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Relationship of Cortical Excitability and Strength of the Gluteus Maximus and Gluteus Medius and Landing Biomechanics in Females

by

Allison M. Strouse, ATC

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

Dr. Brian Pietrosimone, Committee Chair

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May 2012
An Abstract of

Relationship of Cortical Excitability and Strength of the Gluteus Maximus and Gluteus Medius and Landing Biomechanics in Females

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Objective: To examine neuromuscular measures of the gluteus medius and gluteus maximus in healthy females, specifically strength and cortical excitability through measures of maximal isometric voluntary contraction (MVIC) and AMT respectively. It is of interest to identify if a relationship exists between these measures of neuromuscular function and lower extremity dynamic jump-landing mechanics as scored by the Landing Error Scoring System (LESS). Design and Setting: Pearson Product Moment correlation matrixes were performed for the predictor dependent variables, active motor threshold (AMT), motor evoked potentials (MEP), maximal voluntary isometric contractions (MVIC) and the criterion dependent variable, Landing Error Scoring System (LESS) scores. Significance was set as P≤0.05. All data was collected in a research laboratory. Subjects: 40 healthy females (21.08±2.15 yrs; 164.8±5.9 cm; 65.4±12.0 kg) participated in this study. Measurements: To assess MVIC, a Biodex System 2 Pro inclinometer was used. AMT measurements were taken with a Magstim Rapid. Dynamic Jump-landing was recorded using two video cameras, sampling at 60 Hz, and placed 136 inches away from a force plate with one in the frontal plane and one in the sagittal plane. Results: A moderate, positive correlation was found between dominate gluteus maximus MEP and
LESS scores ($r = 0.666$, $p=0.007$). No other significant correlations were obtained for MVIC, AMT, or MEP for the gluteus maximus and gluteus medius, regardless of limb.

**Conclusions:** No substantial relationship was found between gluteal MVIC and measures of cortical excitability with a clinical measure of jump-landing biomechanics. Future research is needed to understand the effect cortical level pathways have on neuromuscular control and jump-landing biomechanics.
I would like to dedicate this paper to my parents, Robert and Susan Strouse, who have shown me throughout my life how love, hard work, and perseverance, are never wasted. Thank you, always, for your love and support.
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List of Abbreviations

AMT = Active Motor Threshold
EMG = Electromyography
ERLP = Exercise-related Leg Pain
LBP = Low Back Pain
LESS = Landing Error Scoring System
MEP = Motor Evoked Potential
MVIC = Maximal Voluntary Isometric Contraction
PFPS = Patellofemoral Pain Syndrome
TMS = Transcranial Magnetic Stimulation
Chapter One

Introduction

The hip/pelvic complex, composed of the sacroiliac and acetabulofemoral joints, serves as the link between the trunk and lower extremity. Normal function of these joints is important for proper function of the spine and distal lower extremity joints, such as the knee and ankle. The gluteus medius and gluteus maximus have important roles in dynamic stabilization of the pelvis and femur, both working eccentrically to decelerate hip adduction and hip internal rotation. The gluteus maximus concentrically controls hip extension and external rotation, while the gluteus medius concentrically abducts the femur. Dysfunction of the gluteus maximus and gluteus medius has been linked to lower extremity joint injuries, altered posture, muscular imbalances, and neuromuscular inhibition of surrounding musculature. Impairment of both gluteal muscles is specifically associated with patellofemoral pain syndrome (PFPS), and low back pain.

A common technique used to examine coordination of the lower extremity is dynamic jump-landing. This functional screening method allows researchers and clinicians to observe and measure visual altered kinematics, which have been associated as risk factors for common lower extremity injuries. Current literature suggests that increased hip internal rotation during dynamic jump-landing increases risk of injury. Reduced activation of hip external rotators, such as the gluteus maximus, could lead to excessive hip adduction and valgus knee positions. It is well documented that females tend to land in a more valgus position at the knee and with a more extended hip then
males during single-leg landing.\textsuperscript{2,8} Research suggests this may be the result of either muscle weakness or altered neuromuscular control of the gluteal muscles.\textsuperscript{2} Individuals with poor landing mechanics may not have the necessary neuromuscular control patterns to counteract these potentially harmful forces and positions, especially at the knee.

Altered neural pathways, such as cortical and spinal reflexive, may contribute to diminished muscle strength and activation deficits, representing a possible factor affecting jump-landing mechanics. Transcranial magnetic stimulation (TMS) is commonly used to measure cortical excitability of muscle tissue.\textsuperscript{9-12} Through the use of TMS, researchers can quantify active motor threshold (AMT), or the lowest level of stimulation capable of causing a measurable muscle response.\textsuperscript{9} A higher AMT signifies decreased corticomotor excitability because more magnetic energy is needed to produce a motor evoked potential.\textsuperscript{11,12} This technique has previously been used on muscles of the upper and lower extremities, indicating a positive correlative relationship between muscle weakness or neuromuscular control deficits, and higher AMT. This suggests that cortical excitability plays a role in altered sensory feedback of the limbs resulting from pain, disuse or restriction.\textsuperscript{13} Decreased cortical excitability may lead to altered gait and possibly joint degeneration.\textsuperscript{10,13} However, there is limited research investigating cortical pathway measures in the gluteal muscles, and the potential effect they may have on altering mechanics during functional task performances, such as a jump-landing.

