined as at least 20 - 30 minutes of cardiovascular activity at least three times a week. All subjects completed the Participation Activity Readiness Questionnaire (PAR-Q) (see Appendix B) and answered “no” to all questions with the possible exception of question #5 for the CAI group which relates to joint injury. Subjects also completed the Tenger Activity Level Scale which allowed subjects to document the amount of physical activity they performed on a weekly basis (see Appendix C). This helped to insure all participants were involved in regular amounts of cardiovascular activity as noted in the inclusion criteria. Means and standard deviations from a previous study involving EMG measures in those with CAI compared to healthy controls was used to perform a power analysis calculation which suggested 15 subjects in each group is sufficient at a statistical significance level of 0.05.

3.3.2 Procedures

3.3.2.1 Electromyography

Placement of silver-silver chloride electromyography (EMG) electrodes in the direction of the muscle fibers on the skin was preceded by shaving the area, if necessary, and then lightly abrading and cleaning the skin with alcohol. The Gmed electrode was be
placed one inch below the iliac crest. For the Gmax, the electrode was placed half-way between the second sacral prominence and the greater trochanter of the femur.

Placement of the TA electrode was just lateral to the tibial tuberosity and the PL electrodes were placed 25% of the distance between the fibular head and the distal end of the lateral malleolus. To aid in correct electrode placement, subjects were asked to contract muscles against manual resistance prior to electrode placement. Before testing began, muscle activity was also checked on the output screen of the computer collecting the EMG signal to recognize any noise or cross-talk. To avoid movement caused by perspiration from the fatigue, prior to hopping, the EMG electrodes, both pre and post fatigue, the TA and PL electrodes were wrapped with Powerflex©. The same investigator (KW) wrapped the legs to ensure similar tension pre and post fatigue. Baseline EMG measurements were then measured for all the muscles in a neutral standing position for the length of a hopping trial.

3.3.2.2 Pre-Testing

Subjects were then asked to perform five lateral hops on each foot onto and off of the force platform.

Figure 3.1 Pre and post test hopping onto and off of the force platform
Right and left footed hops were alternated to prevent fatigue. The horizontal distance hopped was normalized to the length of the subjects’ lower leg (distance from fibular head to distal lateral malleolus) and was marked on the floor with two pieces of tape to direct subjects where to land. The vertical jump height was standardized by having subjects clear a 2” high barrier between the two tape markers. After the hopping was completed, the Powerflex© and the leads for the EMG system were removed so as not to interfere with the tasks of the fatigue protocol. The electrodes themselves remained on the skin during the fatigue.

3.3.2.3 Functional Fatigue Protocol

Subjects were introduced to the previously validated Functional Fatigue Protocol. This involved 5m x 5m cone drills including straight ahead sprint, lateral shuffle, backwards running, a pivot and finish with straight-ahead sprint. From there, subjects completed 30 lateral two-footed hops over a 10cm barrier, and finished with three successive step-ups onto boxes measuring 30cm, 38cm, and 46cm.
Previous authors\textsuperscript{87} have used this protocol with two-footed jumps onto the boxes. This was changed to a step-up and hop down to prevent possible lower leg injuries at the end of the fatigue protocol. Subjects were asked to walk through the protocol to familiarize them with the proper direction of the protocol. A floor mat-activated timing device (Lafayette Instrument Company, Lafayette, IN) was used to time the fatigue trials and times were displayed on a computer monitor. Subjects stepped on the start mat to begin the time and the finish mat as they completed the tasks of the fatigue. A record of the timing of each trial was be kept by the investigator. The subjects had 20 seconds between fatigue bouts to reposition themselves at the start before the next repetition of the protocol. The subjects were considered to be “fatigued” if any of the following occurred: 1) a timing of 50\% increase of the fastest time to complete the protocol, 2) subject was unable to repeatedly clear the 4” barrier on the lateral jump area, 3) subject reported being unable to step onto the plyometric box, or 4) subject reported being unable to continue.

3.3.2.4 Post-testing

As soon as fatigue was achieved, the leads of the EMG system were reattached and the wrap was replaced on the lower-leg electrodes. Two investigators helped with this process and it took approximately two minutes. Subjects then completed the same five lateral, one-footed hops onto and off of the force platform on each leg as was performed during the pre-test. Left and right legged hops were alternated. The post-test hopping was completed within approximately five minutes, making the total time from finishing the fatigue protocol to completing the five hops on each foot approximately seven minutes.
3.3.3 Data Collection and Processing

The EMG activities of the TA, PL, Gmed, and Gmax, were collected at a sampling rate of 1000Hz, smoothed and filtered using a Butterworth filter with a band-pass frequency of 10-500Hz, and full-wave rectified. The common mode ratio was >100 dB, baseline noise < 1µV, and the input impedance was >100 MOhms. The force platform was used to identify initial contact (IC) which was defined as at least 2% of the subject’s body weight. The EMG data used for analysis was for the period of Pre-landing (200 ms pre-IC to IC) and Post-Landing (IC until 200 ms post-IC) and was normalized to the mean peak EMG amplitude from the five hopping trials for each subject. The dependant variables were the pre-landing and post landing EMG activation means for the TA, PL, Gmed, and Gmax. The force platform data was collected at 1000 Hz and was not filtered as it was only used as an indicator of contact.

3.3.4 Statistical Analysis

Data was analyzed using SPSS 15.0 (SPSS Inc, Chicago, IL). For each of the eight dependant variables, a separate two (Fatigue) x two (Group) repeated measures ANOVAs was performed. A priori statistical significance was set at $p=0.05$. 


3.4 Results

Results include normalized % of average peak muscle activation means, ± standard deviation (SD), effect sizes (ES) calculated using Cohen’s d (d), \(^{88}\) and 95% confidence intervals (CI) around the effect sizes.

