A Thesis

entitled

Determining Clinical Impairments that Lead to Changes in Dynamic Knee Valgus Following a 4-week Feedback Intervention

by

Caitlin E. Lefevre, ATC

Submitted to the Graduate Faculty as partial fulfillment of the requirements for the

Master of Science Degree in

Exercise Science

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May 2014
An Abstract of

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Objective: To determine if there is a change in spinal reflex excitability, corticospinal excitability, quadriceps strength, hip strength, hip range of motion, knee range of motion, core endurance and balance before and after a four week jump landing intervention compared to a control group. To determine if there is a change in performance, by means of a vertical jump test, following a four week jump landing intervention. To determine if spinal reflex excitability, corticospinal excitability, quadriceps strength, hip strength, hip range of motion, knee range of motion, core endurance and balance correlates to knee abduction angle during a jump landing task at baseline. To determine if there is a change in spinal reflex excitability, corticospinal excitability, quadriceps strength, hip strength, knee range of motion (ROM), hip ROM, core endurance, balance and vertical jump from baseline to four weeks post-initiation of the intervention; and whether any of those changes affect changes in knee abduction angle during a jump landing task from baseline to four weeks post-initiation of the intervention. Design: Descriptive observational study. Setting: Research Laboratory.

Subjects: A total of 48 healthy females participated in this study, and were split into two
groups: feedback (n=32; age: 19.72±1.49 years; height: 159.15±12.27 cm; mass: 58.24±7.80 kg) and control (n=16; age: 19.56±1.67 years; height: 159.23±11.08 cm; mass: 59.35±8.87 kg), and were included in final analysis. **Measurements:** The outcome measures included those retrieved through TMS (AMT, corticospinal excitability normalized to the M-response at 120, 130, and 140% of AMT, and H:M), gluteus strength (hip extension and abduction), quadriceps strength (knee extension), balance via the SEBT (anterior, posteromedial, posterolateral, and composite, normalized to leg length), hip ROM (hip extension, internal rotation and external rotation), knee ROM (knee flexion), core endurance (3-way plank and prone plank), and maximal vertical jump (2-footed maximum vertical jump normalized to standing reach height). **Results:** The feedback group and control group both decreased the time they were able to hold the prone plank from baseline to four weeks post-initiation of the intervention, $F_{(1,46)}=15.132, P<0.001$. The control group significantly decreased the time they were able to hold the left plank compared to the feedback group, $F_{(1,46)}=6.032, P=0.018$. Both groups increased their posterolateral reach distance from baseline to four weeks post-initiation of the intervention, $F_{(1,46)}=12.629, P=0.001$. The feedback group and control group both increased their vertical jump performance from baseline to four weeks post-initiation of the intervention, $F_{(1,46)}=5.101, P=0.029$. A weak, negative correlation was found between dominant knee abduction angle and dominant AMT at baseline, $r_{(46)}=-0.360, P=0.014$. A moderate, positive correlation was found between dominant knee abduction angle and knee flexion ROM at baseline, $r_{(46)}=0.309, P=0.033$. A weak, positive correlation was found between the percent change in dominant knee abduction angle and the percent change in dominant H:M, $r_{(46)}=0.318, P=0.038$. A weak, negative correlation
was found between the percent change in dominant knee abduction angle and the percent change in dominant hip external rotation range of motion, \( r(46)=-0.359, P=0.019 \).

**Conclusions:** The control group significantly decreased the time they were able to hold the left plank compared to the feedback group. Those participants who demonstrated a greater knee abduction angle also demonstrated a lower AMT; this decreased AMT may be some sort of compensation to make up for the increase in knee abduction angle. Those participants who demonstrated a greater knee abduction angle also demonstrated increased knee flexion ROM. As knee abduction angle decreased, spinal reflex excitability decreased and hip external rotation ROM increased. Optimizing feedback is pivotal in determining an intervention that is both monetarily and physiologically beneficial in prophylactically treating ACL injury. Future studies should aim to determine whether there is a significant interaction between clinical impairments with other kinetic and kinematic measures, in those who respond positively to feedback and those who do not during a jump landing task.
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# Table of Contents

Abstract .................................................................................................................................................. iii

Acknowledgements ............................................................................................................................... v

Table of Contents .................................................................................................................................. iv

List of Tables ........................................................................................................................................... x

List of Figures ......................................................................................................................................... xi

List of Abbreviations ............................................................................................................................. xii

1 Introduction ......................................................................................................................................... 1

1.1 Statement of the Problem ............................................................................................................... 5

1.2 Statement of the Purpose .............................................................................................................. 6

1.2.1 Specific Aim 1 ............................................................................................................................. 6

1.2.2 Specific Aim 2 ............................................................................................................................. 6

1.3 Research Hypotheses ..................................................................................................................... 7

1.3.1 Hypothesis 1 ............................................................................................................................... 7

1.3.2 Hypothesis 2 ............................................................................................................................... 7

1.4 Exploratory Aims ........................................................................................................................... 8

1.4.1 Exploratory Aim 1 ..................................................................................................................... 8

1.4.2 Exploratory Aim 2 ..................................................................................................................... 8

1.5 Limitations ...................................................................................................................................... 8

1.6 Significance of the Study ............................................................................................................... 9
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.7</td>
<td>Operational Definitions</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>Literature Review</td>
<td>12</td>
</tr>
<tr>
<td>2.1</td>
<td>Introduction</td>
<td>12</td>
</tr>
<tr>
<td>2.2</td>
<td>The Landing Error Scoring System</td>
<td>13</td>
</tr>
<tr>
<td>2.3</td>
<td>Feedback Interventions in Manipulating Jump Landing Biomechanics</td>
<td>14</td>
</tr>
<tr>
<td>2.4</td>
<td>Spinal Reflex Assessment</td>
<td>17</td>
</tr>
<tr>
<td>2.5</td>
<td>Transcranial Magnetic Stimulation</td>
<td>19</td>
</tr>
<tr>
<td>2.6</td>
<td>Quadriceps Muscle Strength Assessment</td>
<td>23</td>
</tr>
<tr>
<td>2.7</td>
<td>Hip Muscle Strength Assessment</td>
<td>25</td>
</tr>
<tr>
<td>2.8</td>
<td>Hip and Knee Range of Motion Assessment</td>
<td>27</td>
</tr>
<tr>
<td>2.9</td>
<td>Core Endurance Testing</td>
<td>28</td>
</tr>
<tr>
<td>2.10</td>
<td>Star Excursion Balance Test</td>
<td>30</td>
</tr>
<tr>
<td>2.11</td>
<td>Vertical Jump Assessment</td>
<td>32</td>
</tr>
<tr>
<td>3</td>
<td>Methodology</td>
<td>34</td>
</tr>
<tr>
<td>3.1</td>
<td>Research Design</td>
<td>34</td>
</tr>
<tr>
<td>3.2</td>
<td>Experimental Design</td>
<td>34</td>
</tr>
<tr>
<td>3.3</td>
<td>Participants</td>
<td>35</td>
</tr>
<tr>
<td>3.4</td>
<td>Randomization</td>
<td>37</td>
</tr>
<tr>
<td>3.5</td>
<td>Instrumentation</td>
<td>38</td>
</tr>
<tr>
<td>3.5.1</td>
<td>Spinal Reflex Excitability</td>
<td>38</td>
</tr>
<tr>
<td>3.5.2</td>
<td>Corticospinal Excitability</td>
<td>38</td>
</tr>
<tr>
<td>3.5.3</td>
<td>Strength Measurement</td>
<td>39</td>
</tr>
<tr>
<td>3.5.4</td>
<td>Range of Motion Measurement</td>
<td>39</td>
</tr>
</tbody>
</table>
3.5.5 Core Endurance Measurement .................................................. 39

3.5.6 Balance Measurement Using the Star Excursion Balance Test
(SEBT) ............................................................................................................. 39

3.5.7 Vertical Jump Measurement ......................................................... 39

3.5.8 Kinematic Measurement .............................................................. 40

3.5.9 Kinetic Measurement ................................................................. 40

3.6 Procedures ........................................................................................ 40

3.6.1 Landing Error Scoring System (LESS) .......................................... 41

3.6.2 Spinal Reflex Excitability .............................................................. 41

3.6.3 Corticospinal Excitability ............................................................. 42

3.6.4 Strength Assessment ..................................................................... 45

3.6.5 Range of Motion Assessment ..................................................... 47

3.6.6 Core Endurance Assessment ....................................................... 49

3.6.7 Balance Assessment Using the Star Excursion Balance Test
(SEBT) ............................................................................................................. 52

3.6.8 Vertical Jump Assessment .............................................................. 54

3.6.9 Participant Preparation ................................................................. 55

3.6.10 Feedback Training Session ......................................................... 56

3.6.11 Feedback Intervention Groups .................................................. 57

3.6.12 Control Group ............................................................................ 58

3.7 Statistical Analysis ........................................................................... 59

4 Results .................................................................................................... 60

4.1 Subjects ............................................................................................ 60
List of Tables

1. Participant Demographics .......................................................... 60
2. Pre and Four Weeks Post-Initiation of the Intervention Post Means and
   Standard Deviations for the Dominant Limb .................................. 61
3. Pre and Four Weeks Post-Initiation of the Intervention Means and
   Standard Deviations for Vertical Jump Maximum .......................... 62
4. Pearson and Spearman correlation matrix analyzing associations among
   clinical impairments in the dominant limb and knee abduction angle in
   the dominant limb at baseline ...................................................... 63
5. Pearson and Spearman correlation matrix analyzing associations among
   the percent change in clinical impairments in the dominant limb and the
   percent change in knee abduction angle in the dominant limb from
   baseline to four weeks post-initiation of the intervention .................. 64
List of Figures

1-1 Participant positioning for quadriceps muscle response testing .....................42
2-1 Participant positioning for TMS corticospinal excitability testing ..................45
3-1 Participant positioning for strength testing of the quadriceps ......................46
3-2 Participant positioning for strength testing of the hip abductors ..................46
3-3 Participant positioning for strength testing of the hip extensors .................47
4-1 Participant positioning for hip extension range of motion testing ...............48
4-2 Participant positioning for hip internal rotation range of motion testing .......48
4-3 Participant positioning for hip external rotation range of motion testing ......49
4-4 Participant positioning for knee flexion range of motion testing ...............49
5-1 Participant positioning for the two-arm prone plank test .........................50
5-2 Participant positioning for the side plank test .....................................51
5-3 Participant positioning for the extension plank test ................................52
6-1 Participant positioning for the anterior reach during the SEBT ..................53
6-2 Participant positioning for the posteromedial reach during the SEBT ...........53
6-3 Participant positioning for the posterolateral reach during the SEBT ..........54
7-1 Participant positioning for the standing vertical reach height test ...............55
7-2 Participant positioning for the maximum vertical jump height test .............55
List of Abbreviations

ACL...........................Anterior Cruciate Ligament
AMI..........................Arthrogenic Muscle Inhibition
AMT..........................Active Motor Threshold
AROM.........................Active Range of Motion

CNS..........................Central Nervous System

EMG.........................Electromyography

GRF..........................Ground Reaction Forces

H-Reflex......................Hoffman Reflex

LESS.........................Landing Error Scoring System

MEP..........................Motor Evoked Potentials
M-response....................Muscle Response

NMC.........................Neuromuscular Control

OA.............................Osteoarthritis

ROM..........................Range of Motion

SEBT..........................Star Excursion Balance Test
SR..............................Stimulus Response

TMS.........................Transcranial Magnetic Stimulation
Chapter 1

Introduction

Anterior cruciate ligament (ACL) injuries affect 100,000 to 250,000 people in the United States annually.\(^1\)\(^2\) Those who sustain an ACL injury are then faced with a psychological, physical and financial burden. Psychologically, ACL injuries can result in loss of position on a team, loss of athletic identity, depression and other psychological problems.\(^3\) Physically, ACL injuries can cause significant pain and loss of daily function resulting in inactivity and lack of sport participation.\(^3\) This lack of inactivity can lead to an increased risk of obesity, diabetes, metabolic syndrome, heart disease, further risk for injury and a decreased quality of life.\(^3\) An estimated $17,000 per case has been approximated for the cost of surgical repair and rehabilitation, not including medical costs associated with future complications such as osteoarthritis (OA) or total knee arthroplasty.\(^1\) In terms of surgery and rehabilitation costs, female ACL injuries account for an approximated $646 million annually at a national level.\(^4\) ACL injuries lead to increased disability and a substantial burden on the current economic system, costing roughly $6.2 billion annually in the United States.\(^5\)\(^6\)

Within 10-15 years following an ACL injury, approximately 60-80% of these patients develop post-traumatic OA regardless of the treatment administered.\(^7\)\(^8\)
Trends toward increasing OA changes in patellar tendon and hamstring ACL reconstructions have been shown between two and ten years post-surgery. Eight years post ACL reconstruction, patients have demonstrated decreased activity level and a decreased quality of life particularly regarding physical function in sport participation. Radiographic OA has been found in upwards of 50% of soccer players twelve years post ACL surgery and 75% had symptoms substantially affecting their knee related quality of life.

ACL injuries are usually a result of non-contact mechanisms such as sudden deceleration and a change of direction, an unexpected perturbation, or a malpositioned limb during initial contact of a landing task. Approximately 70% of ACL injuries are due to a noncontact mechanism, and are believed to be preventable through modification of altered lower extremity mechanics. The rate at which ACL injury occurs among female athletes is four to six times more likely when compared with their male counterparts. Noncontact ACL injuries are three times greater in female soccer players and four times greater in female basketball players than males participating in the same sports, which indicates a need for prevention programs, specifically targeting female athletes. Although research has not been able to fully determine all of the specific factors that may contribute to an ACL injury in females, structural variations, hormonal changes attributed to the menstrual cycle, and differences in general laxity, muscle activation ratios, styles of play, and kinetics and kinematics have been proposed as risk factors. Previous literature has shown that females perform maneuvers such as landing from a jump, cutting and pivoting with less knee and hip flexion, increased knee valgus, increased internal rotation of the hip
coupled with increased external rotation of the tibia, and increased quadriceps muscle activation.⁸

A proposed predominant modifiable risk factor is neuromuscular inefficiency; including altered movement and activation patterns and increased muscle stiffness of the lower limb while landing.⁴ Neuromuscular inefficiency can manifest into a muscular inhibition, a natural protective mechanism to decrease excessive forces within the joint itself.¹⁴ There is ample evidence to indicate that suboptimal lower extremity biomechanics may predispose females to ACL injury, specifically knee valgus during dynamic tasks.⁴,¹⁵ Kinetic differences have been found between ACL injured and healthy adolescent females, in which the injured group had larger knee valgus moments and higher ground reaction forces (GRF) when these patients were prospectively screened before injury occurred.⁴

Prolonged alterations in neuromuscular function and lower extremity movement may occur as some people never regain pre-injury neuromuscular function.¹⁴ In order to employ prevention strategies aimed at decreasing the incidence of noncontact ACL injuries in female athletes, we must understand the modifiable risk factors that may lead to increased injury rates and the impairments that may lead to these risk factors.