As a cost effective clinical tool, the Landing Error Scoring System (LESS) objectively identifies individuals with poor dynamic jump-landing mechanics. Originally created to determine risk factors for non-contact anterior cruciate ligament (ACL)
injuries, the LESS critiques movement patterns and landing techniques from both the sagittal and frontal planes. Currently, literature has established the LESS as both a valid and reliable clinical assessment tool for identifying altered jump-landing mechanics, such as decreased knee and hip flexion angles, increased knee valgus angles, and increased internal knee and hip internal rotation moments.

It is important to determine the mechanisms leading to appropriate jump-landing mechanics, as alterations can potentially lead to lower extremity injury. As indicated by previous research, the gluteal muscles play a dynamic role in stabilization of the pelvis, with potential neuromuscular deficits compromising normal joint movements associated with dynamic tasks, such as a jump-landing. Understanding the effect neuromuscular measures of gluteal muscles, such as strength and cortical excitability, have on jump-landing mechanics, as measured by the LESS, is imperative to future injury prevention and rehabilitation protocols.

1.1 Statement of the problem

Gluteus maximus and gluteus medius dysfunction may be both a cause of and result from lower extremity joint injury in females. This neuromuscular dysfunction often results in altered biomechanics during functional tasks, such as dynamic jump-landing, which have been associated with an increased risk of lower extremity joint injury. If impairments exist in gluteus maximus or gluteus medius strength and/or cortical excitability, this may result in less optimal jump-landing mechanics, which in turn may increase the risk of injury. Identifying factors associated with gluteal function and jump-
landing mechanics can help aid in the development and optimization of future lower extremity injury prevention and rehabilitation programs.

1.2 Statement of the Purpose

The gluteus medius and gluteus maximus muscles play a pivotal role in dynamic stabilization of the pelvis, specifically during jump-landing tasks. Neuromuscular measures of these muscles, such as strength and cortical excitability, can potentially influence mechanics of lower extremity joints during this jump-landing maneuver. Females, when compared to their male counterparts, have shown greater decrements in normal jump-landing mechanics. Therefore, the purpose of this investigation was to examine neuromuscular measures of the gluteus medius and gluteus maximus in healthy females, specifically strength and cortical excitability through measures of maximal isometric voluntary contraction (MVIC) and AMT respectively. It is of interest to identify if a relationship exists between these measures of neuromuscular function and lower extremity dynamic jump-landing mechanics as scored by the Landing Error Scoring System (LESS).

1.3 Significance of the Study

This study is significant in that it is one of the first to investigate cortical level neural pathways in the gluteal musculature. This study is also unique in that it focused solely on the gluteus medius and gluteus maximus in relation to dynamic jump-landing mechanics. This is one of the pioneer studies examining cortical excitability of the
gluteus medius and gluteus maximus and correlating that information to dynamic jump-landing techniques as scored by the LESS. The significance of using the LESS cannot be overlooked, as it is a cost effective clinical tool that any clinician can use to replicate and apply the information discovered in this investigation. Lastly, females have been shown to exhibit greater deficits in jump-landing mechanics, specifically demonstrating an increase in dynamic knee valgus. This information can be incorporated into the development of injury prevention programs, potentially leading to a reduction in lower extremity injury among this population.

1.4 Research Hypothesis

Current literature shows a correlation between decreased hip external rotation during dynamic jump-landing and injury rates, which may be due to poor landing biomechanics. There are recent studies that indicate a positive correlative relationship between muscle weakness or neuromuscular control deficits of the quadriceps and higher AMT, suggesting that cortical excitability plays a role in altered sensory feedback of the limbs from pain, disuse or restriction. Research also suggests that women with lower levels of neuromuscular control in the pelvis will demonstrate poor landing mechanics. Based on the existing literature, we hypothesize that strength and cortical excitability of both the gluteus maximus and gluteus medius will strongly correlate with LESS scores associated with dynamic jump-landing mechanics. We also hypothesize that there will be no statistically significant difference in all outcome measures between limbs.
1.6 Limitations

As with any research, this study was without limitation. In this investigation, the LESS was used to objectively measure joint kinematics, as opposed to the gold standard 3D videography. The LESS, however, has been shown to be a valid and reliable tool used to assess jump-landing biomechanics\textsuperscript{15} and additionally it is a commonly used clinical tool that is both cost effective and easy to administer.

This study employed only healthy subjects with no current lower extremity pathology. It is understood that these values will not be able to identify people with pathology; however, since this was the first study to specifically look at these outcomes, it was determined that a correlation must first be determined in healthy subjects before it is translated to and investigated in pathological populations.

Additionally, this study examined only females. However, females have been documented as having poor dynamic jump-landing mechanics as compared to males. By looking solely at females rather than males, we were more likely to identify LESS errors, and thus potentially find correlations.

Lastly, this study used only physically active individuals; however this population is most at risk for lower extremity injury during jump-landing tasks and is most often seen in clinical settings.
Chapter Two

Literature Review

2.1 Introduction

Muscles acting on the hip complex, specifically the gluteus medius and gluteus maximus, play a vital role in normal gait function and landing mechanics. It is therefore important for these muscles to demonstrate adequate strength, activation and timing to allow for proper kinematics within both daily activities and dynamic movements. Proper hip joint mechanics have been shown to directly affect function at the spine, knee and ankle joints. During the stance phase of the gait cycle, both the gluteus maximus and gluteus medius work eccentrically to decelerate hip adduction and hip internal rotation. Concentrically, the gluteus maximus controls hip extension and external rotation, while the gluteus medius functions to abduct the femur. Together, they provide both static and dynamic stability to the hip complex. Altered function of the gluteal muscles has the potential to significantly alter locomotion, leading to gait compensations and possibility of lower extremity joint injury.