3.4.1 Pre-Landing Results (200ms pre IC-IC)

Although there were no statistically significant interactions, a moderate ES was observed for the TA (d=0.75), PL (d=0.51), and Gmax (d=0.57) as all displayed higher activation in CAI subjects post fatigue compared to pre fatigue. During the post fatigue hopping, the CAI group demonstrated higher activation compared to controls in the PL and Gmax as evidenced by a strong (d=0.83) and moderate (d=0.73) ES, respectively. (See Table 3.2)

Significant Condition main effects were found for PL and Gmax normalized % of average peak muscle activation (Table 3.3). For the PL, the CAI group demonstrated 11.77% more muscle activation in the CAI group compared to the healthy group \((F_{1,30}=8.60, p=0.01, ES=0.104, 95\% CI=0.27-1.75)\). Similarly, for the Gmax the CAI group displayed 8.74% higher muscle activation in the compared to the healthy group \((F_{1,30}=4.20, p=0.049, ES=0.72, 95\% CI=-0.01-1.42)\) during the pre-landing phase.
Table 3.2: Pre Landing Interaction Results

<table>
<thead>
<tr>
<th>Condition</th>
<th>Pre Fatigue Mean</th>
<th>Pre Fatigue SD</th>
<th>Post Fatigue Mean</th>
<th>Post Fatigue SD</th>
<th>F</th>
<th>p</th>
<th>CAI Pre:Post Fatigue ES CI lower CI upper</th>
<th>Post Fatigue CAI: Control ES CI lower CI upper</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAI</td>
<td>40.22%</td>
<td>3.90%</td>
<td>44.15%</td>
<td>6.53%</td>
<td>0.01</td>
<td>0.94</td>
<td>0.75 0.01 1.44</td>
<td>0.26 -0.95 0.44</td>
</tr>
<tr>
<td>Control</td>
<td>42.50%</td>
<td>6.86%</td>
<td>46.22%</td>
<td>8.35%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TA</td>
<td>48.07%</td>
<td>7.70%</td>
<td>57.71%</td>
<td>25.43%</td>
<td>1.35</td>
<td>0.25</td>
<td>0.51 -0.21 1.20</td>
<td>0.83 0.09 1.53</td>
</tr>
<tr>
<td>PL</td>
<td>40.96%</td>
<td>13.72%</td>
<td>41.29%</td>
<td>11.63%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CAI</td>
<td>42.17%</td>
<td>6.53%</td>
<td>42.02%</td>
<td>7.38%</td>
<td>0.34</td>
<td>0.56</td>
<td>0.03 -0.72 0.66</td>
<td>0.28 -0.97 0.42</td>
</tr>
<tr>
<td>Control</td>
<td>46.53%</td>
<td>13.81%</td>
<td>44.70%</td>
<td>11.41%</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Gmed</td>
<td>42.17%</td>
<td>6.53%</td>
<td>42.02%</td>
<td>7.38%</td>
<td>0.34</td>
<td>0.56</td>
<td>0.03 -0.72 0.66</td>
<td>0.28 -0.97 0.42</td>
</tr>
<tr>
<td>Control</td>
<td>46.53%</td>
<td>13.81%</td>
<td>44.70%</td>
<td>11.41%</td>
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<td></td>
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</tr>
<tr>
<td>Gmax</td>
<td>40.55%</td>
<td>4.83%</td>
<td>50.55%</td>
<td>23.98%</td>
<td>2.84</td>
<td>0.10</td>
<td>0.57 -0.15 1.26</td>
<td>0.73 0.00 1.43</td>
</tr>
<tr>
<td>Control</td>
<td>36.84%</td>
<td>11.93%</td>
<td>36.77%</td>
<td>11.36%</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

TA= Tibialis Anterior, PL=Peroneus Longus, Gmed=Gluteus Medius, Gmax=Gluteus Maximus, CAI=Chronic Ankle Instability, SD=Standard Deviation, ES=Effect Size, CI=95% Confidence Intervals
A significant main effect for Fatigue for the TA was revealed with post fatigue (45.2%±0.01) being significantly higher than pre-fatigue muscle activation (41.4%±0.01) (F_{1,30}=8.61, p=0.006, ES= 0.81, 95%CI= 0.07, 1.51). There were no statistical differences between Condition or Fatigue for the GMed.

<table>
<thead>
<tr>
<th>Table 3.3: Pre Landing for Condition Results</th>
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<tr>
<td></td>
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<tr>
<td></td>
</tr>
<tr>
<td>TA</td>
</tr>
<tr>
<td>PL</td>
</tr>
<tr>
<td>Gmed</td>
</tr>
<tr>
<td>Gmax</td>
</tr>
</tbody>
</table>

TA= Tibialis Anterior, PL=Peroneus Longus, Gmed=Gluteus Medius, Gmax=Gluteus Maximus, CAI=Chronic Ankle Instability, SD= Standard Deviation, ES=Effect Size, CI=95% Confidence Intervals, *=p=0.05

<table>
<thead>
<tr>
<th>Table 3.4: Pre Landing for Fatigue Results</th>
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<td></td>
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<tr>
<td>PL</td>
</tr>
<tr>
<td>Gmed</td>
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<tr>
<td>Gmax</td>
</tr>
</tbody>
</table>

TA= Tibialis Anterior, PL=Peroneus Longus, Gmed=Gluteus Medius, Gmax=Gluteus Maximus, CAI=Chronic Ankle Instability, SD= Standard Deviation, ES=Effect Size, CI=95% Confidence Intervals, *=p=0.05

3.4.2 Post Landing Results (IC-200ms post IC)

The only statistically significant findings for the time of IC -200ms post IC, were in the TA which demonstrated significantly higher activation post fatigue compared to pre-fatigue (F_{1,30}=7.45, p=0.01, ES=0.62, 95%CI= -7.89, 9.06). (Tables5-7)
### Table 3.5: Post Landing Interaction Results

<table>
<thead>
<tr>
<th>Condition</th>
<th>Pre Fatigue</th>
<th>Post Fatigue</th>
<th>CAI Pre:Post Fatigue</th>
<th>Post Fatigue CAI: Control</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>TA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CAI</td>
<td>42.11%</td>
<td>5.87%</td>
<td>45.19%</td>
<td>7.15%</td>
</tr>
<tr>
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<td></td>
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<td></td>
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</tr>
<tr>
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<td>44.48%</td>
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<tr>
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<td>9.17%</td>
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</tr>
<tr>
<td>Gmed</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CAI</td>
<td>43.70%</td>
<td>8.60%</td>
<td>42.54%</td>
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<tr>
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<td>42.86%</td>
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<tr>
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<td>12.84%</td>
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</table>

TA= Tibialis Anterior, PL=Peroneus Longus, Gmed=Gluteus Medius, Gmax=Gluteus Maximus, CAI= Chronic Ankle Instability, SD= Standard Deviation, ES=Effect Size, CI=95% Confidence Intervals
Table 3.6: Post Landing for Condition Results