Prevention programs for ACL injuries have been implemented to target improving neuromuscular control (NMC) and altering lower extremity biomechanics in order to decrease injury risk and possibly improve performance measures.¹⁶ Significant effects on downstream NMC and patient function may result from the development of a new therapeutic model that focuses on restoring proper upstream neural function.¹⁴ Potential prevention programs for decreasing ACL injuries may be feedback
interventions that provide visual or auditory corrections to the participant in an effort
to induce changes in particular jump landing mechanics. Feedback intervention
programs are hypothesized to prompt individuals to make cortically driven changes in
neuromuscular function.\textsuperscript{17,18} Feedback interventions have been successful in
manipulating landing biomechanics for the purpose of decreasing GRF and altering
potentially harmful kinematics by increasing hip flexion, hip abduction and knee
flexion angles.\textsuperscript{17,18}

Development of jump landing feedback interventions seem to be a favorable
intervention in preventing ACL injury. Feedback modalities have shown promising
results in improving detrimental jump landing biomechanics by reducing peak
vertical GRF and anterior shear forces, and increasing hip and knee angular
displacement flexion angles during a jump landing task.\textsuperscript{17,18} Real-time feedback is an
innovative approach to traditional jump landing feedback as it allows participants to
observe themselves as they are completing a task, thus allowing the user to make real-
time biomechanical adjustments. Although real-time feedback is hypothesized to
allow for a quicker cortical processing of the feedback, this piece of equipment is
costly and time consuming for the clinician.

Determining the efficacy of a feedback intervention in preventing non-contact
ACL injuries is vital. Furthermore, it is important to determine which individuals will
respond favorably to a feedback intervention in order to maximize the benefits of
these programs and decrease the overall cost associated with them. The current study
determined if clinical impairments can predict an individual’s ability to jump and land
appropriately and if a four week intervention could lead to positive changes in these
impairments and hazardous lower extremity biomechanics, ultimately leading to a reduction in ACL injury and the overall cost spent on these intervention programs. Currently, there is not an available successful method for screening and identifying athletes at increased risk of ACL injury. More effective screening practices could be implemented to identify those athletes who are at increased risk if we are able to identify a link between lower limb NMC parameters and ACL injury. Through identification of these clinical impairments we may be able to predict which athletes will respond positively to a feedback intervention, and which athletes will not. Being able to make these predictions will decrease the time and money spent on athletes who may not respond favorably to a feedback intervention, as well as decreasing the rate of ACL injury in those who can improve their hazardous landing mechanics following a feedback intervention. Answering these questions will be fundamental in optimizing ACL intervention programs and ultimately preventing the high incidence of ACL injury in females.

1.1 Statement of the Problem

ACL injuries are a common injury that hinders the ability to perform activities of daily living and produces a large economic burden on the United States. ACL injuries produce immediate impairments such as decreased NMC, altered lower extremity biomechanics, and strength deficits which lead to long-term disability such as OA, a detrimental pathology and debilitating condition leading to further disability and an even bigger economic burden. Focusing on preventing the initial injury from occurring is economically and physiologically beneficial. Females are thought to be at an increased risk of ACL injury because they have been found to exhibit altered NMC
strategies when compared to their male counterparts. Feedback interventions have been implemented in an attempt to target these potentially harmful biomechanical patterns, and therefore prevent ACL injury.

Although feedback interventions appear to be effective, this modality has yet to be optimized and therefore can be costly and time consuming. Identifying an intervention targeting a modifiable risk factor for ACL injury will have a great impact on decreasing the monetary and physiological effects of ACL injury. Also, identifying whether there are predictors of who will or will not respond to a feedback intervention will be extremely beneficial. This study will allow us to determine if we can predict which athletes will benefit from a four week feedback intervention based upon the presence of clinical impairments related to the individual’s ability to jump and land correctly, and make changes in their jump landing mechanics. This will allow us to better optimize these feedback interventions, ultimately decreasing the cost of implementing these programs and decreasing the amount of ACL injury sustained.

1.2 Statement of the Purpose

1.2.1 Specific Aim 1:

To determine if there is a change in spinal reflex excitability, corticospinal excitability, quadriceps strength, hip strength, hip range of motion (ROM), knee ROM, core endurance and balance before and after a four week jump landing intervention compared to a control group.

1.2.2 Specific Aim 2:
To determine if there is a change in performance, by means of a vertical jump test, following a four week jump landing intervention.

**1.3 Research Hypotheses**

**1.3.1. Hypothesis 1:**

Recent studies indicate a positive correlative relationship between NMC deficits of the quadriceps and higher active motor threshold (AMT), suggesting that cortical excitability plays a role in altered sensory feedback of the limbs from pain, disuse or restriction.\(^{20}\) Based on the existing literature, we hypothesize that cortical excitability of the vastus lateralis oblique will be increased from baseline to four weeks post-initiation of the intervention in those participants who receive feedback. We hypothesize that spinal reflex excitability will decrease from baseline to four weeks post-initiation of the intervention in those participants who receive feedback, due to increased cortical excitability following the four week intervention. Our hypothesized increase in cortical excitability will also result in increased quadriceps and hip strength because of increased muscle control and coordination resulting in an increase in force production. We also hypothesize an increase in core endurance capability and balance in the feedback intervention group, as a result of the jump landing program.

**1.3.2. Hypothesis 2:**

It is not clear whether a jump landing program will compromise an athlete’s performance level. In a recent study, the results revealed modifying an athlete’s jump stop movement mechanics greatly reduced peak tibial shear force without compromising performance.\(^{21}\) The athletes maintained or improved their jump height
with the modified movement mechanics therefore we hypothesize performance will not be compromised upon completion of the jump landing program.

1.4 Exploratory Aims

1.4.1 Exploratory Aim 1:

To determine if spinal reflex excitability, corticospinal excitability, quadriceps strength, hip strength, hip ROM, knee ROM, core endurance and balance correlates to knee abduction angle during a jump landing task at baseline.

1.4.2 Exploratory Aim 2:

To determine if there is a change in spinal reflex excitability, corticospinal excitability, quadriceps strength, hip strength, knee ROM, hip ROM, core endurance, balance and vertical jump from baseline to four weeks post-initiation of the intervention; and whether any of those changes affect changes in knee abduction angle during a jump landing task from baseline to four weeks post-initiation of the intervention.

1.5 Limitations

As with any research investigation, this study was not completed without limitations. This study was completed with only healthy participants, having no current lower extremity pathology. It has been documented that pathological populations have altered levels of corticospinal and spinal reflex excitability as well as deficits in quadriceps strength. In order to account for the variability of these measures in a pathological population, we had to first assess the effects of a four week feedback intervention in healthy individuals to ensure the changes that are seen are strictly the effects of the intervention.
This study also only examined females, however noncontact ACL injury occurs more frequently in females than males.

This study only used physically active individuals; participants had to have a BMI less than 30, and they also had to be physically active at a level of at least three times per week for at least 30 minutes each time. However, this physically active population is most at risk for lower extremity injury during jump-landing tasks and is most often seen in clinical settings.

1.6 Significance of the Study

This study was significant because it sought to determine if there are clinical impairments, which can identify participants who will respond to jump landing feedback. Optimizing the delivery of feedback is critical in determining an intervention that is both economically and physiologically beneficial in prophylactically treating ACL injury.

This study sought to determine whether spinal reflex excitability, corticospinal excitability, quadriceps strength, hip strength, core endurance and balance correlated with knee abduction angle during jump landing. This study also sought to determine if spinal reflex excitability, corticospinal excitability, quadriceps strength, hip strength, core endurance and balance were affected by a feedback intervention over a four week intervention; and determine whether the changes in the clinical impairments affected changes in knee abduction angle during a jump landing task following the feedback intervention. These explorations were vital in determining which outcome measures or impairments correlated with peak knee abduction angle, and which athletes would respond favorably to a four week feedback intervention.
Finally, this study also sought to determine whether completing a four week jump landing intervention affected performance. An intervention that is found to be effective in preventing ACL injury, but decreases performance, is not appealing to most athletes. Optimizing an intervention program that is economically and physiologically effective in preventing ACL injury, and coincidently increases performance, will appeal to clinicians, athletes and coaches.

1.7 Operational Definitions

ACL = Anterior Cruciate Ligament
OA = Osteoarthritis
NMC = Neuromuscular Control
GRF = Ground Reaction Forces
MEP = Motor Evoked Potentials
AMT = Active Motor Threshold
ROM = Range of Motion
LESS = Landing Error Scoring System
H-Reflex = Hoffman Reflex
CNS = Central Nervous System
EMG = Electromyography
M-response = Muscle Response
AMI = Arthrogenic Muscle Inhibition
TMS = Transcranial Magnetic Stimulation
SR = Stimulus Response
AROM = Active Range of Motion
SEBT = Star Excursion Balance Test
Chapter 2

Literature Review

2.1 Introduction

Female ACL injuries have become a substantial burden on the economic system, accounting for an approximated $646 million annually in the United States in terms of surgery and rehabilitation, not including medical costs associated with future complications such as OA or total knee arthroplasty.\textsuperscript{6,12,22} ACL injuries result in immediate impairments such as decreased NMC, altered lower extremity biomechanics, and strength deficits which can lead to long-term disability such as OA, a detrimental pathology and debilitating condition leading to further disability and an even bigger economic burden.\textsuperscript{19} Regardless of the treatment administered, approximately 60-80\% of patients sustaining an ACL injury in the United States develop post-traumatic OA.\textsuperscript{7,8}

Approximately 70\% of ACL injuries are due to a noncontact mechanism, and may be preventable through modification of altered lower extremity mechanics.\textsuperscript{12} Previous literature\textsuperscript{8} demonstrates that females perform maneuvers such as landing from a jump, cutting and pivoting with less knee and hip flexion, increased knee valgus, increased internal rotation of the hip coupled with increased external rotation of the tibia and
increased quadriceps muscle activation. Gaining a better understanding of the modifiable risk factors that may lead to increased injury rates and the impairments that may lead to these risk factors will allow clinicians to employ prevention strategies aimed at decreasing the incidence of noncontact ACL injuries in female athletes.

Feedback interventions that provide visual or auditory corrections to the participant in an effort to induce changes in particular jump landing mechanics are potential prevention programs for decreasing ACL injuries. Although feedback modalities have shown promising results in improving detrimental jump landing biomechanics, implementing this intervention is costly and time consuming for the clinician. Being able to make predictions via a screening program will enable clinicians to determine which athletes may respond favorably to a feedback intervention, thereby decreasing the rate of ACL injury in those who can improve their hazardous landing mechanics following a feedback intervention. More effective screening regimens need to be implemented to identify those athletes who are at increased risk and whether there is a link between lower limb NMC parameters and ACL injury.22

2.2 The Landing Error Scoring System

The Landing Error Scoring System (LESS) will be used to screen all potential participants for the presence of knee valgus. The LESS is a clinical tool used to quantify errors during a jump landing task by scoring individual joint motions at various points of the landing process.23 Poor jump-landing mechanics such as decreased knee and hip flexion angles, increased knee valgus and hip adduction
angles, result in reduced scores on the LESS test. The LESS has demonstrated concurrent validity, strong interrater and intrarater reliability and evidence for identifying individuals who may be at a greater risk for non-contact ACL or other lower extremity injuries.

ACL injuries hinder the ability to perform activities of daily living, produce a large economic burden on the United States and produce immediate impairments which may lead to long-term disability. Using the LESS as a screening tool is useful in its ability to rapidly provide accurate information about an individual’s jump landing technique, identify biomechanical abnormalities and successfully identify individuals who are at an increased risk of non-contact ACL injury. The LESS allows clinicians to target at risk individuals and provide feedback on their specific jump landing errors, thereby reducing their risk for future injury, allowing for a decrease in the associated financial costs and a decreased risk of developing knee OA after injury.

2.3 Feedback Interventions in Manipulating Jump Landing Biomechanics

Feedback interventions have been implemented to teach proper landing biomechanics for the purpose of preventing future injury. These modalities prompt an individual to correct potentially harmful biomechanics such as dynamic knee valgus and reduce high GRF. Feedback prevention programs aim to reduce injury risk by educating athletes to land properly for the purpose of reducing stress on the lower extremity.
There are various types of feedback methods including augmented, sensory, expert provided feedback, self-initiated and combination feedback which utilizes both expert feedback and feedback conducted through self-analysis. Augmented feedback aims to supplement information already available to the subject via external or additional information about the motor task. Sensory feedback is provided through information naturally available such as vision, hearing, and touch as a result of the motor task. Expert provided feedback provides information through verbal correction, verbal instruction or visual demonstration. Self-initiated feedback allows participants to identify their own movement characteristics through video tape or self-analysis and make alterations.

Real-time feedback is an innovative approach to traditional jump landing feedback as it allows participants to observe themselves as they are completing a task, thus allowing the user to make real-time biomechanical adjustments. Using a real time motion analysis system, the subject is able to match joint angles to a normative target range provided on a monitor. Real-time kinematic feedback has been suggested to be an effective treatment of patellofemoral pain in female runners in terms of gait retraining. Real-time feedback has also been shown to be effective in retraining gait by reducing the external knee adduction moment, an indicator of tibiofemoral joint OA progression, in participants without knee injury. Although real-time feedback is hypothesized to allow for a quicker cortical processing of the feedback and better retention over time, this piece of equipment is costly and time consuming for the clinician. Utilization of these feedback methods can allow for alteration of hazardous lower extremity mechanics during the landing phase of a
jump, resulting in reduced GRF, increased knee flexion angles and decreased anterior tibial shear forces, therefore decreasing lower extremity injury risk. Self-initiated and combination feedback groups have demonstrated greater increases in knee flexion angles compared to expert provided feedback. Studies have shown participants who were instructed to perform a softer landing, demonstrated lower GRF and their muscles absorbed up to 19% more kinetic energy. If the muscular system is able to absorb more kinetic energy, the knee joint may not have to attenuate as much energy, therefore reducing injury risk.

Determining which individuals will respond favorably to a feedback intervention will maximize the benefits of these programs by decreasing the overall cost and time associated with them. Developing an effective screening regimen that identifies those athletes who are at increased risk of ACL injury and allows clinicians to predict which athletes will respond positively to a feedback intervention, will decrease the time and money spent as well as decrease the rate of ACL injury in those who can improve their hazardous landing mechanics following a feedback intervention. Optimizing an ACL intervention program will ultimately prevent the high incidence of ACL injury in females.