Proper activation of the gluteus maximus and gluteus medius may be most significant during a dynamic jump-landing task. Jump-landing maneuvers require the lower extremity and trunk musculature to quickly respond to ground reaction forces and determine appropriate counter force and activation. These muscles must absorb the forces while maintaining joint stability in order to prevent any unwanted movements that would lead to possible injury. The jump-landing technique has been frequently used to
assess altered biomechanics and formulate comparisons of musculature between injured and healthy limbs.\textsuperscript{2,6,7,18-20} This dynamic task is a functional assessment of an activity routinely seen in many sporting activities, allowing researchers to generalize their findings and report applicable data to clinicians. The main focus of current jump-landing research revolves around the quadriceps musculature, although future examination is necessary to investigate the effects of other lower extremity musculature in response to dynamic activities.\textsuperscript{18,20} Currently, preliminary data involving muscle activation in the gluteal muscles during jump-landing exists,\textsuperscript{2,7,18,19} however evidence is limited. To better understand the entire kinetic chain during dynamic functional activities, gluteus maximus and gluteus medius involvement merits further study.

Another approach to studying gluteal function lies in cortical excitability. Fast becoming a widespread measurement, cortical excitability provides numerical data for central nervous system excitability.\textsuperscript{21} Measured by a method called Transcranial Magnetic Stimulation (TMS), cortical excitability quantifies the brain’s ability to control muscles tissue. Current TMS research focusing on the lower extremity investigates the quadriceps musculature,\textsuperscript{10-13,18} though similar methods could be conducted on any muscle, including the gluteus maximus and gluteus medius. In finding the active motor threshold (AMT), or the amount of stimulus required to cause a muscle twitch, researchers can determine what is defined as cortical excitability of the muscle.\textsuperscript{9} The smaller amount of stimulus needed to produce a muscle twitch equates to a more excitable and potentially active muscle.
2.2 Normal function of the gluteus medius

Function of the gluteus medius is dictated by both its anatomical position as well as its physiological characteristics. The primary roles of the gluteus medius include stabilization of the pelvis and controlling motion of the proximal femur during active lower extremity motion. The gluteus medius is a multipennate muscle, with multiple fiber orientations allowing for hip abduction as well as internal rotation. Fiber subdivisions are known as the anterior, middle, and posterior portions, which all act in accordance with muscle fiber direction. The fibers in the anterior and middle subdivisions align more vertically, suggesting higher function during internal rotation. The posterior fibers align more horizontally, correlating with lateral hip moments.

These different functional subdivisions allow for higher muscle activation and timing during different exercises. One study examined activity in all three subdivisions of the gluteus medius, noting dissimilarity in muscle activation during wall squats, pelvic drops, and wall presses between fiber directions. Although this research shows that different regions of the gluteus medius can produce higher muscle activation simultaneously, they also can work together synergistically. The muscle’s subdivisions allow the gluteus medius to adapt to the load demands being placed on the body at any given time. Other functions of the gluteus medius include preventing excessive lateral tracking of the patella and controlling hip abduction.
2.3 Normal function of the gluteus maximus

The gluteus maximus is a large muscle, superficial to the gluteus medius, concentrically responsible for hip extension and external rotation. The anatomical position of the gluteus maximus demonstrates an important link between the lower extremity and the trunk. This muscle is relied on to transfer kinetic forces between these two body segments, as exemplified by research involving gluteus maximus activity during stair-stepper exercise. This research investigated gluteus maximus metabolic muscle activation using an MRI during a short and long stair-stepper technique. Stair-stepper exercises appear to be helpful in addressing low back pain due to its ability to activate the gluteus maximus, and reduce forces applied at the lumbar spine.

Though the gluteus medius and gluteus maximus serve different chief tasks, their respective locations in the body link them together functionally. Since both the gluteus maximus and gluteus medius share a common eccentric function, any alteration of one of these muscles may cause the other to work harder to accommodate any weakness or dysfunction in the other. Their synergistic relationship makes them both central to lower extremity kinetics and kinematics, making normal gluteal function important in not only dynamic tasks, but also in activities of daily living.

2.4 Impaired function of the gluteal musculature

Impairment of the gluteus medius can result in altered gait and landing kinematics. Muscular imbalances, leg length discrepancy, and innominate rotations are among the most common causes, and also results, of gluteus medius impairments.
Varied postural behaviors and alterations in normal kinematics, such as compensations made to overcome pain from another lower extremity injury, can also result in abnormal gluteus medius function. Common adjustments include depression of the pelvis to the contralateral side, or a “hip-hiking” modified gait known as Trendelenburg gait, which can alter other lower extremity joint biomechanics. Weakness in the gluteus medius can also be caused by side-lying with the superior leg in an adducted position over the other leg, leading to modified lengthening of the posterior gluteus medius muscle fibers.\textsuperscript{4} Debilitating pain in the lumbar region, as well as other lower extremity areas, can also lead to impaired function of the gluteus medius. A previous investigation\textsuperscript{5} has found that hypertonic saline injections at the T5 joint of the lumbar spine, representing joint injury and swelling, led to a significant reduction of peak amplitude muscle activation of the gluteus medius by 39.6%.