<table>
<thead>
<tr>
<th></th>
<th>CAI</th>
<th>Control</th>
<th>Mean</th>
<th>SD</th>
<th>Mean</th>
<th>SD</th>
<th>F</th>
<th>p</th>
<th>ES</th>
<th>CI lower</th>
<th>CI upper</th>
</tr>
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<tbody>
<tr>
<td>TA</td>
<td>43.65%</td>
<td>6.85%</td>
<td>44.44%</td>
<td>6.85%</td>
<td>0.106</td>
<td>0.75</td>
<td>-0.12</td>
<td>0.75</td>
<td>-7.61</td>
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<tr>
<td>PL</td>
<td>46.01%</td>
<td>7.80%</td>
<td>46.41%</td>
<td>7.80%</td>
<td>0.021</td>
<td>0.87</td>
<td>-0.05</td>
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<td>-7.08</td>
<td>6.99</td>
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<td>Gmed</td>
<td>43.12%</td>
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<td>0.001</td>
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<td>0.01</td>
<td>0.98</td>
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<td>Gmax</td>
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<td>8.40%</td>
<td>0.12</td>
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<td>0.12</td>
<td>0.73</td>
<td>-6.67</td>
<td>6.90</td>
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TA= Tibialis Anterior, PL=Peroneus Longus, Gmed=Gluteus Medius, Gmax=Gluteus Maximus, CAI=Chronic Ankle Instability, SD= Standard Deviation, ES=Effect Size, CI=95% Confidence Intervals, *=p=0.05

Table 3.7: Post Landing for Fatigue Results

<table>
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<tr>
<th></th>
<th>Pre Fatigue</th>
<th>Post Fatigue</th>
<th>Mean</th>
<th>SD</th>
<th>Mean</th>
<th>SD</th>
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<th>p</th>
<th>ES</th>
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<td>-7.46</td>
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</table>

TA= Tibialis Anterior, PL=Peroneus Longus, Gmed=Gluteus Medius, Gmax=Gluteus Maximus, CAI=Chronic Ankle Instability, SD= Standard Deviation, ES=Effect Size, CI=95% Confidence Intervals, *=p=0.05
3.5 Discussion

The results from this study demonstrated a higher activation of the PL and Gmax in subjects with CAI compared to healthy subjects during the pre landing phase of a lateral hop. This data could suggest a feed-forward protective mechanism implemented to protect the ankle from injury in those with CAI. Repeated ankle joint injury results in deficits in neuromuscular control which hinder the dynamic protective mechanism of the ankle, making it more vulnerable to repeated injury. Because of these deficits, the neuromuscular system may be exhibiting alternative means to protect the ankle from injurious positions by modifying activation of muscles in both the proximal and distal portions of the lower extremity. These finding are consistent with other literature that has demonstrated pre-programmed neuromuscular changes during dynamic postural control in patients with CAI.

3.5.1 Foot positioning

Robbins and Waked stated that improper positioning of the foot can be a mechanism of injury for ankle inversion sprains. When landing from a jump, if the center of pressure (COP) at the foot is located medial to the subtalar-joint axis when the foot makes contact with the ground, the vertical ground reaction forces, acting in the opposite direction, cause a greater supination moment which may lead to an inversion
ankle sprain. Additionally, it has been suggested by previous research that a more inverted position of the ankle could shift the position of the center of gravity, which may make landing from a jump more difficult. It has also been established that repeated injury to the ankle, as seen in those with CAI, may result in disrupted peripheral receptors, leading to decreased dynamic postural stability. The results of this may be a reflection of those disrupted peripheral receptors, evidenced by both distal and peripheral alterations of muscle activation.

3.5.2 Distal Alterations

The increased muscle activation for the PL demonstrated just prior to landing in the selected lateral hop suggests the neuromuscular system may be attempting to position the foot in a more everted position to avoid an inversion motion during the lateral hop landing. Delahunt et al collected kinematic, kinetic, and EMG data also during a lateral hop. The results of that study found those with functional ankle instability displayed a less everted position of the ankle and higher activation of the rectus femoris, TA, and soleus muscles prior to landing compared to healthy subjects. The subjects in our study may have displayed increased activity of the PL due to information from proprioceptors at the ankle sensing a more inverted position as suggested in the Delahunt et al study. This cannot be stated conclusively, as our study did not collect kinematic data. Although Delahunt et al did collect EMG activation data for the PL, they did not find changes in PL activation as our study did. It is unclear as to why the two studies found conflicting data in relation to the PL activation during a lateral hop. Delahunt et al also found significant changes in TA activation which would further solidify the argument for a pre-programmed protective position as activation of the TA would place the foot in a more
dorsiflexed position, which allows for a more stable, close-packed orientation of the ankle joint. Although the present study did see an increase in mean TA muscle activation for the CAI group, no significant changes were noted except when fatigue was involved. In this case, there were no differences in the two groups, but rather TA displayed higher activation at post fatigue for both groups.

Other investigations of CAI subjects performing dynamic functional tasks have also found evidence to support changes in neuromuscular control and pre-programmed feed-forward mechanisms at the proximal lower extremity. Caulfield et al.\(^8^9\) compared two different jump landing tasks, an anterior jump-landing and jump for distance, in subjects with and without CAI. Their study involved activation of the PL, TA, soleus muscles. Their results also demonstrated alterations in neuromuscular control as evidenced by decreased activation on PL prior to both jump landing tasks. Gribble and Robinson\(^8^4\) compared CAI subjects to healthy subjects while performing an anterior-directed jump. The outcomes found that at initial contact of landing, the CAI group demonstrated decreased ability to stabilize their landing. In a separate study, Caulfield and Garrett\(^5^6\) also studied an anterior jump in those with and without ankle pathology and found increased ankle dorsiflexion.

When collecting data for ground reaction forces during a drop jump, Caulfield and Garrett’s\(^5^8\) findings continued to lend evidence to pre-programmed feed-forward theory as they found earlier force peaks in GRFs in the anterior and lateral directions of those with CAI. Finally, during walking gait, Delahunt et al.\(^8^3\) noted prior to heel strike, those subjects with CAI demonstrated a more inverted position of the ankle prior to heel strike, a strong effect size (d=1.17) for increased PL activation prior to heel strike, and
higher PL activity just after heel strike. These investigations including the current study, build a strong case for pre-programmed feed-forward distal alterations in the neuromuscular system as it attempts to compensate for previous ankle injury by modifying ankle joint positioning.