Neuromuscular inefficiency is a proposed predominant modifiable risk factor that contributes to female noncontact ACL injury. Ample evidence has indicated that suboptimal lower extremity biomechanics may predispose females to ACL injury, specifically knee valgus during dynamic tasks. Employing prevention strategies that target modifiable risk factors may lead to a decreased incidence of noncontact
ACL injury rates in female athletes.\textsuperscript{14,22} Feedback modalities seem to be a favorable intervention in preventing ACL injury and have shown promising results in improving detrimental jump landing biomechanics by reducing peak vertical GRF and anterior shear forces, and increasing hip and knee angular displacement flexion angles during a jump landing task.\textsuperscript{17,18}

### 2.4 Spinal Reflex Assessment

The Hoffman reflex (H-reflex) is an electrically induced reflex analogous to the mechanically induced spinal stretch reflex.\textsuperscript{29} The H-reflex bypasses the muscle spindle making it a valuable tool in assessing modulation of monosynaptic reflex activity in the spinal cord and is an estimate of alpha motor neuron excitability when presynaptic inhibition and intrinsic excitability of the alpha motor neurons remain constant.\textsuperscript{29} Assessment of the H-reflex has been used to examine the response of the nervous system to various neurologic conditions, musculoskeletal injuries, application of therapeutic modalities, pain, exercise training and performance of motor tasks.\textsuperscript{29}

Previous research observing the effect of seasonal changes in training load on neuromuscular function in female collegiate swimmers determined at peak training H-reflex of the soleus was reduced below baseline values.\textsuperscript{30} Another study assessing the effect of balance training on H-reflex of the triceps surae and tibialis anterior in healthy adults found that subjects were able to significantly reduce the soleus H-reflex while balancing and after balance training.\textsuperscript{31} These results indicate that short term training, such as possibly a 4-week feedback intervention, can cause progressive
reduction in the H-reflex and therefore may represent functional adaptation in the central nervous system (CNS).\textsuperscript{31}

H-reflex measures are elicited by electrical stimulation in which the stimulus travels in afferent fibers through the motor neuron pool of the corresponding muscle to the efferent fibers, producing a twitch response in the EMG) tracing.\textsuperscript{29} The H-reflex can obtain valid and reliable information regarding neural function.\textsuperscript{29} The H-reflex or \( H_{\text{max}} \) is expected to decrease following injury, inferring the athlete is unable to recruit as many motor neurons during contraction because the muscle surrounding the injured joint is inhibited.\textsuperscript{29}

Electric stimulation of the peripheral nerve causes direct activation of the efferent fibers, sending action potentials directly from the point of stimulation to the neuromuscular junction, producing a response in the EMG known as the muscle response (M-response).\textsuperscript{29} The M-response or \( M_{\text{max}} \) represents activation of the entire motor neuron pool, meaning every motor neuron that supplies the muscle of interest is thought to be activated and therefore the value should be stable.\textsuperscript{29} In order to make between-subject comparisons, the value of H-reflex must be normalized because the amplitude of the H-reflex varies amongst subjects. One common method of normalizing this measurement is by taking a ratio of \( H_{\text{max}} \) to \( M_{\text{max}} \).\textsuperscript{29} This ratio can be interpreted as the proportion of the entire motor neuron pool capable of being recruited, based on the assumption that the M-response amplitude is a stable value.\textsuperscript{29} The \( H_{\text{max}}/M_{\text{max}} \) ratio is more commonly used when the data are being collected on more than one occasion because movement of the stimulating electrodes makes it
more difficult to assume the same portion of the motor neuron pool is being
stimulated.  

H-reflex has been found to decrease in the joint musculature of the affected limb
in reaction to joint effusion. A depressed H-reflex of the quadriceps muscle suggests
the muscle is inhibited and is therefore unable to recruit as many motor neurons. A
decrease in volitional activation or motor firing exists in the quadriceps of patients
who have ACL injuries. ACL injuries often result in chronic knee instability and a
substantial 15-40% decrease in strength of the quadriceps muscle, contributing
ultimately to functional limitations. Arthrogenic muscle inhibition (AMI) is
characterized by a reflexive decrease in motor neuron pool excitability, resulting in a
persistent state of diminished ability to contract the musculature surrounding a joint
after injury. This damage and distension of joint structures affects the excitability
of spinal interneurons and ultimately the ability to produce motor output. One study
evaluating participants with a history of unilateral knee dysfunction secondary to
ACL injury concluded that the injured side had a tendency for the H-reflex to be
smaller than compared to the uninjured side, exhibiting signs of inhibition. These
findings suggest that bilateral differences in healthy subjects may represent a sign of
inhibition, and therefore possibly an athlete at risk of ACL injury.

2.5 Transcranial Magnetic Stimulation

Diminished muscle strength and activation deficits may be the result of altered
cortical and spinal reflexive neural pathways. Transcranial magnetic stimulation
(TMS) is a noninvasive technique that involves directing an electric current through a
copper-stimulating coil to produce a transient magnetic field. A small electric current is induced in the underlying brain tissue when the coil is held over the scalp causing a depolarization of nerve cells that is propagated via the corticospinal tract to contralateral peripheral muscles where a motor response can be logged with surface EMG electrodes. A figure of eight coil consists of two round coils and produces more focal stimulation. TMS has been previously used for the study of plasticity in the human motor system by evaluating corticospinal excitability and measuring adaptations in the CNS. This technique has been used to study quadriceps NMC following ACL reconstruction, the fibularis longus muscle following ankle injury, and patients suffering from stroke, hemiparesis, and focal hand dystonia. Researchers have also been seeking to determine if cortical excitability can be altered to improve clinical outcomes via various therapeutic interventions.

AMT and MEP are two different aspects of corticospinal excitability that can be assessed through TMS. The AMT is the lowest level of stimulation capable of causing a measurable response in the muscle. Decreased corticomotor excitability is indicated by a higher AMT because more magnetic energy is required to generate a motor evoked potential. Previous research involving this technique has revealed a correlative relationship between muscle weakness and NMC deficits in the upper and lower extremity with a higher AMT; indicating altered sensory feedback of the limbs from pain, disuse or limitation is often affiliated with decreased cortical excitability.

Non-contact ACL injuries are often associated with a jump stop movement. NMC is the unconscious activation of dynamic restraints in response to joint motion
and joint loading to maintain and restore functional joint stability. NMC is the body’s innate protection from injury and can be affected by altered movement patterns, altered activation patterns and altered muscle stiffness. Prospective kinetic differences have been found between ACL injured and healthy adolescent females in which the injured group had larger knee valgus moments and high GRF. Research studies involving TMS and NMC in the quadriceps musculature have drawn conclusions suggesting that decreased cortical excitability in the quadriceps might lead to altered kinematics during gait and other functional activities, possibly even progressing to joint degeneration. The relationship between the rise in corticospinal excitability and the increase in TMS intensity is displayed by a stimulus-response (SR) curve. Research has found correlations between the extent of quadriceps motor representation, as reflected by the steepness of SR curves, and quadriceps strength was strongly associated in patients with unilateral knee dysfunction secondary to ACL injury. Voluntary quadriceps activation is potentially influenced by both spinal and cortical pathways as it is determined by motor unit recruitment and firing rate. A positive correlation between voluntary muscle activation and muscle strength exists. Bilateral deficits in voluntary quadriceps activation have been following unilateral injury, making it difficult to determine whether these neuromuscular alterations were a result of joint injury or a predisposing factor to joint injury. Further research evaluating muscle strength and cortical excitability of the quadriceps is needed to determine if neuromuscular alterations are a predisposing factor to joint injury.
AMI can be seen following ACL injuries in which chronic knee instability and residual weakness in the quadriceps muscle can contribute to a persistent state of diminished ability to contract the musculature surrounding the knee joint. Previous research has compared patients with ACL ruptures to healthy controls and discovered significant deficits in voluntary activation in both the injured and uninjured legs and alterations at the cortical level. In a study examining participants who presented with a history of unilateral knee dysfunction secondary to ACL injury, the injured leg exhibited lower threshold values when compared to the uninjured leg due to changes in excitability at the cortical level. This increase in excitability following ACL injury is thought to reflect changes primarily at the motor cortical level via reductions in GABAergic inhibition. TMS has also evoked greater MEP in the quadriceps of patients with patellofemoral pain syndrome, suggesting an increase in cortical excitability. Corticomotor projections targeting muscles adjacent to a pathological joint seem to exhibit increased excitability in many conditions in which a limb is altered as a result of pain, disuse or restrictions. One case report on an individual with unilateral knee OA reported that cortical excitability was reduced in the injured limb compared to the uninjured limb. Following an eight week muscle strengthening intervention, increases in cortical excitability of the affected limb were made evident.

A previous study has analyzed AMT and peak-to-peak MEP measurements to determine if TMS in the quadriceps and fibularis longus muscles can be a reliable measure of cortical excitability over a four week time period. The study concluded that when using TMS in the lower extremity to assess neural function, both AMT and
MEPs are reliable outcome measures.\textsuperscript{47} The analysis of this study determined that TMS is a reliable method for assessing neural excitability over a 4 week time frame and is also a method producing acceptable agreement between measurements.\textsuperscript{47}

Through determination that TMS is a reliable tool when measuring the quadriceps over a 4 week time period, clinicians can begin measuring the effects of interventions targeting patients with altered levels of corticomotor excitability. A clinician can have confidence that any changes in the levels of cortical excitability are due to physiological changes within the person, and not due to error associated with the technician or equipment. Clinically implementing TMS is a favorable tool in detecting altered levels of cortical excitability and determining the effect of a treatment or an intervention over time.

**2.6 Quadriceps Muscle Strength Assessment**

Altered muscle activation is a proposed modifiable risk factor for ACL injury, especially for females, as they often demonstrate high levels of quadriceps activity and low levels of hamstring activity, commonly referred to as quadriceps dominance.\textsuperscript{48} Quadriceps dominance is the tendency to stiffen and stabilize the knee joint by primarily using the quadriceps muscles.\textsuperscript{48} When the quadriceps contract, they pull the tibia anterior relative to the femur, placing the ACL at greater risk for injury. An anterior shear stress to the tibia and ACL is induced when a female athlete uses her quadriceps to stabilize the knee joint.\textsuperscript{48} Adult females of all levels exhibit quadriceps dominance during landing and cutting.\textsuperscript{48} Females tend to land from a jump with less knee flexion than males, and this extended knee joint component of the
injury mechanism coupled with eccentric contraction of the quadriceps relates to a neuromuscular imbalance and results in greater anterior tibial shear. Decreased knee flexion also minimizes the posterior shear forces of the hamstrings. Males also use the posterior chain muscles to control the limb and stabilize the knee joint; the hamstrings increase flexion at the knee providing a mechanical advantage for using the muscles to absorb force.

ACL injuries often result in residual weakness in the quadriceps muscle, and this residual weakness can decrease by 15-40%, persisting for months and even years following the initial injury. Following ACL injury, quadriceps isokinetic strength deficits have been found. In ACL deficient patients, knee extension strength deficits were reported between six months and 15 years post-injury. Possible risk factors to chronic joint pathologies following ACL injury are quadriceps avoidance gait patterns and decreased ability to absorb shock during stance.

Important clinical information about muscle weakness that may relate to functional limitations can be provided through a muscle strength assessment. Muscle strength can be measured through manual muscle testing, handheld dynamometers and stationary isokinetic dynamometers. The Biodex is a stationary isokinetic dynamometer that is known to provide better stabilization for the patient during testing. Determination of a mechanically reliable instrument assures the clinician that observed changes in muscle function are due to actual performance differences rather than inconsistent measurement capabilities of the instrument. Although this device is expensive and lacks portability, researchers have found this
instrument to yield highly reliable strength measurements. The Biodex isokinetic dynamometer has been shown to provide mechanically reliable measure of torque, position and velocity on repeated trials performed on the same day as well as on different days. For both clinical and research purposes, isometric torque and position measurements were also found to be valid.

### 2.7 Hip Muscle Strength Assessment

Structural differences between males and females may lead to altered movement patterns, which may in turn make females more susceptible to particular injuries such as patellofemoral pain syndrome, illiotibial band friction syndrome, lower extremity stress fracture and traumatic ACL ruptures. Kinematic differences such as greater hip adduction, knee abduction, hip internal rotation, and tibial external rotation, place greater demands on female lumbo-pelvic musculature. Athletes must possess sufficient strength in the hip and trunk musculature to provide stability in all planes of motion. The hip abductors play an important role in lower extremity alignment by assisting in the maintenance of a level pelvis, preventing hip adduction and internal rotation during single limb support and by affecting the ability of the quadriceps and hamstrings to generate or resist forces experienced by the entire leg during jumping. Previous research has identified males as having a reported 19% greater isometric hip abduction strength than females. Female athletes with either lower extremity or low back injury have also demonstrated a greater difference in side-to-side hip extension strength symmetry when compared with their male counterparts.
Having an accurate and reliable method for assessing muscle strength is important in making clinical decisions about patients who may have altered NMC and therefore are predisposed to ACL injury. Hip musculature is a stabilizer of the knee joint, eccentrically controlling femoral adduction and internal rotation. Strong hip abductors and internal rotators help to minimize knee valgus, a landing mechanism often demonstrated by females and component of the typical ACL injury mechanism. A hand-held dynamometer (HHD) is a portable device often used to assess hip muscle function, and is more sensitive to discrete, objective differences in muscle strength than the traditional manual muscle test. The HHD is suitable for the clinical setting as it is inexpensive and easy to administer. A reliable hip muscle strength assessment can provide a screening tool for the detection of hip muscle weaknesses in healthy individuals, which would result in poor jump landing biomechanics, and therefore increased risk of ACL injury.

Previous research has concluded that assessing hip muscle strength with a HHD shows great promise as an inexpensive and reliable clinical tool that is easy to administer for evaluating hip strength. Previous literature also supports the validity and reliability of the HHD to measure strength of elderly, weak, or physically impaired patients when the clinician is physically strong, highly skilled, and experienced in application of the HHD. Reliable measures using a HHD were also found as long as the clinician had a mechanical advantage over a subject along with the necessary strength to isometrically resist a given movement’s maximal contraction when testing healthy, physically active, young adults. High intratester reliability has also been shown, proving the HHD may be a clinically reliable tool.
when taken and reported by the same clinician.\textsuperscript{52} Additionally, the utilization of a second strap wrapped around the dynamometer and testing table has been reported to eliminate the effect of tester strength, a limitation of hand-held dynamometry.\textsuperscript{51}

### 2.8 Hip and Knee Range of Motion Assessment

A rapid increased in ACL injuries in females over the last 30 years has fueled intense examination of the mechanisms responsible for the gender disparity in these debilitating sports injuries.\textsuperscript{48} ROM is the amount of movement that occurs at a joint, and is one intrinsic risk factor suggested to predispose athletes to ACL injury.\textsuperscript{4,54} Previous literature has shown that females perform maneuvers such as landing from a jump, cutting and pivoting with less knee and hip flexion, increased knee valgus, increased internal rotation of the hip couple with increased external rotation of the tibia, and increased quadriceps muscle activation.\textsuperscript{8}

Functional movement is often assessed through active range of motion (AROM), in which the patient voluntarily moves the body part through the ROM without assistance.\textsuperscript{54} A universal goniometer is a 180° or 360° protractor with one axis that joins a stationary arm and a movable arm; this tool is a consistent method for measuring joint ROM and is essential for accurate assessment of a patient’s present status, progress, and effectiveness of a treatment program.\textsuperscript{54} Use of a goniometer allows a clinician to obtain an objective measure of the patient’s ability to perform functional activity. Research has confirmed high criterion-related validity of the universal goniometer by comparing x-ray bone angle measurements compared to goniometric measurements of knee joint position.\textsuperscript{54} Studies determining the reliability
of the universal goniometer have indicated that joint ROM can be measured reliably when the same therapist performs the repeated measures and uses a rigid standardized measurement protocol.\(^{54}\)

### 2.9 Core Endurance Testing

The core is defined as the region of the body conjoined by the pelvis and diaphragm and includes the muscles of the abdomen and lower back.\(^{55}\) Increases in core strength and stability often lead to improved athletic performance as well as assistance in the treatment and prevention of injury.\(^{55}\) Abdominal muscle activity provides a stable base for movement of the limbs. External forces that may cause the spine to extend, laterally flex, or rotate is controlled by the abdominal muscles.\(^{56}\)