Differences in gender have also been reported to predispose an individual to gluteus medius dysfunction. A decrease in strength of the gluteus medius in women has been shown to correlate with lack of frontal and transverse plane hip stabilization\textsuperscript{8}. This possibly demonstrates that dysfunction of the gluteus medius can cause facilitation and/or inhibition in surrounding musculature.\textsuperscript{8} However, this impairment was only found after a certain degree of hip and knee flexion during squats, and may not translate to more dynamic tasks. Further research is needed on gluteal muscle function through entire ranges of motion during sport specific movements to conclude more definitive inferences, specifically between genders.
Gluteus medius dysfunction may lead to profound effects on the proper kinematic motions at other joints, including the hip, knee, and trunk. The most profound effect of gluteus medius dysfunction is seen at the knee joint, most notably resulting in patellofemoral pain syndrome (PFPS). Impairment of the gluteus medius has shown to cause a decrease in pelvic stability, which can lead to an increased amount of femoral internal rotation. This abnormal rotation at the femur can often result in increased lateral patellar tracking. Brindle et al. 2003 reported both a delay and shorter duration of gluteus medius activation relative to the quadriceps muscles in patients with PFPS as they performed a stair-stepping task. Other investigations found similar delayed activation of the gluteus medius in patients with PFPS. This study specifically noted a delay in both the anterior and posterior fibers of the gluteus medius in symptomatic subjects. These studies show a correlation between neuromuscular dysfunction of the gluteus medius and PFPS, however, it remains unclear whether PFPS caused gluteus medius dysfunction, or if it was a result from the muscle impairment. Currently, there is limited research concerning neuromuscular activity of hip musculature in patients diagnosed with PFPS. Consequently, more research is needed to form a more confident conclusion about this relationship.

Along with knee pathologies, gluteus medius dysfunction has also been linked to exercise-related leg pain (ERLP). ERLP is defined as pain that is located between the knee and the ankle that is experienced during weight-bearing activities and is diminished when activities cease. Examples of ERLP include medial tibial stress syndrome, periostitis and stress fractures. As mentioned earlier, an increased external adduction
moment at the knee, often caused by gluteus medius dysfunction, can force rotation of the lower leg and foot medially, resulting in a varus force at the knee. These abnormal forces can lead to a plethora of acute and/or chronic lower extremity injuries. Delays in gluteus medius onset latency, as well as a shorter length of muscle activation, have been suggested to cause excessive frontal plane motion at the hip, resulting in disturbances at the knee joint, again, leading to gait abnormalities and possible injury in the lower extremity. Recent research supports the idea that a correlation exists between impaired gluteus medius function and lower leg pain and functional deficits. Greater severity of pain in ERLP has been shown to correlate with a greater impairments in the gluteus medius. These authors conclude that decreases in gluteus medius activation could be a predisposing factor in both the onset and reoccurrence of ERLP. Patients with chronic ankle instability have also shown similar gluteus medius dysfunction during inversion ankle perturbations, comparable to patients with anterior knee pain during a stair-climbing task.

Gluteus medius dysfunction does not only affect distal segments of the body, as it has been shown to increase the presence and severity of low back pain (LBP). This relationship is hypothesized to occur from altered hip joint function, which leads to altered sacroiliac (SI) and vertebral mechanics. SI dysfunction can lead to many significant factors leading to dysfunction of trunk mechanics. Patients with LBP have displayed decreased endurance and delayed firing patterns of hip extensor muscles, although there is little evidence regarding the role of hip abductors. These authors did note that participants who developed an onset of LBP during prolonged standing showed
co-activation of both the left and right gluteus medius muscles, as opposed to a synergistic reciprocal activation associated with healthy, pain-free individuals. Utilizing activation patterns of the gluteus medius, researchers were able to correctly guess 17 of the 23 (74%) participants that developed an onset of LBP. The authors suggest that their strong sensitivity value (0.87) shows that determining bilateral muscle co-activation of the gluteus medius may serve as a helpful screening tool in determining at-risk patients for developing LBP. More research is needed in order to further the evidence between not only hip external rotators and LBP, but also other pathologies arising at the knee, ankle, and lumbar spine. Restoring normal function of the gluteus medius may play a large role in the prevention and rehabilitation of many other pathologies.

Along with the gluteus medius, gluteus maximus impairment can both result from and cause lower extremity injuries, altered posture, muscular imbalances, and neuromuscular inhibition of surrounding musculature. Dysfunction of the gluteus maximus is not always a result from another injury, and can also lead to further pathology. For example, when neural firing patterns of the gluteus maximus become compromised, postural muscles such as the hamstrings or erector spinae become responsible for the gross movements of the gluteus maximus. This leads to increase torque on these muscles, which lay beyond their capabilities, possibly resulting in further injury. Limb load sensory feedback, which can become impaired in lower extremity injury, is thought to modulate hip torque. Impairments in this feedback can lead to further impairment of the gluteus maximus and consequently, hip torque production. There are limitations in the current evidence, lacking a close examination at the gluteus
maximus and its possible involvement in lower extremity pathology. As an integral link between the trunk and lower extremity and an important muscle in human locomotion, it is likely the gluteus maximus plays a part in dysfunction of the muscles and joints from both above and below.