3.5.3 Proximal Alterations

Proximal joint alterations pointing to pre-programmed feed-forward mechanism have also been documented in subjects with CAI.\textsuperscript{56, 57, 59, 89, 90} The muscles of the hip, particularly the Gmed and Gmax are involved with positioning the femur which, through the kinetic chain, affects the positioning of the tibia, and subsequently, the ankle joint. The results of this study found increased activity of the Gmax prior to landing a lateral hop in those with CAI. The Gmax controls internal rotation and extension of the femur. In a previous investigation, a single leg squat position has been associated with high level of muscle activity of the Gmax.\textsuperscript{65} Weight acceptance during gait to control hip flexion and internal rotation of the femur during midstance are another group of motions where the Gmax has been documented to be highly active.\textsuperscript{12} These are similar positions to what subjects were asked to perform during the landing of a lateral hop. The increase in Gmax activity prior to landing may suggest the need to position the foot under the base of support, moving it into slight hip extension. It may also be more highly activated as it prepares to limit internal femoral rotation at landing, position which would put greater stress on the ankle to stabilize landing than if the femur was properly positioned under the body.

Another explanation as to why Gmax demonstrated higher activation in those with CAI may be due to it being a particularly powerful muscle, additionally explaining
why we did not see increased activation of the Gmed. Although the medius would seem to be more likely to be active during a lateral hop due to the frontal plane movement, it may be that the assumed altered neuromuscular system of CAI subjects defers to the larger, more powerful muscle to help eccentrically slow the impact of landing, allowing the ankle to be more prepared for maintaining dynamic postural control. It may be that dynamic rehabilitation exercises focused on the Gmed would help to enhance stabilization in those with CAI.

In a recent study, CAI subjects also showed altered neuromuscular control in the Gmax compared to healthy subjects. Subjects were asked to perform a rotational lunge exercise as well as a single leg rotational squat exercise while EMG data was collected from the Gmed and Gmax. Results indicated that at the lowest point during the rotational squat exercise, the CAI group produced significantly lower Gmax activation than the healthy group. It may be that the Gmax was more highly activated in the current study due to the faster speed and more plyometric nature of the task of landing a lateral hop. Jump landing may demand more of the powerful muscles to control the landing.

Other previous research has produced data to suggest neuromuscular changes in activation timing of the Gmed and Gmax in subjects with CAI compared to healthy subjects. Beckman and Buchanan placed subjects on a platform equipped with a trap door which dropped on the lateral side causing sudden ankle inversion and observed subjects with CAI recruited the Gmed significantly faster than the healthy subjects. Additionally, a later onset of Gmed was demonstrated in CAI subjects while transitioning from two to single leg stance in a study by Van Duen. From the body of research presented, it is difficult to conclude how the neuromuscular system is finding means to
compensate for repeated injury at the ankle. Because previous data mentioned above has shown alterations not only for muscle amplitude but also for onset activation times, the data were examined for muscle onset activation times in this present study. When the common practice of using two standard deviations above the baseline was implemented, it was found the muscles all exceeded this mark during the 200ms prior to landing the lateral hop. When the process signal was visually inspected, the author was unable to find a consistent time when the muscles reached a higher level of activation compared to a baseline, quiet standing position. This would indicate the neuromuscular system is not acting consistently to accomplish this dynamic task of landing a lateral hop. The above mentioned studies that found consistent onset timing patterns utilized a much less dynamic task which might explain why in our task, the muscles were already “on” as they were preparing for landing a lateral hop. It is clear more research is necessary in this area to continue to investigate patterns of pre-programmed feed-forward neuromuscular control during dynamic movement as this is when injury is occurring and re-occurring in those with CAI.

3.5.4 Fatigue

The fatigue protocol of this study was implemented to simulate a practice or game situation. It included elements of lateral shuffles as well as an extended period of lateral hopping. It was thought this repetitive lateral hopping might especially influence and fatigue the ankle. Evidence has pointed towards greater injury and decreased neuromuscular control for subjects in a fatigued state.\textsuperscript{3,82} The authors felt the post-fatigue analysis of activation would allow greater changes in neuromuscular control to be demonstrated as compared to a rested state.
In the results for fatigue, a non-significant trend, corroborated by notable effect sizes, demonstrated the PL (d=0.83) and Gmax (d=0.73) muscles both increased in activity in the CAI group compared to controls after a functional fatigue protocol during the pre-land phase. (Table 2) One possible explanation for these results may be that the increase in muscle activity due to fatigued state begins to enhance the CAI subjects’ previously discussed pre-programmed feed forward alterations in muscle activity. It is believed that as fatigue sets in, muscle contractile capability decreases, resulting in additional motor-recruitment and frequency. For EMG signals, the increase in amplitude during fatigue is a result of decreases in contribution of type II fibers leading to the recruitment of additional motor units. The increased amplitude in the EMG signal of a fatigued CAI subject can also be explained by the reduction in conduction velocity seen with fatigue, which widens the pulse and increases the area under the curve, resulting in a larger mean amplitude of the rectified EMG signal. This is more pronounced in the CAI group compared to healthy subjects due to their altered neuromuscular system.

3.5.5 Post-Landing

There was only one statistically significant finding for the post landing phase. This was a significantly higher TA activation post fatigue compared to pre fatigue. This difference was not seen between the groups, but individually in the main effects for Fatigue. The TA may be fatigued fastest and highly involved in the acceptance of weight from landing, leading to the higher activation at the time of landing.

During two jump-landing activities studied by Caulfield et al89 in the article previously mentioned, although decreases in PL activation were demonstrated prior to
landing, similar to our study, they did not find any significant difference between groups during a period of 150ms following jump landing. The authors concluded the pre-programmed, feed-forward mechanisms were only evidenced prior to impact.

Furthermore, similar jump-landing studies observing GRFs in CAI and healthy controls revealed no group differences during post-impact period.\textsuperscript{58}

The lack of statistical significant data during the post landing phase for all other muscles in our study as well as the evidence from the aforementioned studies suggests the CAI and controls are handling the landing of the jump similarly, despite the altered neuromuscular control system of CAI subjects. The changes seem to only be occurring as CAI subjects prepare for landing.