Evidence has led researchers to believe that the knee may be a victim of core instability with respect to lower extremity stability and alignment during athletic movements, often in reference to injuries of the ACL.\(^{51}\) The core is a significant contributor to athletic function as many athletic movements require a transfer of energy from the limbs through the core to complete a task.\(^{55}\) The abdominals have been reported to increase the stability of the spine though co-contraction with the lumbar extensors and are suggested to control excessive anterior pelvic tilt, which is believed to be coupled with femoral internal rotation and adduction.\(^{51}\) Biomechanically, the core is responsible for positioning about half of an athlete’s body mass over the lower extremity; being a large influence of lower extremity injury by altering the load of the lower extremity at risk.\(^{55}\) Lower extremity injury risk can
be increased by a malalignment of mass causing an increased adverse of loading of the joints and other structures in the legs.\textsuperscript{55}

A meta-analysis of ACL injury prevention programs found success with programs that include exercises directed to core strength and ability.\textsuperscript{57} Knee loading patterns implicated in ACL injury were reduced by an intervention program that incorporated core strength and balance training components.\textsuperscript{58} Gender differences in the performance of core stabilizing muscles have also been noted, identifying females with decreases in proximal strength measures suggesting they have a less stable foundation upon which to develop or resist force in the lower extremities and therefore are predisposed to lower extremity injury.\textsuperscript{51} Activation of the core musculature may resist external forces placing increased loads on the ACL.\textsuperscript{48} Core dysfunction is a common contributor of the valgus position of the knee and is frequently observed in women during varied motor tasks such as landing from a jump.\textsuperscript{48} Core motion and proprioception has been shown to predict risk of future knee ligament injuries in females, thereby taking measurements of core endurance may lead to predictions of who can position their lower limb correctly during a jump landing task.\textsuperscript{48}

The side bridge test is a measure of lateral core muscle capacity,\textsuperscript{51} and has been justified as an ideal training exercise to target the quadratus lumborum and the abdominal wall with minimal spinal loading.\textsuperscript{59} The side bridge test may be used to evaluate endurance capabilities and ratios of endurance balance around the torso, and has been qualified as a good test in relation to cost, safety, and reliability.\textsuperscript{59} The
Biering-Sorensen test measures the muscle capacity of the posterior core, and has been shown to be consistently reliable as a measure of back extensor endurance.\textsuperscript{59}

### 2.10 Star Excursion Balance Test

Postural-control assessments are often used to evaluate risk of injury, initial deficits resulting from injury, and level of improvement after intervention for an injury by clinicians.\textsuperscript{60} There are two categories associated with postural-control: static and dynamic. In static measures of postural-control, the individual is required to establish a base of support and maintain this position while minimizing body movement during the assessment.\textsuperscript{60} Dynamic measures of postural-control more closely mimic the demands of physical activity, as it involves some level of expected movement around a base of support.\textsuperscript{60} Discovering dynamic measures of postural stability that provide reliable, sensitive and cost-effective information is important because these assessments have the ability to closely mimic demands of physical activity, identify deficits in patients with a variety of lower extremity conditions and predict risk of lower extremity injury.\textsuperscript{60}

The Star Excursion Balance Test (SEBT) is a dynamic postural-control assessment involving an attempt to create purposeful segmental movement without compromising the established base of support.\textsuperscript{60} The measurements from the SEBT can be compared between injured and uninjured limbs or before and after an intervention to quantify deficits or improvements in dynamic postural control.\textsuperscript{60} The SEBT was originally a rehabilitative tool which included a series of single-limb squats using the non-stance limb to reach maximally to touch a point along one of
eight designated lines arranged on a grid $45^\circ$ from one another on the ground. The different reaching directions require combinations of sagittal, frontal and transverse movements. The SEBT has been recently modified as great redundancy was found with the participant performing the eight reach directions. Now, the modified SEBT recommends that only three reach directions (anterior, posteromedial, and posterolateral) should be performed, resulting in a substantial reduction of time required for completing the assessment. Researchers have also found that reaching distances need to be normalized to each participant’s limb length: anterosuperior iliac spine to the medial malleolus, to make valid comparisons of SEBT among individuals or groups.

Previous literature suggests that the SEBT has the potential to predict injury to the lower extremity. Clinicians often focus on the NMC, postural-control and function performance deficits that exist among ACL reconstructed and deficient patients. One study used the SEBT as a screening tool to examine ACL deficient patients and found the ACL deficient limb and the uninjured limb exhibited worse dynamic postural control than the limb of the healthy matched control. The SEBT is a reliable screening tool that can be quickly administered and has been recommended for use in pre-participation physical examination to identify those at greater risk of lower extremity injury. The SEBT can be used to discriminate NMC abilities at more demanding levels that are required for athletes, as the farther the distance reached indicates better dynamic postural-control. Shorter normalized reaching distances have been linked to decreased hip and knee flexion and decreased NMC abilities; risk factors often associated with poor jump landing mechanics seen in females and a
significant contributor to increased risk of ACL injury.\textsuperscript{60} This link is likely due to the influence of large joint muscle groups controlling these joints which are important for motion and stability during dynamic tasks, such as landing from a jump.\textsuperscript{60}

\textbf{2.11 Vertical Jump Assessment}

Vertical jump height is commonly assessed as a measurement to calculate lower-body power to discriminate between levels of performance.\textsuperscript{66} Implementing a reliable method to assess vertical jump is important given that muscular power is an important determinant of performance in many sports and a critical factor in the mobility and the functional capacity of injured athletes.\textsuperscript{67} The Vertec is a device used to assess vertical jump height by measuring the difference between the fully extended reaching height and the maximal vertical jump-and-reach height.\textsuperscript{66} The Vertec contains plastic swivel vanes arranged in half-inch increments attached to a telescopic metal pole that can be adjusted for each participant’s reach height.\textsuperscript{67}

Previous literature has not found the Vertec system to be the most reliable method of measuring vertical jump height.\textsuperscript{66,68,69} One study assessed the intrasession and intersession reliability of the Vertec, Just Jump System, and Myotest for measuring countermovement vertical jump height, and determined the Myotest demonstrated the best reliability in males and females.\textsuperscript{66} The study also suggested the practitioner allow the athletes to complete numerous repetitions until performance plateaus when using the Vertec.\textsuperscript{66} Another study compared vertical jump height reliability data from a newly created instrumented platform to those derived from the Vertec and attained results showing heights calculated from platform take-offs were more reliable than
the Vertec values. A third study evaluated inter-day reliability of a modified Vertec in comparison to a Yardstick and a Board, and concluded the Yardstick was the preferred mode of testing in terms of maximizing reliability. Using a Yardstick vertical-jump device, standing-reach height was measured by asking the participant to stand with feet flat on the ground and extend their arm and hand to reach as high as possible. Each participant also completed two jumping trials by beginning in a crouched position and then springing upward to touch the Yardstick at the highest possible point. Vertical jump was calculated as the distance from standing reach height to the highest point reached during the jumping trials.
Chapter 3

Methodology

3.1 Research Design

Study Design: Randomized Controlled Trial

The independent variables in this study included time (baseline and four weeks post) and group (traditional feedback, traditional plus real time video feedback, and control). The dependent variables were the outcome measures retrieved through H-reflex (H:M), TMS (AMT, and corticospinal excitability normalized to the M-response at 120, 130, and 140% of AMT, gluteus strength (hip extension and abduction), quadriceps strength (knee extension), balance via the SEBT (anterior, posteromedial, posterolateral, and composite, normalized to leg length), hip ROM (hip extension, internal rotation and external rotation), knee ROM (knee flexion), core endurance (3-way plank and prone plank), and maximal vertical jump (2-footed maximum vertical jump normalized to standing reach height).

3.2 Experimental Design

A single-blinded randomized control trial study design was utilized to assess outcome measures for spinal reflex excitability, corticospinal excitability, strength, ROM, core endurance, balance and maximal vertical jump; both before and
immediately after the four week intervention. The examiner was blinded to which group participants were allocated. Participants who were allocated to one of the feedback groups (real-time, traditional, taper or no taper) were blinded to which feedback intervention was the experimental condition (real-time feedback).

3.3 Participants

Forty-eight female participants were recruited between the ages of 18-30 from all races. Participants were excluded if they had a history of: serious head injury or increased intracranial pressure (including loss of consciousness due to head injury); cardiovascular disease, neurologic disorder, fibromyalgia, peripheral neuropathy; metal implants in the head, neck, or shoulders (excluding dental work); personal or familial history of seizures or epilepsy; implanted foreign objects including ocular foreign objects, cochlear implants, brain stimulator, aneurysm clip, medication pumps, intra-cardiac lines, or cardiac pacemakers; illicit drug use, current smoker, alcohol abuse, or anyone currently withdrawing from any substance; and those currently taking medications that lower seizure threshold (e.g., tricyclic antidepressants, neuroleptic agents, Baclofen, Tramadol, etc.). Pregnant females were also excluded for protection of the fetus from electrical and magnetic stimuli. Since this study is looking at a healthy population only, all participants with previous lower extremity orthopedic surgery, fracture, or any ligamentous injury in the past six months were also excluded. Participants had to be physically active for at least three times per week for at least 30 minutes each session, have a body mass index of less than 30 and maintain current level of physical activity throughout the entire study. Participants also refrained from caffeine intake prior to coming to the lab on the day
of testing to prevent increased neural excitability effects from caffeine. Participants with chronic ankle instability (Foot and Ankle Ability Measure <90%) were also excluded. Participants had to exhibit excessive dynamic knee valgus during a screening using video analysis from the Landing Error Scoring System (LESS). All participants provided written informed consent approved by the institutional review board at the University of Toledo prior to performing any of the proposed experiments (Appendix A).

Sample size was estimated using knee abduction kinematics from our preliminary data. We chose abduction kinematics because they demonstrated the smallest effect sizes of the outcomes being collected. With a predetermined alpha level of .05 and 1-β of 0.8, we used a mean difference of 1.19 (real-time – control) and a within participant standard deviation of 0.8 to calculate sample size. We estimated 15 participants in each group (45 total) would be needed to detect the presence of statistically significant differences, using our most conservative outcome measure. Participants were initially allocated into one of three groups (real-time, traditional or control). After two weeks of the intervention, the real-time and traditional groups were further separated into real-time, real-time taper, traditional and traditional taper, making 8 participants in each of the intervention groups and 15 in the control group. In order to keep the groups consistent after the separation, we initially recruited 48 participants.

Participants were recruited from the University of Toledo community using advertisements, and by meeting with groups of students in various classrooms. All recruitment methods were approved by the Institutional Review Board at the
University of Toledo (#107936). Upon arrival in the laboratory, all participants were provided a standardized explanation of the study via a brief PowerPoint presentation, and filled out the injury history questionnaire, the Godin exercise questionnaire, (Appendix B) and gave consent to participate in this study. The Godin Leisure-Time Exercise Questionnaire is a brief four-item query of usual leisure-time exercise habits. Weekly frequencies of strenuous, moderate, and light activities are multiplied by nine, five, and three MET’s, respectively, to calculate this measure.  

3.4 Randomization

Outcome measures were measured on two separate days, with 28 days between the sessions. Both sessions took place the same time of day within one hour of the baseline testing session. During the first testing session, it was randomly determined which limb (dominant or non-dominant) was to be tested first. That order was then repeated for the post-test. Spinal reflex excitability, corticospinal excitability and quadriceps strength were always tested first, in that specified order. Hip strength, ROM, core endurance, balance and vertical jump outcome measures were counterbalanced. The order determined for each participant was then repeated for the post-test.

A block randomization was used with concealed allocation of participants into one of five groups (real-time feedback, traditional feedback, control, real-time feedback tapered or traditional feedback tapered). The opaque envelope containing group membership was opened by the examiner implementing the intervention immediately prior to starting the intervention. Participants who were allocated to one of the feedback groups (real-time, traditional, taper or no taper) were blinded to
which feedback intervention is the experimental condition (real-time feedback). We did not blind the control group. All outcome measures for all groups were conducted at 4 separate time points (baseline, week 2, week 4 and week 5 following initiation of the intervention).

3.5 Instrumentation

3.5.1 Spinal Reflex Excitability

H-reflex and M-response measurements were collected with surface EMG (MP100C BIOPAC Systems, Inc., Goleta, CA). Analog to digital signal conversion was processed with a 16 bit converter (MP150, BIOPAC Systems, Inc.). The Acqknowledge BIOPAC Software (BIOPAC Version 3.7.3., BIOPAC Systems Inc.) was used to visualize the signals as well as manipulate the stimuli. Signals were sampled at 1024 Hz and EMG amplification was set at a gain of 1000 (EMG100C BIOPAC Systems, Inc.). The common mode rejection ratio of our EMG amplifier was 100 dB and the input impedance was 2Mohms. The disk-shaped electrodes used to acquire signals were disposable, 10 mm pre-gelled Ag/AgCl (BIOPAC Systems, Inc.). The electrodes were positioned 1.75 mm apart over the vastus lateralis oblique. Reflexes were elicited with the BIOPAC stimulator module (STIM100A, BIOPAC Systems, Inc.), a 2 mm shield disk electrode (EL254S BIOPAC Systems Inc.), and a 7 cm carbon impregnated dispersive pad.

3.5.2 Corticospinal Excitability

Corticospinal excitability was evaluated using the Magstim Rapid (Magstim Company, Wales, UK) via a double cone coil (Magstim Company, Wales, UK). The magnetic stimulation did not exceed 1.4 Tesla. Corticospinal excitability was
measured in the peripheral muscles using the disk-shaped electrodes using a shield disk electrode. The disk-shaped electromyography electrodes used to acquire signals were disposable, 10 mm pre-gelled Ag/AgCl (BIOPAC Systems, Inc.). The before mentioned Acqknowledge BIOPAC Software (BIOPAC Version 3.7.3., BIOPAC Systems, Inc.) was used to visualize the signals.

3.5.3 Strength Measurement

The Biodex Isokinetic Dynamometer (Biodex System 2, Biodex Medical Systems Inc., Shirley, NY) was used to measure strength of the quadriceps. For strength measurement of the gluteal muscles, the Hand-Held Dynamometer (microFET2, Hogan Health Industries, West Jordan, UT) was used.

3.5.4 Range of Motion Measurement

A handheld goniometer was used to measure hip extension, hip internal rotation, hip external rotation and knee flexion ROM.

3.5.5 Core Endurance Measurement

A stopwatch was used to track the total time the participant was able to maintain the required position.

3.5.6 Balance Measurement

Tape measures were used to measure leg length and to form the three reaching lines (anterior, posteromedial and posterolateral). The lines were arranged in a grid that extends from a center point and were 135° from one another. The reaching distances (anterior, posteromedial and posterolateral) are named in orientation to the stance limb.

3.5.7 Vertical Jump Measurement
A Vertec jump training system (Sports Imports, Columbus, OH) was used to measure maximal vertical jump height ($\text{Vert}_{\text{max}}$).

**3.5.8 Kinematic Measurement**

All kinematics were collected with a 12 camera, digital Eagle motion analysis system (Motion Analysis Corporation, Santa Rosa, CA) at a sampling rate of 200 Hz. Movement data were processed in Visual 3D (C-Motion, Inc., Germantown, MD). Knee flexion angle was quantified as a negative angle between the shank segment (represented by the shank markers) and the thigh reference segment (represented by the thigh markers) in the sagittal plane. Hip flexion angle was quantified as a positive angle between the thigh and the pelvis reference segment in the sagittal plane. Knee abduction angle was quantified as a negative angle between the shank and the thigh reference segment in the frontal plane.