This scenario often occurs with the hip and the knee joints, where compromised hip function leads to either direct injury of the knee, or a kinematic environment that predisposes the knee for chronic injury.\(^3,17\) Weak hip musculature, such as the gluteus maximus, may lead to an increase in hip internal rotation, increasing the valgus force at the knee, which often leads to further complications, such as a laterally tracking patella and increased risk for anterior cruciate ligament (ACL) rupture.\(^17\) Other factors, such as fatigue, may further propagate this relationship. Research has shown\(^20\) greater varus/valgus moments at the knee joint during jump-landing tasks in women following sessions designed to cause fatigue. A combination of preceding gluteus maximus weakness coupled with fatigue, a normal occurrence in athletic activity, places the knee in a compromised position that may predispose the joint to injury. Research examining a direct relationship between the gluteus maximus and knee joint injury is limited. Authors\(^2\) agree that further investigation is warranted to determine the extent that the hip muscles play in force attenuation at the knee. More research is needed to determine what effect the gluteus maximus has on lower extremity biomechanics as well as in the genesis of lower extremity injuries.
2.5 Dynamic jump-landing and gluteal musculature

Dynamic jump-landing techniques have been widely used to examine functional strength and coordination of lower extremity musculature.\textsuperscript{5,7} Joints in the lower extremity are protected from injury during functional activities through muscle stiffness, especially preparatory joint stiffness from the anticipation of forces placed upon the body.\textsuperscript{6} Dynamic jump-landing, through the use of electromyography (EMG), force platforms and measurement of joint angles, can determine a person’s ability to maintain neuromuscular control while shifting from a dynamic to a static state.\textsuperscript{6} Modifiable risk factors for common lower extremity injuries such as PFPS, as stated above, include weakness of the hip musculature and altered functional kinetics and kinematics.\textsuperscript{27} Specifically, an increase of knee valgus moments during dynamic landing due to weak hip musculature could lead to further injury among athletes. Greater hip external rotator activity may act to control internal rotation at the hip during dynamic jump-landing. Current research\textsuperscript{2,7} shows that less hip external rotator moments during dynamic jump-landing increases the chance of injury compared to those with greater hip external rotation moments. As a primary hip abductor, the gluteus medius, along with the gluteus maximus, provides control of femoral internal rotation during activity. We can therefore hypothesize that weakness or reduced neuromuscular control of the gluteus medius and gluteus maximus may lead to decreased resistance to hip internal rotation, increasing dynamic knee valgus moments, and increasing risk of lower extremity joint injury.\textsuperscript{2} Dynamic jump-landing tests provide a technique to examine any such risk factors.
The Landing Error Scoring System (LESS) is an objective test that examines measures and scores dynamic-jump landing mechanics. Created to detect individuals with poor jump-landing mechanics to identify those who may be at risk for non-contact ACL injury, the LESS involves scoring individual joint motions at various points of the landing process.\textsuperscript{14} Specifically, investigators and clinicians video tape a jump-landing task in both the frontal and sagittal planes, where the subject or patient’s jump landing is critiqued based on select criteria. Current research has shown that the LESS is both a valid and reliable tool for finding poor jump-landing biomechanics, and also demonstrates good interrater and intrarater reliability.\textsuperscript{15} Reduced scores on the LESS represent poor dynamic jump-landing mechanics, such as decreased knee flexion and hip flexion angles, and increased knee valgus and hip adduction angles.\textsuperscript{15} This clinically reliable tool can provide accurate information about an individual’s jump-landing technique, providing a helpful tool for identifying biomechanical abnormalities. Though the current literature that examines dynamic jump-landing mostly concentrates on the musculature that surrounds the knee and ankle, preliminary observations are beginning to suggest the importance of hip musculature in the coordination of dynamic movements, such as landing.\textsuperscript{5,7} One investigation\textsuperscript{7} examined dynamic jump-landing in participants who underwent anterior cruciate ligament reconstruction (ACL-R) in order to search for a predictive factor of sustaining a second ACL injury. Interestingly, the research showed that the highest predictive variable for a recurrent ACL injury was frontal plane loads at the knee, which significantly relates to hip adduction motion.\textsuperscript{7} The information from this study demonstrates that a deficit in overall hip external rotation torque in the early phases
of dynamic jump landing is a very strong predictor of further ACL injuries, predicting ACL injury risk with an area under the receiver operating characteristic (ROC) curve of 0.81. Researchers concluded that strengthening hip external rotators, specifically citing the gluteus maximus, after an ACL injury might reduce the risk of reoccurring ACL injuries.