3.5.6 Limitations

There are a few limitations to the study. The fatigue portion of the study was partially dictated by the subjects’ opinion of when they felt “fatigued” rather than by an objective measure. Although they were instructed that the goal would be to repeat cycles of the protocol until they achieved one and half times their fastest time, they were also told that if they felt they were unable to continue they could stop the repetitions and move to post-testing. This was most often the case, which may have led to various levels of general fatigue. This subjectivity may have influenced the level of activation if some subjects did not give their full effort. The authors attempted to control various levels of cardiovascular fitness by incorporating an inclusion criterion of participation of 20-30 minutes of cardiovascular fitness at least three times a week. Despite this, subjects may still may have been at various levels of cardiovascular fitness or may not have given their full effort for one reason or another.
A second limitation may be in the slight delay in collected data following the fatigue protocol. It would have been very difficult for subjects to complete the functional fatigue protocol with all the EMG leads attached. Investigators worked quickly to replace the leads and allow the subjects to complete the post-test hopping as soon as possible following their last bout of the fatigue protocol. The process of replacing the electrodes was well-practiced by investigators and took approximately 2 minutes before the subjects were hopping following the fatigue. Although this caused a slight delay in data collection, this should have been well within the window of general muscle fatigue.

3.5.7 Conclusions

Higher activation values were observed in both the PL and Gmax muscles of those with CAI compared to control subjects when performing the pre-landing phase of a lateral hop. These proximal and distal neuromuscular alterations may be a result of a pre programmed feed forward mechanism developed after repeated ankle injury which attempts to prepare the lower extremity for an injury-free landing. A trend with strong and moderate effect sizes suggest these values increased in CAI after a functional fatigue protocol was completed.

Although studies continue to show alterations at the proximal and distal musculature during dynamic tasks in those with CAI, more research is necessary to perhaps find more consistent results in subjects with CAI so that a more concrete conclusion can be drawn to address neuromuscular deficits in this pathology.

3.5.8 Clinical Applications

This study further substantiates previous research demonstrating alterations during dynamic tasks for CAI subjects in neuromuscular control through pre programmed
feed forward mechanisms. Earlier studies have indicated dynamic, closed chain exercises help to improve measures of dynamic postural control as well as subsequent ankle injury. This suggests clinicians continue to implement this type of rehabilitation in those with CAI to support the neuromuscular system’s alternative means for stabilizing the ankle thereby preventing recurrent ankle joint injuries.
Chapter 4

Article 2: A comparison of plantar pressure peaks of a lateral hop landing in those with and without chronic ankle instability

4.1 Introduction

For those with repetitive inversion ankle injury, both mechanical and function aspects of joint instability contribute to a condition commonly known as chronic ankle instability (CAI). Those presenting with this pathology often report episodes of the ankle “giving way” as they participate in athletic activity or even activities of daily living. A more complete picture of how patients with CAI complete functional tasks may help clinicians and researchers understand more effective ways to help prevent subsequent injuries in these subjects.

The mechanisms of injury which are most commonly reported to cause lateral ankle sprains involve common physical activities such as gait or landing from a jump on an externally rotated lower leg combined with excessive supination of the rearfoot. Other documented mechanisms involve unanticipated placement on an unstable or
uneven surface or inappropriate positioning of the foot prior to surface contact. With this in mind, altered positioning of the foot at contact with the ground could cause the mechanisms described above leading to injurious episode. When landing from a jump, if the center of pressure (COP) at the foot is located medial to the subtalar joint axis when the foot makes contact with the ground, the vertical ground reaction forces can cause a greater supination moment which may lead to an inversion ankle sprain. In a cadaveric study, it was found that as the foot makes contact with the ground, even a misjudgment of approximately 10° of inversion can result in ankle inversion torques which the authors speculate would lead to ligamentous injury of the lateral ankle. From this information, we can speculate that not only would increased lateral plantar pressures in those with CAI be the result of a more inverted position, but also that poor placement of the foot or landing on an unstable surface would change the COP and that both or either of these elements could lead to repeated sprains.

A facet that has not been fully explored in those with CAI is plantar pressure measures. The positioning of the foot is reflected in how the pressures are distributed on the plantar surface of the foot. Therefore, the changes noted in COP mentioned above may be displayed objectively in measures of plantar pressure in CAI subjects. Attaining more information on how pressures are distributed on the plantar surface of the foot may help in further understanding of why those with CAI repetitively sprain their ankles during activity.

Previous studies of foot plantar pressure measures in those with CAI have found alterations in how pressure is distributed. These studies’ outcomes have consistently demonstrated increased lateral pressures in those with CAI compared to healthy subjects.
during static standing, walking, and running. However, limited exploration exists of in-
shoe plantar pressures in CAI patients while performing functional tasks, similar to ankle
inversion mechanisms. Therefore the purpose of this study was to examine plantar
pressure measures during landing of a lateral hop in those with and without CAI.
4.2 Materials

An F-Scan foot pressure system including sensor model 3000, transmitters, and software (Tek-Scan Inc, South Boston, MA) were used to collect and process the foot pressure data. This system is equipped with 18mm thick in-shoe sensors composed of 960 individual pressure-sensing locations resulting in four sensors/cm$^2$. Each sensor inserts into a transmitter attached to each ankle with a Velcro® strap. The transmitter provided data to a Dell Optiplex GX520 computer (Dell Inc, Round Rock, TX) via two 9.25m cables. The Tekscan software, F-Scan Research 5.83 was used to produce a visual output of the pressures applied to the sensors by the subject’s foot. The F-Scan system has demonstrated moderate to good reliability.\textsuperscript{101}
4.3 Methods

A case control design was used to examine plantar pressures during a lateral hop before after fatigue in those with and without CAI.