**3.5.9 Kinetic Measurement**

All GRF was collected with two AMTI OR6-5 force platforms (Advanced Motion Technology, Inc., Watertown, MA) at a sampling rate of 2000 Hz, with a gain of 2000 and bridge excitation of 10 V. Through Visual 3D software, inverse dynamics analysis was used to calculate knee and hip joint sagittal and frontal plane moments. The kinetic and kinematic data were filtered with a zero-lag, fourth order, low-pass Butterworth filter at a cutoff frequency of 12 Hz. All moments were normalized through Visual 3D to participant body weight and height (Nm/kg*m). We calculated internal moments and quantified a hip flexion moment as positive, while knee flexion and knee abduction were quantified as a negative value.

**3.6 Procedures**
3.6.1 Landing Error Scoring System (LESS)

The LESS is a clinical tool used to quantify errors during jump landing. This test has been found to be a valid and reliable tool to clinically assess and identify poor jump landing mechanics. After potential participants gave consent into the study, they were screened for the presence of excessive knee abduction using previously described LESS methods. The LESS was immediately scored after completion of three jumps off of a 30 cm box and immediately rebounding for maximum height. If excessive knee abduction was present, the participant was included in the study; if knee abduction was not present, the participant was dismissed from the study.

3.6.2 Spinal Reflex Excitability

Participants were instructed to lie supine for vastus lateralis oblique testing on a padded treatment plinth with their arms comfortably placed at their side with their head in a neutral position (Figure 1). The head of each participant was rested comfortably on a pillow with their knees slightly flexed (~10-15 degrees). The hair over the collection sites was shaved and the skin over the recording electrode site was debrided and cleaned with alcohol. Two 10 mm, pre-gelled Ag/AgCl (EL503, BIOPAC Systems Inc.) surface EMG electrodes were positioned 2 cm apart over the vastus lateralis oblique muscle belly. Electromyographical signals were band-pass filtered from 10 to 50 Hz and collected at 1024 Hz with a common-mode rejection ratio of 110 dB. A 2 mm shielded disc stimulating electrode (EL2524S, BIOPAC Systems, Inc.) was positioned over the femoral nerve and secured with hypoallergenic tape and a 7x13 cm self-adhesive electrode was positioned over the hamstring and used as a dispersive electrode. A 1 ms square wave stimulus was produced with a
BIOPAC stimulator module (STM100A, BIOPAC Systems, Inc.) and a 200 volt maximum stimulus adaptor (STMISOC, BIOPAC Systems, Inc.) and delivered to the femoral nerve.

During testing, participants were instructed to maintain a constant head, eye and hand position by focusing on a circle on the ceiling. The stimulus was first given at a low intensity initially so that the participant could become familiarized with the stimulus. The stimulus was increased in 0.2 volt increments until a maximum H-reflex was elicited, and then three maximal H-reflexes were collected at that voltage. Maximum M-response was found when the amplitude of the M-response no longer increased as the stimulus intensity increases. Three maximal M-responses were recorded and averaged. The M-response was used to normalize each MEP’s amplitude recorded during the TMS testing.

Figure 1-1: Participant positioning for quadriceps muscle response testing.

3.6.3 Corticospinal Excitability
Participants were positioned seated in an upright position on the Biodex System 2 Pro dynamometer (Biodex Medical Systems, Shirley, NY). During quadriceps testing, the knee was placed at 90° of flexion and the hips were placed in 85° of flexion (Figure 2). A lycra swim cap was placed on the participants’ head to allow for location of the optimal stimulating point within the motor cortex. Perpendicular lines were then drawn vertically on the swim cap and connected from the center of the occiput and nose, and from each external auditory meatus. These perpendicular lines were drawn to provide an anterior to posterior and left to right orientation in order for the investigator to know how to move the coil to locate the “hot spot.” Additionally, formable disposable earplugs were used for participant comfort as an audible noise is heard during magnetic stimulation.

Participants were instructed to produce knee extension a maximal voluntary isometric contraction (MVIC) in the position of 90° of knee flexion for quadriceps testing which was measured using a hand-held inclinometer. To achieve this, the shank of the leg was secured to the arm of the isokinetic dynamometer, and the participant was instructed to try and straighten their knee with as much force as possible against the stationary arm. Five percent of the maximal isometric quadriceps contraction was used as a standardized volitional muscle contraction during AMT/MEP testing. To elicit an MEP on the contralateral limb, a double cone coil (Magstim Company, Wales, UK) was used to produce a maximum magnetic stimulus of 1.4 Tesla. Initial stimuli were given at 50% of the maximum stimulator output in order to locate the optimal coil placement to produce MEPs. The coil was moved approximately one cm in an anterior-to-posterior direction over the vertex until a
MEP response was found and marked on the swim cap by the investigator.\textsuperscript{34-71} The area producing the greatest MEP wave amplitude was noted as the optimal stimulating point and marked on the swim cap.\textsuperscript{34-71} The stimulator was secured over this location using an adjustable camera mount and the inside of the coils were traced on the swim cap to ensure exact replication of placement for the post-testing session. At the post-testing session the coil was first lined up with the tracing of the coil from the first session to begin locating the optimal cortical stimulation location.

AMT is defined as the lowest TMS intensity required to evoke a measureable MEP (>100 µV) in the muscle. In order to establish threshold, a total of five out of 10 measureable MEP waves must be elicited at the respective intensity. Once five out of 10 waves were found, the intensity level was decreased by 1\% until a total of six out of 10 negative waves were produced, meaning that the six waves elicited peak to peak measures less than 100 µV. The lowest stimulator output that yielded five out of 10 positive MEPs was used to quantify AMT.

Participants were instructed to sit still with their arms cross over their chest, and to remain focused on the screen. They were then instructed to extend their knee to 5\% of their MVIC value and hold until the stimulus was given. After the stimulus was given, the participant was able to relax until the next stimulus was given. Surface EMG electrodes were positioned on the vastus lateralis muscle as described above to collect the signal elicited by the magnetic stimulation.

A SR curve was then generated based on the determined level of AMT. The outcome measures for peak-to-peak MEP amplitude were assessed according to the SR curve, and were taken at 120, 130 and 140\% of AMT.\textsuperscript{20} An additional five stimuli
were given at 120, 130 and 140% of the AMT. The peak-to-peak amplitude of each MEP generated from the stimulus was recorded, saved, averaged and then normalized to the M-response found from the above spinal reflex testing.

![Figure 2-1: Participant positioning for TMS corticospinal excitability testing.](image)

### 3.6.4 Strength Assessment

To test the strength of the quadriceps muscles, participants were seated in the Biodex Dynamometer with their knees flexed to 90 degrees. Straps were placed over their lap and across their chest, with the lower part of their leg secured to the arm of the dynamometer (Figure 3-1). They first performed three warm-up trials, where they estimated 25, 50 and 75% of their maximum contraction. They were then asked to extend their leg as hard as they could while being given encouragement from the investigator. The participant continued to perform trials with a 30-60 second break in between until there was either a plateau or decrease in their force production. The three greatest trials were recorded and averaged.
Figure 3-1: Participant positioning for strength testing of the quadriceps.

To test the strength of the hip abductors, participants were asked to lie on their side, with a pillow between their legs. The hand-held dynamometer was secured by a belt wrapped around the treatment table and the thigh (Figure 3-2). They were directed to lift their leg up as forcefully as possible with their leg extended and foot dorsiflexed. Participants continued to perform trials with a 30-60 second break in between until there was either a plateau or decrease in their force production. The three greatest trials were recorded and averaged.

Figure 3-2: Participant positioning for strength testing of the hip abductors.

To test the strength of the hip extensors, participants were lying prone on a padded treatment plinth, with their hands above their head. The hand-held
A hand-held goniometer was used to measure hip and knee ROM. The participant would lie prone with their feet over the end of the plinth to measure hip extension ROM. They were stabilized with a strap over the gluteal muscles. The axis of the goniometer was placed over the greater trochanter of the femur, with the stationary arm in line with the midaxillary line of the trunk and the movement arm parallel to the longitudinal axis of the femur. With the knee maintained in extension, the hip was then extended to the limit of motion (Figure 4-1). \(^5\)
Figure 4-1: Participant positioning for hip extension range of motion testing.

Hip internal and external rotation ROM was measured with the participant seated at the edge of the plinth. To maintain stabilization, the therapist maintained the position of the femur without restricting movement while the participant held under the table. The axis of the goniometer was placed at the midpoint of the patella with the stationary arm perpendicular to the floor and the movement arm parallel to the anterior midline of the tibia. To measure internal rotation the foot and leg were moved in the lateral direction (Figure 4-2). To measure external rotation the foot and leg were moved in the medial direction (Figure 4-3).

Figure 4-2: Participant positioning for hip internal rotation range of motion testing.
The participant would lie supine on the plinth to measure knee flexion. The therapist provided stabilization at the femur without restricting movement. The axis of the goniometer was placed at the lateral femoral condyle with the stationary arm parallel to the longitudinal axis of the femur pointing toward the greater trochanter, and the movement arm parallel to the longitudinal axis of the fibula pointing toward the lateral malleolus. The hip and knee were flexed as the heel was moved toward the buttock to the limit of knee flexion (Figure 4-4).

**3.6.6 Core Endurance Assessment**
The 3-way plank and extension plank were performed to test core endurance. Each plank test was performed on a treatment table once, as these tests have been shown to have a reliability value of >0.97. The first plank, the two-arm prone plank, was performed by having the participants prop themselves up onto their elbows (90° shoulder flexion and 90° elbow flexion) and toes. The hips were positioned at zero degrees of flexion. They had to remain in a horizontal position with their body parallel to the floor for as long as possible (Figure 5-1). Time was measured with a stopwatch, and was stopped when any other part of their body, outside the base of support touched the table. The two-arm plank targets muscles of the abdominal wall.

![Figure 5-1: Participant positioning for the two-arm prone plank test.](image)

The side plank was performed on both the right and left side, with the order being randomized for the first session. This order was then repeated for the post-testing session. In order to perform the right side plank, the participant placed their feet on top of one another with the right upper arm perpendicular to the ground and the right elbow resting on the mat. The hips were positioned at zero degrees of flexion. The left arm was placed over the chest with the left hand on the right shoulder. The participant was asked to lift their hips off the treatment table, using
only their feet and right elbow for support (Figure 5-2). Time was kept for the right side plank using a stopwatch, and was stopped when any other part of the body, outside the base of support, touched the table.55

The left side plank was performed by placing their feet on top of one another with the left upper arm perpendicular to the ground and the left elbow resting on the mat. The hips were positioned at zero degrees of flexion. The right arm was placed over the chest with the right hand on the left shoulder. The participant was asked to lift their hips off the treatment table, using only their feet and left shoulder for support. Time was kept for the left side plank using a stopwatch, and was stopped when any other part of the body touched the table. The side planks have been suggested to optimally challenge the quadratus lumborum and the muscle of the anterolateral wall.55

Figure 5-2: Participant positioning for the side plank test.

The extension plank, or modified Biering-Sorensen test, was performed with the participant lying prone off the edge of an examination table with the anterior iliac spine at the edge and the lower leg strapped to the table. The participants supported their torso with their hands on a stool in front of the table until they were instructed to cross their arms and assume a horizontal position (Figure 5-3).
The participant maintained this horizontal position for as long as possible and time was kept using a stopwatch. Time was stopped when the participant was no longer able to maintain the horizontal position and touched down on the stool in front of them. The extension plank is a global measure of back extension endurance capacity and therefore the posterior core. 51-55

Figure 5-3: Participant positioning for the extension plank test.

3.6.7 Balance Assessment Using the Star Excursion Balance Test (SEBT)

The SEBT was performed in the anterior, posteromedial, and posterolateral directions. For the anterior reach, the participant stood with their toes at the beginning of the gridline and reached out as far as possible with the reaching limb along the reaching line with the most distal portion of the reaching foot, without shifting weight or coming to rest; then the participant returned the reaching limb to the start position in the center of the grid to resume a bilateral balance (Figure 6-1). 60

For posteromedial (Figure 6-2) and posterolateral (Figure 6-3) directions, the heel was placed at the beginning of gridline and the participant reached back as far as possible in each direction to tap the measuring tape. A trial was not considered complete if the individual tapped down heavily, came to rest at the touchdown point,
had to make contact with the ground with the reaching foot to maintain balance, or shifted any part of the testing foot. Four practice trials were allowed followed by three test trials in each direction for a total of nine successful trials. The order of reaching directions was randomized.

Figure 6-1: Participant positioning for the anterior reach during the SEBT.

Figure 6-2: Participant positioning for the posteromedial reach during the SEBT.
Figure 6-3: Participant positioning for the posterolateral reach during the SEBT.

3.6.8 Vertical Jump Assessment

Participants were assessed in both standing vertical reach height and a 2-footed maximum vertical jump height. The standing vertical reach height was measured by having the participant reach from under a Vertec jump training system (Sports Imports, Columbus, OH) while keeping both feet flat on the floor, to the highest point they could reach on the Vertec (Figure 7-1). The 2-footed maximum vertical jump height was measured by having the participant take one step towards the Vertec, then jump with both feet to reach as high as possible (Figure 7-2). The participant performed the jumping trial three times. The standing reach height was subtracted from the largest jump height to determine $\text{Vert}_{\text{max}}$. 
3.6.9 Participant Preparation: Jump Landing

Forty-one reflective markers were affixed with double-sided tape to the participant. A modified marker set \(^{22}\) was used for administration of the real-time feedback protocol and for motion capture. This marker set included 41 markers and was modified by including bilateral patella and great toe markers in order to effectively administer the real-time feedback (Appendix C). The participant performed a static trial, to align her with the global laboratory coordinate system, and a dynamic trial, which were both recorded with a 12 Eagle digital camera system.
(Motion Analysis Corporation, Santa Rosa, CA) and processed with Cortex software (Motion Analysis Corporation). Four medial markers were removed after these trials and the participant performed a three-minute warm up on at a self-selected speed on a stationary bike. The outcomes were measured following a jump landing from a 30 cm box and immediately rebounding for maximum height. All outcome measures were collected at the peak during the first 25% of stance (initial contact to toe off). Initial contact was defined as the point at which the vertical GRF exceeds 10N of force upon the subject landing from a jump. All outcome measures were collected with the same task as the pre-test at four separate time points: baseline, 2 weeks, 4 weeks and 5 weeks following the initiation of the intervention. While many kinetic and kinematic measures were collected and can be analyzed in future analyses, the following angles and internal moments have been chosen because of the previous association with ACL injury\textsuperscript{4}: 1) Knee flexion, 2) Hip flexion, and 3) Knee abduction.