Research on dynamic jump-landing suggests that gender differences may predispose females to higher levels of lower extremity injury due to differences in pelvic structure, gluteal strength and neuromuscular control. It is well documented that women tend to land in a more valgus position at the knee and with a more extended hip then men during single-leg landing. Researchers suggest this may be the fault of either a weakened or compromised neuromuscular control of the gluteus medius. One recent study found an average decrease in EMG activity in the gluteus medius of women compared to men while performing a forward jump. Another study found that men have longer gluteus maximus EMG activation in a series of dynamic jumps compared to women. With less activation of hip external rotators leading to hip adduction and valgus knee positions, women with poor landing mechanics may not be able to counteract potentially harmful forces, especially at the knee. More research is needed to further investigate landing mechanics in women to determine if a strong relationship occurs between weakness and neuromuscular deficits in the gluteal muscles and poor landing mechanics during functional dynamic jump-landing tasks.
2.6 Transcranial Magnetic Stimulation

Transcranial magnetic stimulation (TMS) is a method used to both measure cortical excitability and stimulate neural tissue to excite specific muscles at the periphery. This method is performed by placing an electromagnetic coil on the participant’s skull, over the underlying motor cortex. The device then sends magnetic pulses through the skull and into the neural tissue with very little irritation. Essentially, the stimulation travels into the motor cortex, leading to a decrease in presynaptic inhibition, causing a down-regulation in motor-neuron pool excitability. This directly projects on motor neurons, increasing volitional activation, and is measured at the peripheral muscle through the use of EMG. Among others, this technique has been used to study quadriceps neuromuscular control after surgery, such as ACL-R.

TMS is used to determine an active motor threshold (AMT), or the lowest level of stimulation capable of causing a measurable response in the muscle. If the muscle has a higher AMT, more magnetic stimulation is needed to produce a voluntary muscle twitch, demonstrating a block or slowing in neuromuscular control. This outcome has been studied in numerous upper extremity muscles, and more recently in muscles of the lower extremity. These studies indicate a positive correlative relationship between muscle weakness or neuromuscular control deficits and higher AMT, suggesting that cortical excitability plays a role in altered sensory feedback of the limbs from pain, disuse or restriction.

Currently, there is little to no research involving TMS and the gluteus maximus and gluteus medius. Similarly to jump-landing, there is some research involving TMS
and neuromuscular control in the quadriceps musculature. These studies 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. If these assertions hold true for the quadriceps muscle, then perhaps similar effects could occur at the hip. Discerning impaired cortical excitability at the hip joint may provide new insight into causes for chronic injuries in the lower extremity, such as PFPS, and ESLP. It may also help to further understand the correlation between neuromuscular control of the gluteal muscles and potentially hazardous jump-landing positions.

As the link between the upper extremity and the lower extremity, the hip joint holds an important role in dynamic stabilization. Through measurements of cortical excitability, researchers can help establish the link between neuromuscular control of the gluteal muscles and jump-landing mechanics. Any increase in AMT, indicating a decrease in cortical excitability, may present clinically as weakness. If the issue is impairment of cortical excitability, focusing on routine strengthening protocols may not address the underlying neural issue. Research is needed to answer the question of a correlation between cortical excitability and impaired gluteal function, which will hopefully lead to innovative clinical interventions used by athletic trainers and other members of the sports medicine team.

Cortical excitability, EMG, strength and jump-landing are all techniques which provide objective information and measurements of how muscles function what occurs at the muscle during activity. It is important to look both at what happens neurologically, as
well as gross motor movements to understand how one affects the other. Dynamic jump-landing demonstrates how muscle activation and cortical excitability work together to produce voluntary and controlled motion. It is reasonable to hypothesize that if cortical excitability is compromised or impaired, lower extremity joint kinematics may be altered. Dynamic activities require the body to both anticipate and react to forces placed upon it. If jump-landing mechanics are altered, then perhaps a reason might be due to a decrease in the brain’s ability to control muscular tissue, which would be indicated by a lower AMT. As with kinetics and kinematics, change in one factor usually leads to change elsewhere in the body as well, which leads to the question: do changes or decreases in motor evoked potentials correspond with changes or decreases in gross motor movements?

It is important to establish a correlation between these variables in healthy populations before expanding to further investigations. In the case of the present study, evidence will be collected in order to determine a correlational relationship between jump-landing techniques and cortical excitability. This relationship must be recognized before determining the extent of that relationship how exactly one factor may affect or predict the other. Should a relationship be found, future investigations could determine the effects of this relationship on individuals with specific pathologies related to gluteal impairment, such as PFPS and other lower extremity injuries. Also, these data may reveal if joint injury causes altered cortical excitability, and how that alteration leads to changes in kinetics and kinematics.
With the strong inferred relationship between weak gluteal musculature and altered mechanics, such as an increased knee valgus,\textsuperscript{3,8,17} perhaps changes in the gluteus musculature can lead to implications at the cortical level over time. If this holds true, rehabilitation programs of the hip joint may need to be reevaluated in order to accommodate these changes. In fact, with the strong link between gluteus maximus and gluteus medius weakness and injuries at the ankle, knee, and low back,\textsuperscript{1,3,4,17} perhaps rehabilitation of pathologies at these areas may need to incorporate more focus at the hip joint to help correct and prevent recurring or chronic injuries.
Chapter 3

Methods

3.1 Research Design

Study Design: Descriptive laboratory study.

The independent variables in this study were limb (dominant, non-dominant) and muscle (gluteus maximus and gluteus medius). The dependent variables were active motor threshold (AMT), motor evoked potentials (MEP), maximal voluntary isometric contractions (MVIC) and Landing Error Scoring System (LESS) scores. AMT, MEP and MVIC served as predictor variables whereas LESS score was our criterion variable.

3.2 Experimental Design

Testing was completed during one session lasting approximately 2 hours. The order in which the subject completed the outcome measures (AMT, MVIC) was randomized, as well as which limb (dominant, non-dominant) was tested first.