4.3.1 Subjects

Thirty-two subjects volunteered for the study. Sixteen CAI subjects (8M, 8F, 172.25 ±10.87cm, 69.13±13.31kg, 20.50±2.00yrs) were matched to 16 healthy subjects (8M, 8F 170.50 ±9.94cm, 69.63±14.82kg, 22.00±3.30yrs) by height, weight, mass, sex, and side. No statistical differences existed between groups aside from scores on the Foot and Ankle Disability Index (FADI) and FADI-Sport. (See Table 4.1)

<table>
<thead>
<tr>
<th>Table 4.1: Subjects' Demographics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
</tr>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>CAI</td>
</tr>
<tr>
<td>Control</td>
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For the CAI group, 16 subjects were recruited with previous history of ankle injury which caused limping or pain for at least 24 hours. Since the time of the initial injury, subjects in the CAI group reported having at least two episodes of the ankle “giving way”, and at least one episode in six months preceding testing. At the time of testing, patients were able to perform normal activity with no pain and scored 90% or lower on the (FADI) or 80% or lower on the FADI-Sport (See Appendix A). Sixteen
subjects were included in the healthy control group and each was matched by side, age, height, mass, and sex to the CAI group. Those in the healthy control group were free from previous ankle sprain. Both groups were free from any previous lower extremity fracture or surgery and any vestibular changes including concussions within the last six months.

Subjects reported in athletic clothing to the Motion Analysis lab for a one-time data collection session. Subjects read and signed the university-approved informed consent then were assigned a subject number. Demographic information and leg dominance was also collected. When asked which leg they would use to kick a ball, all subjects reported using the right leg.

4.3.2 Procedures

Foot pressure inserts were fit for each subject according to shoe size, and then secured inside their athletic shoes with double sided tape. As directed by the manufacturer, subjects were asked to take at least 20 steps with sensors inserted to allow the sensors to adjust to heat and pressure of the foot and allow subjects to acclimate to the sensors in their shoes. Calibration of left and right sensors was performed as subjects maintained hand contact with the wall for balance, and then stood in a single leg stance.

The length of the subject’s lower leg (head of the fibula to lateral malleolus) was marked on the floor as the horizontal hop distance. The vertical distance was standardized using a 5cm barrier over which subjects were asked to laterally hop. Subjects stood on one foot and completed five trials of an individual lateral hop and return. The recording of data began before the subject hopped laterally and ended once they returned to the original position. Each trial created a “movie” within the F-scan
Research software. This was completed for both limbs but only the injured side of the CAI subjects was utilized and matched to the healthy control’s limb.

4.3.3 Data Processing

The five movie hopping trials were collected at rate of 50 Hz and processed within the F-scan Research 5.83 software. The average peak for the landing of the lateral hop was calculated by the software and presented on one output display of the plantar side of a subject’s foot. A pre-calculated template was then placed over the plantar surface of the output display. This template was visually inspected for each trial and adjusted, if necessary, to fit properly around the outside of the foot. (See Figure 4.1)

Figure 4.1 Plantar Pressure Template Display
Utilizing the horizontal separations of the rearfoot, midfoot, and forefoot and the vertical line separating medial and lateral rearfoot created by the F-scan Research software’s template, boxes were placed over the template to find the peak pressures for six areas of the foot: 1) lateral rearfoot, 2) lateral midfoot, 3) lateral forefoot, 4) medial rearfoot, 5) medial midfoot, and 6) medial forefoot. (See Figure 4.2)

Figure 4.2 Placement of Areas of the Plantar Foot to be Analyzed
Once the boxes were placed over the foot display, the peak pressures were revealed for each area in measures of pounds per square inch (PSI). These numbers were then transferred to an Excel file for trial averaging, then to Statistical Package for the Social Sciences (SPSS), 15.0 for data analysis.

4.3.4 Statistical Analysis

Data was analyzed using SPSS 15.0 (SPSS Inc, Chicago, IL). A two (Group) x six (Foot Area) analysis of variance (ANOVA) was performed to evaluate differences in group and across the six previously mentioned areas of the foot in peak pressure.
4.4 Results

Results demonstrated no significant group differences across the six areas (Group by Area interaction: $F_{1,30}=0.72$, $p=0.62$, ES=0.39, 95%CI=-0.32, 1.08). There were no main effects for Group ($F_{1,30}=1.24$, $p=0.27$). There were significant differences between peak pressures amongst the six areas of the foot with medial and lateral forefoot displaying the highest areas of pressure. (See Tables 4.2, 4.3, and Figure 4.3)

<table>
<thead>
<tr>
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<td>19.84</td>
<td>6.82</td>
</tr>
<tr>
<td>Med Mid</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CAI</td>
<td>17.17</td>
<td>6.22</td>
</tr>
<tr>
<td>Control</td>
<td>16.20</td>
<td>6.98</td>
</tr>
<tr>
<td>Med Fore</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CAI</td>
<td>46.34</td>
<td>15.32</td>
</tr>
<tr>
<td>Control</td>
<td>48.06</td>
<td>15.00</td>
</tr>
</tbody>
</table>

Lat= lateral, Med=medial, Rear=rearfoot, Mid=midfoot, Fore=forefoot, SD= Standard Deviation, PSI= pounds per square inch
Table 4.3: p Values for Areas of Plantar Pressure

<table>
<thead>
<tr>
<th></th>
<th>Lat Rear</th>
<th>Lat Mid</th>
<th>Lat Fore</th>
<th>Med Rear</th>
<th>Med Mid</th>
<th>Med Fore</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lat Rear</td>
<td>0.003*</td>
<td>0.000*</td>
<td>0.000*</td>
<td>0.438</td>
<td>0.000*</td>
<td></td>
</tr>
<tr>
<td>Lat Mid</td>
<td>0.000*</td>
<td>0.188</td>
<td>0.000*</td>
<td>0.000*</td>
<td>0.000*</td>
<td></td>
</tr>
<tr>
<td>Lat Fore</td>
<td>0.000*</td>
<td>0.000*</td>
<td>0.000*</td>
<td>0.000*</td>
<td>0.000*</td>
<td></td>
</tr>
<tr>
<td>Med Rear</td>
<td></td>
<td></td>
<td></td>
<td>0.004*</td>
<td>0.000*</td>
<td>0.000*</td>
</tr>
<tr>
<td>Med Mid</td>
<td></td>
<td></td>
<td></td>
<td>0.000*</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Lat = lateral, Med = medial, Rear = rearfoot, Mid = midfoot, Fore = forefoot, *=p=0.05

Figure 4.3 Means and SD for the 6 Plantar Areas in CAI and Control Subjects
4.5 Discussion

The results revealed no differences in plantar pressure between CAI and healthy controls while performing a landing of a lateral hop. (See Figure 4.3) This is contrary to previous studies of plantar pressure in those with CAI which have revealed greater lateral pressures compared to healthy controls.