### 3.6.10 Feedback Training Session

All participants in the feedback groups participated in a four-week feedback training session in which they returned to the laboratory three times per week to complete a jump-landing intervention in combination with the allocated feedback. The investigator providing the feedback identified and collected specific landing errors that were explained to participants via a PowerPoint prior to each intervention: 1) landing with both feet at the same time, 2) landing in a neutral valgus/varus position, 3) landing with feet shoulder width apart, 4) landing on your toes, rocking back onto your heels, 5) landing with increased bending in your knees and hips, and 6) landing softly (Appendix D). The participants were asked to fill out a check-list for
landing (self-analysis feedback), by asking participants to respond “Yes, No or I don’t know” to how they think they completed the 6 landing instructions (Appendix E). Participants were progressed from jumping off of a 30 cm high box (Level 1) to jumping off of a 45 cm high box (Level 2) through the feedback intervention. Progression was advanced when the examiner observed 2 sets of 6 consecutive jumps completed error free in the same session. Once the participant completed this task, she immediately moved up to the next level of progression and started the next training session at that same level. After being progressed to level 2, if the participant was not able to correct errors observed in three consecutive sets, they were moved back down to level 1. After two weeks of the feedback intervention, the intervention groups were further separated into real-time, real-time taper, traditional and traditional taper. The amount of feedback administered to the two taper groups was slowly decreased as the intervention progressed. The participants received the PowerPoint, self-analysis feedback and real-time feedback (if allocated into the real-time group) for each set of jumps the first two weeks of the four week intervention. Week three started the taper in which the participants did not receive any feedback concerning their jumps for 2 or 3 of the 6 sets each day. In week four, participants continued to taper down to only receiving feedback for 2 of the 6 sets.

Every effort was made to have the participants complete 3 sessions within a 7 day period for each of the 4 weeks of the study. If a participant participated in 9 of the 12 total sessions, she was included in the post-testing analysis. Participants not meeting this criterion were dropped from the study.

3.6.11 Feedback Intervention Groups
In addition to the intervention described above, participants in the real-time feedback group were shown a PowerPoint with proper landing technique, which included both writing and pictures explaining how to properly land from a jump. In addition to this, the real-time feedback group was given the following instructions: 1) you will now be able to see markers representing your dominant knee and toe on the screen in real time (Appendix F), 2) start with your toe marker in line with the reference line and then line your knee marker up with the reference line also. This is the way the markers should end up when you land, 3) this time when you jump we want you to watch the video monitor focusing on keeping the red line in line with the blue reference line when you land from your jump. For the feedback session, the real-time feedback group performed six sets of six jumps off of a 30 cm box and had to stick the landing. After each set of six jumps, the participants received individualized feedback based on which item from the checklist for landing she needed to focus on for the next series of jumps and was shown the corresponding PowerPoint slide/s.

Participants in the traditional feedback group were shown the Power Point with proper landing technique, without the real-time feedback. Participants in this group completed the same amount of jumps and received the individualized feedback based on which item she needed to focus on for the next series of jumps and was shown the corresponding PowerPoint slide/s.

3.6.12 Control Group

Participants in the control group sat quietly for 10 minutes instead of performing the jumps and receiving feedback and then were tested for the baseline
post-test. They returned to the lab to be post-tested three additional times: 2, 4 and 5 weeks post, as part of a larger clinical trial.

3.7 Statistical Analysis

* A priori * alpha levels were set at $P \leq 0.05$ for all inferential statistics, which were evaluated using SPSS 19.0 (SPSS, Inc., Chicago, IL) statistical software. A series of 2x2 ANOVAs with repeated measures on time was used to determine if spinal reflex excitability, corticospinal excitability, quadriceps strength, hip strength, core endurance, balance, and performance measures change from baseline to four weeks post-initiation of the intervention for those participants in the feedback and control groups. A Tukey post hoc multiple comparison test was used if a significant interaction was found between the feedback group and the control group. Pearson product moment correlation matrices and a two-tail bivariate correlation were used to determine if spinal reflex excitability, corticospinal excitability, quadriceps strength, hip strength, core endurance and balance correlate to knee abduction angle during a jump landing task at baseline. Change scores were calculated from baseline to four weeks post-initiation of the intervention for spinal reflex excitability, corticospinal excitability, quadriceps strength, hip strength, core endurance and balance. A Pearson product moment correlation and a two-tailed bivariate correlation were used to determine if changes in any of these outcome measures affected changes in knee abduction angle during a jump landing task following a four week intervention.
Chapter 4

Results

4.1 Subjects

A total of 48 healthy females participated in this study. Prior to performing our formal statistical analysis, outcomes were compared between the real-time and traditional feedback groups. No differences were observed between the interventions, so data were collapsed across groups and represented as the feedback group in the remaining statistical analyses. No significant differences were found between groups in demographics at baseline. Demographic information can be found in Table 1.

Table 1: Participant Demographics

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>Age (yrs)</th>
<th>Height (cm)</th>
<th>Mass (kg)</th>
<th>Godin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feedback</td>
<td>32</td>
<td>19.72±1.49</td>
<td>159.15±12.27</td>
<td>58.24±7.80</td>
<td>48.97±17.19</td>
</tr>
<tr>
<td>Control</td>
<td>16</td>
<td>19.56±1.67</td>
<td>159.23±11.08</td>
<td>59.35±8.87</td>
<td>51.56±26.74</td>
</tr>
</tbody>
</table>

4.2 Specific Aim 1

The feedback group and control group both decreased the time they were able to hold the prone plank from baseline to four weeks post-initiation of the intervention, \( F_{(1,46)} = 15.132, P<0.001 \). The control group significantly decreased the time they...
were able to hold the left plank compared to the feedback group, $F_{(1,46)}= 6.032, P= 0.018$. Both groups increased their posterolateral reach distance from baseline to four weeks post-initiation of the intervention, $F_{(1,46)}= 12.629, P= 0.001$. No statistical differences were found between groups or over time for spinal reflex excitability, corticospinal excitability, quadriceps strength, hip strength, hip ROM, knee ROM, the right plank, the extension plank, anterior reach, and posteromedial reach (Table 2).

Table 2: Pre and Four Weeks Post-Initiation of the Intervention Means and Standard Deviations for the Dominant Limb

<table>
<thead>
<tr>
<th>Variables</th>
<th>Feedback</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre</td>
<td>Post</td>
</tr>
<tr>
<td>H:M</td>
<td>0.12±0.11</td>
<td>0.15±0.13</td>
</tr>
<tr>
<td>AMT (% machine output)</td>
<td>38.71±12.43</td>
<td>37.84±13.62</td>
</tr>
<tr>
<td>Quadriceps Strength (Nm/kg)</td>
<td>2.73±0.58</td>
<td>2.71±0.70</td>
</tr>
<tr>
<td>Hip Abduction Strength (N/kg)</td>
<td>3.03±0.97</td>
<td>2.93±0.79</td>
</tr>
<tr>
<td>Hip Extension Strength (N/kg)</td>
<td>2.06±0.69</td>
<td>2.01±0.75</td>
</tr>
<tr>
<td>Hip Extension ROM (°)</td>
<td>22.38±5.08</td>
<td>22.66±6.01</td>
</tr>
<tr>
<td>Hip IR ROM (°)</td>
<td>37.88±8.07</td>
<td>38.66±9.08</td>
</tr>
<tr>
<td>Hip ER ROM (°)</td>
<td>33.88±8.76</td>
<td>33.56±8.18</td>
</tr>
<tr>
<td>Knee Flexion ROM (°)</td>
<td>142.63±4.57</td>
<td>142.16±5.76</td>
</tr>
<tr>
<td>Prone Plank (s)</td>
<td>85.25±36.25</td>
<td>72.45±34.24*</td>
</tr>
<tr>
<td>Left Plank (s)</td>
<td>39.53±18.13</td>
<td>37.40±21.03*#</td>
</tr>
<tr>
<td>Right Plank (s)</td>
<td>46.49±24.10</td>
<td>46.31±25.75</td>
</tr>
</tbody>
</table>
### Specific Aim 2

The feedback group and control group both significantly increased their vertical jump performance from baseline to four weeks post-initiation of the intervention, $F_{(1,46)}=5.101$, $P=0.029$ (Table 3).

**Table 3: Pre and Four Weeks Post-Initiation of the Intervention Means and Standard Deviations for Vertical Jump Maximum**

<table>
<thead>
<tr>
<th>Variables</th>
<th>Feedback</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical Jump Maximum (in)</td>
<td>13.69±3.75</td>
<td>13.28±3.81</td>
</tr>
<tr>
<td></td>
<td>14.88±3.15*</td>
<td>14.06±2.01*</td>
</tr>
</tbody>
</table>

*Significantly different from baseline

### Exploratory Aim 1

A weak, negative correlation was found between dominant knee abduction angle and dominant AMT at baseline, $r_{(46)}=-0.360$, $P=0.014$. A moderate, positive correlation was found between dominant knee abduction angle and knee flexion ROM at baseline, $r_{(46)}=0.309$, $P=0.033$. There were no other significant correlations for spinal reflex excitability, quadriceps strength, hip strength, hip ROM, core endurance and balance (Table 4).
Table 4: Pearson and Spearman correlation matrix analyzing associations among clinical impairments in the dominant limb and knee abduction angle in the dominant limb at baseline

<table>
<thead>
<tr>
<th></th>
<th>Knee Abduction Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>H:M</td>
<td>$r_s = -0.032$</td>
</tr>
<tr>
<td>AMT</td>
<td>$r_s = -0.360^*$</td>
</tr>
<tr>
<td>Quadriceps Strength</td>
<td>$r = 0.049$</td>
</tr>
<tr>
<td>Hip Abduction Strength</td>
<td>$r = -0.014$</td>
</tr>
<tr>
<td>Hip Extension Strength</td>
<td>$r = 0.188$</td>
</tr>
<tr>
<td>Hip Extension ROM</td>
<td>$r = 0.144$</td>
</tr>
<tr>
<td>Hip External Rotation ROM</td>
<td>$r_s = 0.104$</td>
</tr>
<tr>
<td>Hip External Rotation ROM</td>
<td>$r_s = 0.110$</td>
</tr>
<tr>
<td>Knee Flexion ROM</td>
<td>$r = 0.309^*$</td>
</tr>
<tr>
<td>Prone Plank</td>
<td>$r = -0.125$</td>
</tr>
<tr>
<td>Left Plank</td>
<td>$r = -0.118$</td>
</tr>
<tr>
<td>Right Plank</td>
<td>$r_s = -0.112$</td>
</tr>
<tr>
<td>Extension Plank</td>
<td>$r = 0.059$</td>
</tr>
<tr>
<td>Anterior Reach (SEBT)</td>
<td>$r_s = 0.149$</td>
</tr>
<tr>
<td>Posteromedial Reach (SEBT)</td>
<td>$r = -0.083$</td>
</tr>
<tr>
<td>Posterolateral Reach (SEBT)</td>
<td>$r_s = -0.157$</td>
</tr>
</tbody>
</table>

Abbreviations: H:M, Hoffmann reflex normalized to maximal muscle response; AMT, active motor threshold; ROM, range of motion

*denotes significant correlation at $P \leq 0.05$.

4.5 Exploratory Aim 2

A weak, positive correlation was found between the percent change in dominant knee abduction angle and the percent change in dominant H:M, $r_{(46)} = 0.318$, $P = 0.038$. A weak, negative correlation was found between the percent change in dominant knee abduction angle and the percent change in dominant hip external...
rotation range of motion, $r_{(40)}= -0.359$, $P= 0.019$. There were no other significant correlations for cortical motor evoked potentials, quadriceps strength, hip strength, knee flexion ROM, hip extension ROM, hip internal rotation ROM, core endurance and balance (Table 5).

**Table 5:** Pearson and Spearman correlation matrix analyzing associations among the percent change in clinical impairments in the dominant limb and the percent change in knee abduction angle in the dominant limb from baseline to four weeks post-initiation of the intervention

<table>
<thead>
<tr>
<th></th>
<th>Knee Abduction Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>H:M</td>
<td>$r_s= 0.318^*$</td>
</tr>
<tr>
<td>AMT</td>
<td>$r_s= -0.097$</td>
</tr>
<tr>
<td>Quadriceps Strength</td>
<td>$r= -0.002$</td>
</tr>
<tr>
<td>Hip Abduction Strength</td>
<td>$r= -0.009$</td>
</tr>
<tr>
<td>Hip Extension Strength</td>
<td>$r_s= -0.165$</td>
</tr>
<tr>
<td>Hip Extension ROM</td>
<td>$r_s= 0.021$</td>
</tr>
<tr>
<td>Hip Internal Rotation ROM</td>
<td>$r= -0.253$</td>
</tr>
<tr>
<td>Hip External Rotation ROM</td>
<td>$r_s= -0.359^*$</td>
</tr>
<tr>
<td>Knee Flexion ROM</td>
<td>$r= -0.064$</td>
</tr>
<tr>
<td>Prone Plank</td>
<td>$r= 0.045$</td>
</tr>
<tr>
<td>Left Plank</td>
<td>$r= -0.037$</td>
</tr>
<tr>
<td>Right Plank</td>
<td>$r_s= 0.004$</td>
</tr>
<tr>
<td>Extension Plank</td>
<td>$r= 0.143$</td>
</tr>
<tr>
<td>Anterior Reach (SEBT)</td>
<td>$r= 0.086$</td>
</tr>
<tr>
<td>Posteromedial Reach (SEBT)</td>
<td>$r= 0.003$</td>
</tr>
<tr>
<td>Posterolateral Reach (SEBT)</td>
<td>$r= 0.026$</td>
</tr>
<tr>
<td>Vertical Jump Maximum</td>
<td>$r= 0.078$</td>
</tr>
</tbody>
</table>

Abbreviations: H:M, Hoffmann reflex normalized to maximal muscle response; AMT, active motor threshold; ROM, range of motion

*denotes significant correlation at $P \leq 0.05$. 

64
Chapter 5

Discussion

Verbal and visual feedback has been suggested to enhance the efficacy of ACL injury prevention programs. This study sought to determine if a 4-week feedback intervention could improve lower extremity biomechanics and functional performance measures.

5.1 Specific Aim 1

The feedback and control groups decreased the time they were able to hold the prone plank from baseline to four weeks post-initiation of the intervention. Additionally, the control group did not perform the left plank as well as the feedback group. Both groups demonstrated similar right plank performance before and after the intervention. We hypothesized that the feedback group would improve core endurance via engaging their core muscles during the intervention. However, our results suggest that the jump-landing intervention did not influence core endurance. Biomechanically, the core is responsible for positioning about half of an athlete’s body mass over the lower extremity, making it a large influence of lower extremity injury by altering the loads placed on the joints of the lower extremity.55 Previous studies suggest that knee loading patterns implicated in ACL injury, including
increased knee abduction, were reduced by an intervention program that incorporated core strength. Interventions seeking to improve core endurance in conjunction with landing biomechanics may benefit from inclusion of exercises specifically targeting the core musculature.

The feedback group and control group both increased their posterolateral reach distance from baseline to four weeks post-initiation of the intervention. Both groups demonstrated similar anterior reach and posteromedial reach performance before and after the intervention. We hypothesized that the feedback group would improve balance as dynamic measures of postural-control closely mimic the demands of a jump landing task by involving some level of expected movement around a base of support. However, our results suggest that the jump-landing intervention did not influence balance. Shorter normalized reaching distances have been linked to decreased hip and knee flexion and decreased NMC abilities, risk factors that are often associated with poor jump landing biomechanics seen in females and are a significant contributor to increased risk of ACL injury. Previous studies suggest that knee loading patterns implicated in ACL injury were reduced by an intervention program that incorporated balance. Previous studies have suggested that the inclusion of multiple neuromuscular training components, including balance, may provide some level of ACL risk reduction. Our results suggest that dynamic balance may need to be targeted directly in conjunction with a feedback intervention program in order to improve balance. Our results may also suggest that a single-leg dynamic balance task does not relate to a double-leg jump landing task.
The feedback and control groups demonstrated similar AMT and H:M before and after a four week feedback intervention. We hypothesized that cortical excitability of the vastus lateralis would be increased and spinal reflex excitability would be decreased from baseline to four weeks post-initiation of the intervention in those participants who received feedback. However, our results suggest that the jump-landing intervention did not influence cortical or spinal reflex excitability. Previous studies suggest that feedback intervention programs may prompt individuals to make cortically driven changes in neuromuscular function, but there are currently no data to support these changes. Our results suggest that the changes made are not cortically driven via AMT measurements. We may have seen different results if we used alternative measures of cortical excitability, including paired pulse measures of facilitation and inhibition. Previous studies have not assessed the effect of a feedback intervention on H-reflex of the quadriceps musculature.