3.3 Participants

All participants were healthy females between the ages of 18 and 35 and were recruited from all races. A total of 37 subjects were recruited to participate in this study. Participants were excluded if they had any history of lower extremity orthopedic surgery or a history of any lower extremity ligamentous injury in the past 6 months. Also, participants currently experiencing low back pain (LBP) were excluded, individuals with LBP demonstrate inhibited gluteal musculature. Participants were also excluded if they
had a history of a diagnosed heart condition that would preclude them from exercise, a
history of a seizure, a history of a concussion in the past 6 months, or if they were taking
medication that may alter neural function, such as antidepressants or muscle relaxers.
We also excluded participants if they had a previous history of diagnosed cancer over
magnetic stimulation points on the brain.

3.4 Randomization

Outcome measures took place on the same day during one session. Limb and
outcome measures were randomly selected to determine the order of testing.

3.5 Instrumentation

3.5.1 Cortical Excitability

Active motor thresholds and motor evoked potentials were obtained 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. All AMTs
and MEPs were measured in the gluteus maximus and gluteus medius using a shield disk
electrode. The disk-shaped electrodes used to acquire signals were disposable, 10 mm
pre-gelled Ag/AgCl (BIOPAC Systems Inc., Goleta CA, USA). Signals were sampled at
1024 Hz and electromyography (EMG) amplification was set at a gain of 1000 (EMG
100C BIOPAC Systems, Inc.). Acknowledge BIOPAC Software (BIOPAC Version
3.7.3, BIOPAC Systems, Inc.) was used to visualize the signals.
3.5.2 Maximal Voluntary Isometric Contractions

Gluteus medius and gluteus maximus MVIC were assessed with a Biodex System 2 Pro inclinometer (Biodex Medical Systems, Shirley, NY).

3.5.3 Camera System for Landing Error Scoring System (LESS)

Two video cameras (Sony Cyber-Shot DSC-HX9/HX9V, San Diego, CA) were set up 136 inches from a force plate, one recording in the sagittal plane and one in the frontal plane. These cameras were used to record video data of the subjects performing the jump landing task. This video data was analyzed for formulation of the LESS score.

3.6 Procedures

3.6.1 Subject Preparation

Both the gluteus maximus and gluteus medius muscle belly were identified and debrided on both limbs. Electrodes were placed on the appropriate muscle belly following the protocol suggested by Distefano et al 2009.28,29

3.6.2 Maximal Voluntary Isometric Contraction

Maximum voluntary isometric contractions were utilized as a measure of muscular strength for both the gluteus maximus and gluteus medius. For gluteus maximus testing, participants were positioned prone in the Biodex System 2 Pro inclinometer with the testing limb in 0 degrees of hip extension, which was measured using a hand held inclinometer (Figure 1).
For gluteus medius testing, participants were positioned side lying on the inclinometer with the testing limb in 10 degrees of hip abduction which was measured using a hand held inclinometer (Figure 2). The participant’s torso and contralateral limb were secured in the inclinometer as their arms folded across their chest during testing to ensure measurement of only the muscle of interest. Subjects performed three MVICs in hip extension (gluteus maximus) and hip abduction (gluteus medius), and all scores were averaged to each limb.
3.6.3 Cortical Excitability

During gluteus maximus testing position, participants were positioned supine in the Biodex System II inclinometer with their tested hip in 0 degrees of extension. The participant’s arms were crossed under the chair, with the torso and contralateral limb strapped down to control for unwanted movement.

For gluteus medius testing, participants were side lying on the limb contralateral to the one being tested. The participant’s hip was placed in 10 degrees of abduction with their arms folded across their chest. The participant’s torso and contralateral limb were strapped down to control for unwanted movement.

For testing of both the gluteus maximus and gluteus medius, a lycra swim cap was placed on the participant’s head to allow for identification of the location of the motor cortex. Straight lines were drawn vertically on the swim cap and connected from the center of the occiput and nose, and from each external auditory meatus. Where the lines
intersect located the optimal location of the motor cortex. Formable disposable ear plugs were given to the participants. Five percent of the participant’s MVIC were used as a constant contraction load during AMT/MEP testing. A double cone coil (Magstim Company, Wales, UK) was positioned over the vertex of the cranium. Beginning stimuli was given at 50% of the maximal stimulator output in order to locate the “hot spot”, or optimal motor cortex location, and then moved 1cm in an anterior-to-posterior direction over the vertex. These procedures were done until the highest MEP response is located. This location was then marked on the swim cap, and the simulator was secured into that spot using a flexible camera mount.

Once the stimulator was secured, AMT was determined. AMT is defined as the lowest TMS intensity required to evoke a measurable MEP, which was >100µV. To determine AMT in the gluteus maximus and gluteus medius, 5 out of 10 measurable MEP waves were collected at a respective intensity. As soon as a total of 5 out of 10 measurable waves were collected, the intensity of the stimulator was reduced by 1% until there were 6 out of 10 negative waves collected. This signifies that 6 waves show a peak-to-peak measurement of less than the measurable MEP. AMT will be defined as the intensity that evoked 5 out of 10 measurable waves, with the intensity precisely below it evoking 6 out of 10 waves that do not measure <100µV for the gluteus maximus and gluteus medius.