4.5.1 Group Comparisons

An earlier investigation utilizing a pressure plate in barefoot CAI and healthy control subjects to measure plantar pressures during walking gait reported the midfoot and lateral forefoot had significantly higher relative forces in the CAI group compared to healthy group. Our study did show a trend towards this pattern but not statistically significant. Another study observed foot pressures during walking gait in those with functional ankle instability compared to mechanical instability and found those with functional instability demonstrated a significant increase in lateral loading of the foot, compared to a more medially loaded foot in the mechanical instability group.

Our results may have been different from these two studies due to the type of foot pressure system used for measurement. The previous investigations mention utilized barefoot walking over a pressure plate, where our study implemented in-shoe sensors. It is possible the added support of the subjects’ shoes changed the distribution of peak plantar forces, allowing for more equal distribution of forces. Although this was a
consideration by investigators, it was concluded that most subjects with CAI experience instability or giving way of the joint while wearing shoes.

One other study\textsuperscript{19} which did utilize an in-shoe pressure measuring device during running gait revealed that CAI subjects displayed significantly greater peak pressure, pressure time integral, maximum force, and force time integral in the lateral midfoot compared to their healthy matched subjects. When moving to the forefoot, CAI demonstrated significantly greater peak force, force time integral, and peak pressure compared to healthy subjects.\textsuperscript{19}

The differing results in our study may be a result of the task. Previous studies have observed plantar pressures during walking or running gait. A lateral hop was chosen for our study because we were interested in studying an activity which involved a common mechanism of injury for those with CAI. Both cutting and jump landing have been demonstrated as mechanisms for injury during activity for those with CAI.\textsuperscript{42-44} Our task attempted to combine the two.

Despite the functionality of the task and its possibility for injury, none of our subjects actually suffered an ankle sprain or giving way as they performed the lateral hop. This may be a result of a pre-programmed, feed forward mechanism implemented by the CAI subjects. Multiple authors have proposed this feed forward mechanism as explanation for alterations in dynamic neuromuscular control in subjects with CAI.\textsuperscript{4-6,56-58,83,102} It may be that the repeated inversion injury suffered by those with CAI occurs when they perform an unexpected cut, or when they are not solely concentrating on the hop landing itself. Typically, during athletic activity or activities of daily living, subjects would be concentrating on following a ball, defender, or simply not paying attention to a
maneuver such as walking on an uneven surface. Santello\textsuperscript{103} documented the importance of vision for accurate timing of muscle activity onset and lower extremity kinematics during jump landing. Subjects during our testing were able to freely focus without constraint to perturbations around them.

Moreover, when faced with unanticipated landing situations, subjects in multiple studies have demonstrated modifications in lower extremity mechanics. Alterations in knee\textsuperscript{104, 105} and hip moments\textsuperscript{80, 104} as well as altered foot placement,\textsuperscript{106} and muscle activation throughout the lower extremity\textsuperscript{105, 107} have all been demonstrated during unanticipated landings. Moritz\textsuperscript{107} utilized surface changes which resulted in changes in kinematics, leg stiffness, and EMG activation in a surprise hard surface. All of these experiments utilized healthy subjects and none reported subjects incurring injury during testing. Because healthy subjects are able to react and compensate for changes utilizing an unaltered neuromuscular system, it is possible that the altered neuromuscular system of CAI subjects is less likely to adapt to changes and therefore, sustain injury which is why we see repetitive reinjury in CAI subjects. Our study observed the plantar pressure during a very controlled task with which the subject was familiar and could anticipate normal landing circumstances.

This pre-programmed feed-forward mechanism may be allowing subjects to reposition the lower extremity to handle the task of lateral hop-landing. As the lower extremity is repositioned, it is possible that peak plantar pressures are redistributed to alleviate excess pressure on the lateral side of the foot. Perhaps future research should focus on measuring in-shoe plantar pressures while performing functional tasks with attention focused on something outside of simply landing a hop.
4.5.2 Area Differences

Our results found multiple significant findings in comparison of the six areas of plantar pressure. (See Table 4.2) It is not surprising the area with the highest pressure was the medial forefoot. The task of jump landing would explain higher pressures on the forefoot as the body attempts to attenuate the forces of landing. The higher pressures found on the medial compared to lateral forefoot may be a result of landing and preparing for the medial hop to return to the original position.

4.5.3 Limitations

One limitation of our study was that subjects were permitted to wear their own athletic shoes. Differences in shoe construction may have influenced how the peak pressures were distributed. Previous studies that demonstrated group differences for plantar pressure in those with CAI did not control for this variable so we did not feel it would be necessary.

Another limitation may be related to jump height. Although a 10cm barrier was provided, this did not limit the amount of height a subject reached while jumping. Disparity in jump height may have added variability in peak force pressures. Anecdotally, investigators did not observe subjects greatly exceeding the 5cm barrier when performing the lateral hop. For both these limitations, the effects of shoes or jump height would be randomly distributed across both groups.

4.5.4 Conclusions

Subjects with CAI did not differ from control subjects in peak plantar pressures when landing from lateral hop. This may be the result of a pre programmed, feed -
forward mechanism which allowed CAI subjects to make corrections and land the hop in a manner similar to healthy controls.

Areas of plantar pressure across the foot demonstrated multiple significant differences, regardless of group, with medial forefoot and lateral forefoot demonstrating the highest pressures compared to lateral and medial midfoot, and lateral and medial rearfoot. The higher forefoot pressures are to be expected with jump landing.
Chapter 5

Summary

Research on subjects with CAI continues to both answer and beg more questions with each study. Results can be confounding and force researchers to consider outside variables and synthesize previous work with their own to develop reasonable explanations for their findings. This project was no exception. But this is what drives future research and forces exploration to new possibilities not yet tapped.

This investigation was based on the premise that inquiry into both proximal and distal measures in those with CAI may allow a more complete and lucid picture of the entire lower kinetic chain during functional tasks. The findings were meant to contribute to the body of research already established for those with CAI and to assist clinicians with more evidence-based research when treating those with CAI.