The feedback and control groups demonstrated similar quadriceps and hip strength before and after a four week feedback intervention. We hypothesized that individuals would gain increased muscle control and coordination of their quadriceps and hip musculature during the intervention, and thereby increase force production of their quadriceps and hip musculature. However, our data does not support this hypothesis. We may have not seen changes in force production because strength training was not specifically targeted in conjunction with the intervention.

5.2 Specific Aim 2

The feedback group and control group both increased their vertical jump performance from baseline to four weeks post-initiation of the intervention. This
finding suggests that in accordance with our hypothesis, performance was not compromised as a result of our intervention. An intervention program that is found to be effective in preventing ACL injury, but decreases performance, will not appeal to most athletes. Optimizing an intervention program that is physiologically effective and coincidentally increases performance will better appeal to clinicians, athletes, and coaches.

5.3 Exploratory Aim 1

At baseline, participants who demonstrated a greater knee abduction angle, indicating less control of movement during a jump landing task, also demonstrated a lower AMT. This inverse relation was contrary to our expectations. As a patient is better able to control his/her knee abduction angle during a jump landing task, we expected to see increased corticospinal excitability, and thereby a decreased AMT. Our results suggest that the quadriceps may be activating to stop excessive knee abduction, but are just unable to because they do not have a sufficient moment arm to control knee abduction. Although the quadriceps muscles play a role in preventing excessive knee abduction, they are not the primary muscle to do so.\textsuperscript{73} The gluteus medius is the primary muscle that controls frontal plane postures at the knee.\textsuperscript{73} Taking measurements of corticospinal excitability of the gluteus medius may have provided some insight in order to truly understand how control of knee abduction angle changes as a result of this type of intervention. However, previous research has suggested that corticospinal excitability of the gluteal muscles does not influence landing mechanics.\textsuperscript{74} Further research is needed to determine the relationship between gluteal corticospinal excitability and landing biomechanics.
At baseline, participants who demonstrated a greater knee abduction angle also demonstrated greater knee flexion ROM. It is not clear why this relation exists. However, it is possible that the greater knee flexion ROM suggests a greater overall ROM available at the knee joint. During dynamic activity, this could translate to an increase in the knee abduction angle. Additional research is needed to further our understanding of this relation.

Spinal reflex excitability, quadriceps strength, hip strength, hip ROM, core endurance, and balance were not associated with knee abduction angle at baseline during a jump landing task. Ours is the first investigation to explore the association between these variables. While we explored the relation between these variables and knee abduction angle given its implication in the non-contact ACL injury mechanism, it is possible that these variables are more closely related to other factors that contribute to ACL injury risk, including knee flexion angle.

5.4 Exploratory Aim 2

We found a weak, positive correlation between dominant limb knee abduction angle and dominant limb H:M. We hypothesized that spinal reflex excitability would decrease from baseline to four weeks post-initiation of the intervention in those participants who received feedback. Therefore, we expected to see that as our participants went through the intervention, they would decrease knee abduction angle and concurrently decrease spinal reflex excitability. Our results do suggest that as knee abduction angle decreases, spinal reflex excitability also decreases. Why corticospinal excitability did not change in conjunction with spinal reflex excitability is unclear but may suggest a more spinally-mediated control strategy was adopted by
the participants in this study. Our study is the first to assess the correlation between changes in knee abduction angle via a feedback intervention and changes in spinal reflex excitability.

We found a weak, negative correlation between dominant limb knee abduction angle and dominant limb hip external rotation range of motion. We hypothesized that ROM would not change from baseline to four weeks post-initiation of the intervention. Our results suggest that as knee abduction angle decreases, hip external rotation ROM increases. Previous literature has demonstrated that females perform maneuvers such as landing from a jump, cutting and pivoting with less knee and hip flexion, increased knee valgus, increased internal rotation of the hip coupled with increased external rotation of the tibia, and increased quadriceps muscle activation.8 Our participants were pre-screened and included only if they exhibited dynamic knee valgus. The gluteus medius and gluteus maximus play a vital role during weight-bearing, as these muscles eccentrically contract to regulate the proximal component of dynamic knee valgus, such as internal rotation and adduction of the femur.75,76 If participants were making a change in knee abduction angle, they may have also began externally rotating their hip more by activating their gluteal musculature in order to control internal rotation and adduction of the femur, and therefore land in a neutral valgus/varus position with their feet shoulder width apart.

We did not see a significant correlation between changes in AMT, quadriceps strength, hip strength, knee ROM, core endurance, or balance, and changes in knee abduction angle. We hypothesized that there would be a decrease in AMT, an increase in quadriceps strength, an increase in hip strength, no change in knee ROM,
an increase in core endurance and an increase in balance in those participants receiving feedback from baseline to four week post-initiation of the intervention. Therefore, we expected those changes to occur as participants also decreased their hip abduction angle. However, our results show that there was not a significant correlation between these measures. As stated previously, our results may suggest a more spinally-mediated control strategy was adopted by the participants in this study.

5.5 Other Main Points

This study only used physically active individuals. Participants had to have a BMI less than 30 kg/m², and they had to be physically active at a level of at least three times per week for at least 30 minutes each time. Participants filled out the Godin-Lesuire Time Exercise questionnaire prior to the start of the study. We advised participants to avoid making drastic changes in their workout routine through the duration of the intervention, but we did not monitor for this or have them fill out the Godin at the conclusion of the intervention. Our results suggest that physical activity levels did not have an influence as there were not differences between groups at baseline. Future studies should be careful to monitor changes in exercise routine throughout the duration of the intervention. Previous studies have suggested using the reported frequency of strenuous and moderate activities to compute a health contribution score. The following rule has been recommended: 24 units or more is considered active with substantial benefits, 14-23 units is considered moderately active with some benefits, and less than 14 units is considered insufficiently active with low benefits. Based on this rule, on average both groups of subjects were considered active with substantial benefits.
During core endurance testing, the investigator did not provide any feedback or encouragement to the participant. In future studies, the investigator should give consistent encouragement between participants in order to ensure the participant is giving forth their best effort. Also, due to the repeated measures design, the participants may have grown more comfortable and skilled at specific movements. The increase in performance seen with the posterolateral reach in the SEBT and the maximum vertical jump test with the Vertec could be due to a learning effect, in which the participants may have grown more comfortable and skilled at those specific movements. If there was a greater change in knee abduction angle in our participants, we may have seen greater associations with our clinical impairments. Future studies should evaluate the correlation between clinical impairments and other kinetic and kinematic measures, as our participants did not have a change in knee abduction angle, in those who respond positively to feedback and those who do not.

5.6 Limitations

Assessing levels of cortical excitability is also highly dependent on the state of the subject being tested. Levels of corticospinal excitability could increase or decrease outcome measures for the separate testing sessions depending on their ability to remain quiet and clear their mind. However, consistent instruction was provided throughout all testing sessions and to all participants to clear their mind and stay focused.

An additional limitation is that there was no way to ensure the testing equipment, including electrodes, goniometers, swim caps, etc., was placed in the exact same location for all testing sessions, as the testing sessions were four weeks
apart from each other. However, the placement of the testing equipment was standardized to try to account for any differences.

5.7 Conclusion

In conclusion, there was not a significant change in spinal reflexive excitability, corticospinal excitability, quadriceps strength, hip strength, balance, and performance before and after a four week jump landing intervention compared to a control group. The control group significantly decreased the time they were able to hold the left plank compared to the feedback group. Those participants who demonstrated a greater knee abduction angle also demonstrated a lower AMT and increased knee flexion ROM. As knee abduction angle decreased, spinal reflex excitability decreased and hip external rotation ROM increased. Optimizing feedback is pivotal in determining an intervention that is both monetarily and physiologically beneficial in prophylactically treating ACL injury. Future studies should aim to determine whether there is a significant interaction between clinical impairments with other kinetic and kinematic measures in those who respond positively to feedback and those who do not during a jump landing task.
References


Appendix A

Informed Consent Form

ADULT RESEARCH SUBJECT INFORMATION AND CONSENT FORM

TESTING THE RETENTION AND TRANSFERABILITY OF A FOUR WEEK FEEDBACK INTERVENTION PROGRAM ON JUMP LANDING BIOMECHANICS.

Principal Investigator: Abbey Thomas PhD ATC

Other Staff (identified by role): Hayley Ericksen, Caitlin Lefevre, Phillip Gribble, Adam Lepley, Michelle McLeod (Co-Investigators)

Contact Phone number(s): (319) 290-5579

What you should know about this research study:

- We give you this consent/authorization form so that you may read about the purpose, risks, and benefits of this research study. All information in this form will be communicated to you verbally by the research staff as well.
Routine clinical care is based upon the best-known treatment and is provided with the main goal of helping the individual patient. The main goal of research studies is to gain knowledge that may help future patients.

We cannot promise that this research will benefit you.

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

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

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

PURPOSE (WHY THIS RESEARCH IS BEING DONE)
You are being asked to take part in a research study looking at feedback during a jump-landing task. The purpose of this study is to determine the effects of feedback provided during jump landing on your ability to distribute forces during landing and during a cutting maneuver immediately after an initial session and after a 4 week program as well as assessing a variety of additional factors that may contribute to your ability to land and cut. You were selected as someone who may want to take part in this study because you are categorized as a healthy female. There will be approximately 70 people participating in this study at the University of Toledo.

DESCRIPTION OF THE RESEARCH PROCEDURES AND DURATION OF YOUR INVOLVEMENT

If you decide to take part in this study, you will be asked to report to the Musculoskeletal Health and Movement Science Laboratory in the Health Science and Human Services building (Room 1412) and the Joint Injury and Muscle Activation Laboratory (Room 1409). During the initial visit, you will be asked to fill out the Godin Leisure-Time Exercise Questionnaire, a Sport Participation Questionnaire, the Foot and Ankle Disability Index (FADI), and an Injury History Questionnaire. We will then test joint angles and forces exhibited during a jump landing and a cutting maneuver. You may then be randomly put into a traditional feedback group, a real-time feedback group, or a control group, in which you may or may not receive verbal and/or visual feedback concerning your jump landing performance. You will report for an initial session lasting approximately one hour. All subjects in the
Feedback intervention groups will report 3 times per week for 4 weeks, for a total of 12 intervention sessions. Each feedback intervention session will last approximately 30 minutes. All participants will report for a post-intervention session that will last approximately 30 minutes.

In addition we will be testing your ability to balance through measurement of the Star Excursion Balance Test, how high you can jump, the strength in your hips and legs, your core endurance, range of motion of your hip and legs and the excitability of the muscles in your legs through reflex and motor cortex testing. This will take approximately 2 hours to complete.

**Landing Error Scoring System (LESS)**

Two video cameras will be set up 136 inches away from the force plate (which measures how hard you land), one in front of you and one to the side of you. You will be asked to jump off of a 30 cm box to a distance 50% of your height and upon landing, immediately rebound, jumping as high as you possibly can. After instruction of how to complete the task, you will be given as many practice trials as needed to familiarize yourself with the task. Three successful jumps will be recorded.

**Cutting Maneuver**

For the cutting maneuver, you will take a four step approach run toward the force plate and then perform a cut at a 60 degree angle to the right of the force plate. A path will be provided to you using a strip of tape that will be visible on the ground. After the cutting maneuver, you will sprint a short distance. You will again be provided with practice trials until both you and the examiner are comfortable with your ability to correctly perform the task. Five trials with adequate data will be collected for processing.

**Intervention**

After the initial visit, you may be randomly selected for a jumping intervention or a control intervention. During the jumping intervention, you will be asked to return to the lab 12 times in a four week period. The control intervention group will be asked not to change any of their normal daily activities and will be asked to return to the lab for several post-testing sessions approximately 4 weeks later.

For the intervention portion of this study, you may receive feedback regarding your jumps. If you do receive feedback you will be jumping off a 30 cm high box to a distance of 50% of your height and landing on a force plate. Participants in the feedback groups will complete approximately 36 jumps during each intervention session.

**Reflex Testing**
This testing provides an estimate of how well nerves in your legs are functioning. You will be instructed to lie on a table on both your stomach and your back, and you will have sticky electrodes placed on your lower legs and thigh. These electrodes are called EMG electrodes which stand for Electromyography and is a recording of the electrical (reflex) activity in skeletal muscle. The sites of the EMG electrodes will be shaved and cleaned with alcohol. An electrode will be taped behind your knee and in the front of your hip that provides a stimulus. Several reflex measurements will be taken while you are lying down.

- These measurements include a 1-millisecond stimulus.
- The intensity of this stimulus will vary depending on the reflex being elicited.
- The stimuli in this study feel similar to static electricity felt as you touch a door knob after walking across a carpet.
- A series of measurements will be taken on both legs

**Motor Cortex Testing**

This testing provides us important information regarding how your brain is sending messages to muscles in your legs. You will be asked to sit in a chair with your arms across your chest. We will position a coil over your head and adjust the position of the coil until it is in the correct spot. We will ask you to wear a bathing cap and ear plugs. A brief magnetic stimulus will then be produced which will sound like a “click.” You will not have any associated pain or discomfort in your head, but rather may feel a brief muscle contraction in the muscles of your leg or thigh. You will be asked to flex certain leg muscles at a small to moderate intensity while we provide a series of brief magnetic stimuli to your head.

**Strength Measurements**

In order to test the strength of your thigh muscles you will be seated in a chair with your knees flexed to 90 degrees. A strap will be placed over your lap and the lower part of your leg will be secured to the arm of the dynamometer. You will then be asked to forcefully extend your leg as hard as you can for a total of three trials. In the same position a hand held device used to measure force will be placed on the front of your lower leg and you will be asked to extend out as hard as you can into the device. To test the strength of your hips you will be laying on your stomach on a padded table. Your thigh will be secured onto the arm of the dynamometer and will be asked to lift your leg off of the table are forcefully as possible for 3 trials. Then the hand held device will be placed in the same location and you will be asked to lift your leg up as forcefully as possible. You will then be asked to lie on either side, with the arm of the dynamometer secured to your thigh and you will be asked to lift your leg up as forcefully as you can for three trials. Then you will be asked to lift your leg against the hand held device for three trials.
**Balance Testing**

The SEBT will be performed in the anterior, posteromedial, and posterolateral directions. For the anterior reach, you will stand with your toes on the grid line and reach out with the opposite foot to tap as far as possible along the tap measure without raising the test foot. For PM and PL directions, the heel will be at the gridline and you will reach back as far as possible in each direction to tap the measuring tape. Four practice trials are given followed by three test trials in each direction for a total of nine successful trials.