5.1 Questions Answered

The EMG and plantar pressure results of this study both point to the presence of a pre-programmed, feed-forward mechanism developed in conjunction with CAI. Those with this pathology appear to be finding new ways of handling functional tasks. It was established prior to this study that those with CAI have altered neuromuscular patterns.
These have been demonstrated in both positioning of the lower extremity and in firing of stabilizing muscles. The EMG results of higher muscle activation of the Gmax and PL in CAI subjects prior to landing from a lateral hop lends further support to these alterations. The similar plantar pressures during jump landing compared to control subjects also perhaps demonstrate CAI subjects working to maintain proper foot positioning when landing a lateral hop. They supply further evidence to support the observation that those with CAI are finding ways to stabilize the ankle in certain controlled circumstances. Essentially, they are finding some solutions to prevent the constant giving way of the ankle joint. But, these subjects do continue to have instability at unexpected times while performing functional tasks. Therefore, these solutions are not foolproof and practically, are really not “getting the job done” as evidenced by continual giving way.

5.2 Questions Generated

The difficulty with the findings is they are not consistent with many previous studies on this topic. It is important to recognize that these measures have not been taken during this type of task in the past. The previous research on Gmed and Gmax in those with CAI during functional tasks is limited, but what is reported in the published work is markedly inconsistent. The previous research on plantar pressure in those with CAI during functional tasks is even more meager. The answer may be that there is no clear answer. The complexity of the neuromuscular system may be such that it creates alterations differently across subjects with the same pathology. It may be that CAI is a condition in which there are multiple means of attempting to accomplish stability leading clinicians to approach rehabilitation from various directions in order to prevent subsequent injury.
5.3 Future Directions

Clearly more research is necessary in both these areas. Researchers need to continue to investigate measures on neuromuscular control during functional tasks. Unfortunately, it is difficult to find tasks which simulate activity in which injury occurs without placing subjects at risk but still helping to contribute to understanding of what is occurring from a neuromuscular standpoint. It stands to reason that CAI subjects have developed this pre programmed, feed-forward mechanism to facilitate stability during planned activity. Researchers need to continue to discover new methods of functional testing that allow for unplanned events, common to mechanism of injury for these subjects.

Further intervention studies also are needed which involve new methods of rehabilitation to address these neuromuscular alterations. These types of studies will further develop clear directions in helping prevent an ankle sprain from becoming a chronic condition. Although these investigations may be difficult and time consuming, they are necessary because as we all know … CAI kills.
References


Sanna G, O'Connor KM. Fatigue-related changes in stance leg mechanics during sidestep cutting maneuvers. *Clinical Biomechanics (Bristol, Avon).* 2008;23(7):946-954.


105. McLean SG, Borotikar BS, Lucey S. Lower limb muscle pre-motor time measures during a choice reaction task associate with knee abduction loads during dynamic single leg landings. *Clinical Biomechanics (Bristol, Avon)*. 2010.


Appendix A

Foot and Ankle Disability Index (FADI) and Foot and Ankle Disability Index-Sport (FADI-Sport)

Foot and Ankle Disability Index (FADI)

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

If the activity in question is limited by something other than your foot or ankle mark not applicable (N/A).

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

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

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

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

FADI Sports Scale

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

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

1999 FADI intern 2/2
Appendix B

Physical Activity Readiness Questionnaire (PAR-Q)

Please read the following questions carefully and check (X) the appropriate answer. Answer all questions honestly and to the best of your ability.

YES NO

___ ___ 1. Has your doctor ever said that you have a heart condition (had a stroke, heart attack, or heart surgery) and/or that you should only do physical activity recommended by a doctor?

___ ___ 2. Do you feel pain in your chest when you do physical activity?

___ ___ 3. In the past month, have you had chest pain when you were not doing physical activity?

___ ___ 4. Do you lose your balance because of dizziness or do you ever lose consciousness?

___ ___ 5. Have you ever been told by a doctor that you have bone, joint, or muscle problems that could be made worse by physical activity?

___ ___ 6. Do you have a diagnosed illness that could be made worse by physical activity?

___ ___ 7. Is your doctor currently prescribing medication for your blood pressure or heart condition?

___ ___ 8. Are you pregnant?

___ ___ 9. Do you know of any other reason why you should not do physical activity?
Appendix C

Tegner Activity Scale

**TEGNER ACTIVITY LEVEL SCALE**

Please indicate in the spaces below the HIGHEST level of activity that you participated in BEFORE YOUR INJURY and the highest level you are able to participate in CURRENTLY.

**BEFORE INJURY:** Level __________  
**CURRENT:** Level __________

<table>
<thead>
<tr>
<th>Level</th>
<th>Competitive sports- soccer, football, rugby (national elite)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 9</td>
<td>Competitive sports- soccer, football, rugby (lower divisions), ice hockey, wrestling, gymnastics, basketball</td>
</tr>
<tr>
<td>Level 8</td>
<td>Competitive sports- racquetball or handball, squash or badminton, track and field athletics (jumping, etc.), down-hill skiing</td>
</tr>
<tr>
<td>Level 7</td>
<td>Competitive sports- tennis, running, motorcars speedway, handball</td>
</tr>
<tr>
<td></td>
<td>Recreational sports- soccer, football, rugby, bandy, ice hockey, basketball, squash, racquetball, running</td>
</tr>
<tr>
<td>Level 6</td>
<td>Recreational sports- tennis and badminton, handball, racquetball, down-hill skiing, jogging at least 5 times per week</td>
</tr>
<tr>
<td>Level 5</td>
<td>Work- heavy labor (construction, etc.)</td>
</tr>
<tr>
<td></td>
<td>Competitive sports- cycling, cross-country skiing,</td>
</tr>
<tr>
<td></td>
<td>Recreational sports- jogging on uneven ground at least twice weekly</td>
</tr>
<tr>
<td>Level 4</td>
<td>Work- moderately heavy labor (e.g. truck driving, etc.)</td>
</tr>
<tr>
<td>Level 3</td>
<td>Work- light labor (nursing, etc.)</td>
</tr>
<tr>
<td>Level 2</td>
<td>Work- light labor</td>
</tr>
<tr>
<td></td>
<td>Walking on uneven ground possible, but impossible to back pack or hike</td>
</tr>
<tr>
<td>Level 1</td>
<td>Work- sedentary (secretarial, etc.)</td>
</tr>
<tr>
<td>Level 0</td>
<td>Sick leave or disability pension because of knee problems</td>
</tr>
</tbody>
</table>