**Range of Motion Testing**

In order to test range of motion at your hip and knee we will use a goniometer, which is a small device which measures angles at your joints. You will be asked to perform certain motions at the knee and hip and we will measure how far you are able to move.

**Vertical Jump Testing**

In order to test your maximum vertical jump height, we will have you complete a standing vertical reach and a 2-footed maximum vertical jump. For the standing vertical reach you will reach as high as you can with your feet flat on the floor. For the 2-footed maximum vertical jump will reach as high as you can while jumping with both feet off the ground. You will perform the jumping trial three times to determine your maximum vertical jump height.

**Core Endurance Testing**

In order to test your core endurance you will perform 3-way planks and a plank lying on your stomach off of a table. The 3-way planks will be performed on a hard surface by propping yourself up onto your elbow(s). We will keep time of how long you are able to hold the position. For the prone plank test, you will lie on your stomach with your hips at the edge of a table and your legs secured to the table. You will cross your arms over your chest and assume a horizontal position. We will take time with a stopwatch to determine how long you are able to maintain the horizontal position.

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

**Likely Risks**

- You could develop minor, transient muscle soreness from the jump landing or cutting tasks.
• Mild discomfort for a very brief period during the electrical stimulation.

**Less Likely Risks**
• You are at minimal risk of lower extremity injury during the jump-landing or cutting tasks.
• You are at a minimal risk of falling during the jump landing task.
• Mild, transient skin irritation from the sticky electrodes.

**Very Unlikely Risk**

• There are always possibilities that unknown side effects may occur during or following testing.
• Mild, transient headache following magnetic stimulation
  In people with a history of seizures there is a slight possibility of causing a seizure with the magnetic stimulation, therefore you must tell us prior to testing if you have ever had a seizure so we can exclude you from the study.

**ALL PARTICIPANTS WILL BE EXCLUDED IF THEY HAVE ANY OF THE FOLLOWING**

• Concussion or head injury in the past five months
• Stroke
• Cardiac Condition
• Epilepsy
• Cranial Neural Surgery
• Cancer in the brain or thigh musculature
• Diagnosed psychiatric disorder
• A cardiac pace maker
• Implanted cardiac defibrillator
• Intracranial magnetic clips

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

We cannot and do not guarantee or promise that you will receive any benefits from this research.

**RISKS TO UNBORN CHILDREN**

It is unknown how the electrical stimulation used in this study would affect an unborn fetus, therefore, if you are pregnant you will not be allowed to participate in this study.

**COST TO YOU FOR TAKING PART IN THIS STUDY**
You are not directly responsible for making any type of payment to take part in this study. However, you are responsible for providing the means of transportation to the Biomechanics/Athletic Training Research Laboratory. You will not be compensated for gas for travel or any other expenses to participate in this study.

**ALTERNATIVE(S) TO TAKING PART IN THIS RESEARCH**

*The only alternative is not to participate in this study.*

**CONFIDENTIALITY**

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

**IN THE EVENT OF A RESEARCH-RELATED INJURY**

In the event of injury resulting from you taking part in this study, treatment can be obtained at a health care facility of your choice. You should understand that the costs of such treatment will be your responsibility. Financial compensation is not available through The University of Toledo or The University of Toledo Medical Center. By signing this form, you are not giving up any of your legal rights as a research subject. In the event of an injury, contact Brian Pietrosimone, PhD, ATC (419) 530-4467.

**VOLUNTARY PARTICIPATION**

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

**NEW FINDINGS**

You will be notified of new information that might change your decision to be in this study if any becomes available.
OFFER TO ANSWER QUESTIONS
Before you sign this form, please ask any questions on any aspect of this study that is unclear to you. You may take as much time as necessary to think it over. If you have questions regarding the research at any time before, during or after the study, you may contact: Dr. Brian Pietrosimone- (419) 530-4467

If you have questions beyond those answered by the research team or your rights as a research subject or research-related injuries, please feel free to contact the Chairperson of the University of Toledo Biomedical Institutional Review Board at 419-383-6796.

SIGNATURE SECTION (Please read carefully)

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

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

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

Name of Subject (please print) ____________________________ Signature of Subject or Person Authorized to Consent

Relationship to the Subject (Healthcare Power of Attorney authority or Legal Guardian) ____________________________

Name of Person Obtaining Consent (please print) ____________________________ Signature of Person Obtaining Consent
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<th>Name of Witness to Consent Process (when required by ICH Guidelines)</th>
<th>Signature of Witness to Consent Process (when required by ICH Guidelines)</th>
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</table>

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

Participant Paperwork

Godin Leisure-Time Exercise Questionnaire

1. During a typical 7-Day period (a week), how many times on the average do you do the following kinds of exercise for more than 15 minutes during your free time (write on each line the appropriate number).

Times Per Week

a) STRENUOUS EXERCISE
   (HEART BEATS RAPIDLY)
   (e.g., running, jogging, hockey, football, soccer, squash, basketball, cross country skiing, judo, roller skating, vigorous swimming, vigorous long distance bicycling)

b) MODERATE EXERCISE
   (NOT EXHAUSTING)
   (e.g., fast walking, baseball, tennis, easy bicycling, volleyball, badminton, easy swimming, alpine skiing, popular and folk dancing)

c) MILD EXERCISE
   (MINIMAL EFFORT)
   (e.g., yoga, archery, fishing from river bank, bowling, horseshoes, golf, snow-mobiling, easy walking)
2. During a typical 7-Day period (a week), in your leisure time, how often do you engage in any regular activity long enough to work up a sweat (heart beats rapidly)?

1. Often _______
2. Sometimes _______
3. Rarely/Never _______
Please indicate type and level of sport participation by checking the box.

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<td>Tennis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Swimming</td>
<td></td>
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</tr>
<tr>
<td>Other:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Have you previously participated in any formal jump training or injury prevention program?
Yes  No

If yes:
- How long ago did you participate in the program?_____________________________
- How long was the program?______________________________________
- Who ran the program? i.e: coach, athletic trainer, physical therapist etc.________________________________________
**Please Circle (Yes or No) regarding your situation.**

<table>
<thead>
<tr>
<th>Yes</th>
<th>No</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>No</td>
<td>Have you had an injury to either leg that has altered your function in the past 6 months?</td>
</tr>
<tr>
<td>Yes</td>
<td>No</td>
<td>Have you had a surgery to either leg (knee, ankle, hip) in the past six months (other than meniscectomy)?</td>
</tr>
<tr>
<td>Yes</td>
<td>No</td>
<td>Do you have any ruptured knee ligaments that have not been reconstructed?</td>
</tr>
<tr>
<td>Yes</td>
<td>No</td>
<td>Do you have any nerve injuries in your legs or lower back?</td>
</tr>
<tr>
<td>Yes</td>
<td>No</td>
<td>Do you have any known muscular abnormalities?</td>
</tr>
<tr>
<td>Yes</td>
<td>No</td>
<td>Do you have a heart condition that would stop you from exercising?</td>
</tr>
<tr>
<td>Yes</td>
<td>No</td>
<td>Have you ever been diagnosed with cancer over your knee or thigh?</td>
</tr>
<tr>
<td>Yes</td>
<td>No</td>
<td>Do you currently have an infection over your thigh or in your knee?</td>
</tr>
<tr>
<td>Yes</td>
<td>No</td>
<td>Do you know of a hypersensitivity to electrical stimulation?</td>
</tr>
</tbody>
</table>

1. **Which leg would you choose to kick a ball with?** R  L

2. **Have you ever had a knee injury?**

   When (month / year): ____________________ Which leg? R  L

   Explain: ________________________________________________________________

3. **Have you ever had a knee Surgery?**

   When (month / year): ____________________ Which leg? R  L

   Explain: ________________________________________________________________

   Was there subsequent meniscal injury? Yes  No

   If yes, was it repaired? Yes  No  Unknown

   If ACL Reconstruction, What graft type?

4. **Did you participate in physical therapy or therapeutic exercise?**

   When did you start (month / year): ____________________

   For How Long: ____________________

5. **Have you ever had an injury/surgery to you ankle, hip or lower back?**

   When (month / year): ____________________

   Explain: ________________________________________________________________
Musculoskeletal Health and Movement Sciences Laboratory
Transcranial Magnetic Stimulation (TMS) Screening Questionnaire

1. Height: __________  Weight: __________  BMI: __________ (calculated by investigators)

2. Do you currently have pain in either knee?  Yes  No
   a. If yes, please rate your pain from 0 to 10 (0= no pain, 10= worst pain imaginable)
   b. Left: ________/10  Right: ________/10

3. Do you currently have any pain or medical conditions that limit your function?  Yes  No
   a. If yes, please describe

___________________________________________________
___________________________________________________
___________________________________________________
_________________________________________________________________

4. Have you suffered a back or leg injury in the past 6 months?  Yes  No
   a. If yes, please describe

______________________________________________________________
______________________________________________________________

5. Have you ever had surgery to your back or legs?  Yes  No
   a. If yes, please describe

______________________________________________________________
______________________________________________________________

6. Do you smoke?  Yes  No

7. Do you have any of the following conditions:
   a. Fibromyalgia  Yes  No
   b. Diabetes  Yes  No
   c. Peripheral neuropathy (numbness, tingling, loss of sensation in hands or feet)
      Yes  No
   d. Heart disease  Yes  No
   e. Migraine headaches  Yes  No
8. Do you have any metal implants anywhere in your head, neck, or shoulders (excluding dental work)?
   Yes   No

9. Do you or any immediate family members have a history of seizures or epilepsy? Yes
   No

10. Has your physician ever diagnosed you with a neurologic disorder such as Parkinson’s disease, Multiple Sclerosis, or stroke? Yes
    No

11. Do you have any of the following in your body:
   a. Foreign objects in your eyes   Yes   No
   b. Cochlear (ear) implants   Yes   No
   c. Implanted brain stimulator   Yes   No
   d. Aneurysm clip   Yes   No
   e. Implanted medication pump   Yes   No
   f. Cardiac pacemaker   Yes   No
   g. Intra-cardiac lines   Yes   No

12. Is there a chance you could be pregnant? Yes   No

13. Have you ever suffered a serious head injury (including concussion)? Yes   No

   If yes, please answer the following questions:

   a. When did your head injury occur?
      ____________________________________________________________
   
   b. Did you lose consciousness?
      ____________________________________________________________

   c. Do you suffer from any memory loss as a result of your head injury? Yes
      No

14. Do you currently, or have you ever, had a condition that increases the pressure within your brain? Yes   No

15. Do you have a history of illicit drug use, alcohol abuse, or are you currently withdrawing from any substance? Yes   No
16. What medications are you currently taking? Please list all prescription and over the counter medications.

______________________________________________________________________
______________________________________________________________________
______________________________________________________________________
______________________________________________________________________
______________________________________________________________________

Investigator performing screening:

______________________________________________________________________

To be collected only if participant is eligible:

Name: ________________________________________________________________ Date:   

Date of birth: ______________________ Age: ______

Phone: ____________________________ Alternate Phone:                  

Email: ______________________________________________________________


Foot and Ankle Ability Measure (FAAM) Activities of Daily Living Subscale

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).

No Slight Moderate Extreme Unable N/A
Difficulty Difficulty Difficulty Difficulty to do
Standing □ □ □ □ □
Walking on even □ □ □ □ □
Ground
Walking on even ground □ □ □ □ □
without shoes
Walking up hills □ □ □ □ □
Walking down hills □ □ □ □ □
Going up stairs □ □ □ □ □
Going down stairs □ □ □ □ □
Walking on uneven ground □ □ □ □ □
Stepping up and down curbs □ □ □ □ □
Squatting □ □ □ □ □
Coming up on your toes □ □ □ □ □
Walking initially □ □ □ □ □
Walking 5 minutes or less □ □ □ □ □
Walking approximately 10 minutes □ □ □ □ □
Walking 15 minutes or greater □ □ □ □ □

Foot and Ankle Ability Measure (FAAM) Activities of Daily Living Subscale
Page 2

Because of your foot and ankle how much difficulty do you have with:
No Slight Moderate Extreme Unable N/A
Difficulty Difficulty Difficulty Difficulty to do
at all
Home responsibilities □ □ □ □ □
Activities of daily living □ □ □ □ □
Personal care □ □ □ □ □
Light to moderate work □ □ □ □ □
(standing, walking)
Heavy work □ □ □ □ □
(push/pulling,
climbing, carrying)
Recreational activities □ □ □ □ □

How would you rate your current level of function during your usual activities of daily living from 0 to 100 with 100 being your level of function prior to your foot or ankle problem and 0 being the inability to perform any of your usual daily activities.

**Foot and Ankle Ability Measure (FAAM)**

**Sports Subscale**

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

- No
- Slight
- Moderate
- Extreme
- Unable
- N/A

- Difficulty to do
- Difficulty
- Difficulty
- Difficulty
- Difficulty

- Running — — — — —
- Jumping — — — — —
- Landing — — — — —
- Starting and stopping quickly
- Cutting/lateral — — — — —
- Movements
- Ability to perform — — — — —
- Activity with your Normal technique
- Ability to participate — — — — —
- In your desired sport
- As long as you like

How would you rate your current level of function during your sports related activities from 0 to 100 with 100 being your level of function prior to your foot or ankle problem and 0 being the inability to perform any of your usual daily activities?

— — — 0%

Overall, how would you rate your current level of function?

- Normal
- Nearly Normal
- Abnormal
- Severely Abnormal

Appendix C

Marker Set

1. Cervical vertebra 7 (1)
2. Manubrium of sternum (1)
3. Acromioclavicular joints (2)
4. Right scapula (1)
5. Posterior Superior Iliac Spine (2)
6. Iliac crest (2)
7. Anterior Superior Iliac Spine (2)
8. Greater trochanter (2)
9. Anterior femur (2)
10. Patella (2)
11. Lateral femoral condyle (2)
12. Medial femoral condyle (2)
13. Tibial tuberosity (2)
14. Lateral shank (2)
15. Distal shank (2)
16. Medial malleolus (2)
17. Lateral malleolus (2)
18. Navicular (2)
19. 2\textsuperscript{nd} metatarsal head (2)
20. Great toe (2)
21. Base of the 5\textsuperscript{th} metatarsal (2)
22. Calcaneus (2)
Appendix D

Feedback PowerPoint

1. Landing with both feet at same time

Incorrect

Correct
2. Landing in a neutral knee valgus/varus position

Incorrect

Correct

3. Landing with Feet Shoulder Width Apart

Incorrect

Correct
4. Landing on your Toes, Rocking Back to your Heels

Incorrect

Correct

5. Landing with Increased Bending in your Knees and Hips

Incorrect

Correct
6. Landing Softly

- When landing be sure to land as softly as possible
- Use the sound of your feet hitting the floor as an indication of how hard you are landing
- Make adjustments as needed
Appendix E

Self-analysis Checklist for Landing

Which of the following do you think you accomplished in the last set of jumps?

#1—Landing with both feet at the same time?

#2—Landing with a neutral knee (not knock-kneed or bow-legged)?

#3—Landing with your feet shoulder width apart?

#4—Landing on your toes rocking back to your heels?

#5—Landing with increased bending in your knees?

#6—Landing with increased bending in your hips?

#7—Landing Softly?
Appendix F

Real-time Feedback Participant Visual

On box  

In air  

Landing