For the process, each subject was directed to remain still and focus on staying relaxed. Then they were directed to contract the testing limb at 5% of their MVIC, maintaining this contraction while the stimulus was given either to the gluteus medius or
gluteus maximus. Visual feedback of the contraction was shown in real time on the computer screen in order to control for variance. Between stimuli, the participant was allowed to relax. After each AMT was found, we administered a stimulus at 120% of the AMT measure.

### 3.6.4 Landing Error Scoring System (LESS)

Two video cameras, sampling at 60 Hz, were set up 136 inches away from a force plate with one in the frontal plane and one in the sagittal plane relative to the landing area. The subject was instructed to jump off of a 30 cm box onto a force plate positioned at a distance of 50% of the subject’s height away from the force plate. Upon impact, the subject immediately rebounded into a maximal vertical jump. The emphasis of this task was placed on the subjects trying to attain an actual maximal vertical jump. No other feedback or coaching was given. After instruction, subjects were allowed to practice as many times as needed to familiarize them with the task. Three successful jumps were then recorded with the criteria for a successful jump as follows: 1. Jumping off of both feet from box, 2. Jumping forward but not vertically to reach force plate, 3. Landing with entire foot of dominant lower extremity on force plate, 4. Landing with entire foot of non-dominant lower extremity off force plate, 5. Completing the task in a fluid motion. The three successful jumps were recorded and analyzed by two independent researchers using QuickTime software. If differences arose between the independent scores, the two scorers would confer and agree upon a final score.
3.7 Statistical Analysis

Means and standard deviations were calculated for demographics. Pearson Product Moment correlation matrixes were performed to assess the relationships between gluteal strength, gluteal cortical excitability and LESS score with an r cutoff score of 0.7 to determine relationship strength. Separate dependent t-tests were used to determine if there were differences between dominant and non-dominant legs for all outcome measures. A priori levels of significance were set at $P \leq 0.05$. 
Chapter Four

Results

4.1 Subjects

A total of 37 healthy females participated in this study. Demographic information can be found in Table 1.

Table 1: Subject demographics

<table>
<thead>
<tr>
<th></th>
<th>Mean ± sd</th>
</tr>
</thead>
<tbody>
<tr>
<td>N (total)</td>
<td>37</td>
</tr>
<tr>
<td>Age</td>
<td>21.08 ± 2.15</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>164.8 ± 5.9</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>65.4 ± 12.0</td>
</tr>
<tr>
<td>LESS Score</td>
<td>4.8 ± 2.6</td>
</tr>
</tbody>
</table>

Abbreviations: LESS, Landing Error Scoring System

4.2 T-tests

Descriptive analysis of outcome measures can be found in Table 2. Outcome measures could not be acquired for all participants, due to safety requirements of TMS intensity. Therefore, each outcome in Table 2 is associated with the appropriate sample size. No statistical differences were found in MVIC, AMT and MEP measures between dominant and non-dominant limbs (Table 2).
Table 2: Means and standard deviations for outcome measures, reported by muscle and limb.

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Outcome Measure</th>
<th>Dominant mean ± sd</th>
<th>N</th>
<th>Non-Dominant mean ± sd</th>
<th>N</th>
<th>T-test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gluteus Maximus</td>
<td>MVIC</td>
<td>1.62 ± 0.45</td>
<td>37</td>
<td>1.47 ± 0.42</td>
<td>37</td>
<td>t(72)=1.85, P=0.07</td>
</tr>
<tr>
<td></td>
<td>AMT</td>
<td>51.5 ± 9.9</td>
<td>25</td>
<td>49.8 ± 12.2</td>
<td>17</td>
<td>t(40)=0.37, P=0.72</td>
</tr>
<tr>
<td></td>
<td>MEP</td>
<td>0.274 ± 0.263</td>
<td>15</td>
<td>0.244 ± 0.198</td>
<td>11</td>
<td>t(24)=0.32, P=0.75</td>
</tr>
<tr>
<td>Gluteus Medius</td>
<td>MVIC</td>
<td>1.40 ± 0.46</td>
<td>37</td>
<td>1.35 ± 0.45</td>
<td>37</td>
<td>t(72)=0.72, P=0.48</td>
</tr>
<tr>
<td></td>
<td>AMT</td>
<td>49.2 ± 8.7</td>
<td>24</td>
<td>49.7 ± 10.3</td>
<td>23</td>
<td>t(45)=0.32, P=0.75</td>
</tr>
<tr>
<td></td>
<td>MEP</td>
<td>0.214 ± 0.064</td>
<td>15</td>
<td>0.211 ± 0.074</td>
<td>16</td>
<td>t(29)=0.14, P=0.89</td>
</tr>
</tbody>
</table>

Abbreviations: MVIC, maximal voluntary isometric contraction normalized to body weight (Nm/kg); AMT, active motor threshold; MEP, peak-to-peak motor evoked potential at 120% of AMT.

4.3 Correlations

A moderate, positive correlation was found between dominate gluteus maximus MEP and LESS scores (r = 0.562, p=0.029). No other significant correlations were obtained for MVIC, AMT, or MEP for the gluteus maximus and gluteus medius, regardless of limb (Table 3). Associated scatter plots can be found in Appendix D.

Table 3: Correlation matrix corresponding to LESS scores.

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Outcome Measure</th>
<th>Dominant r</th>
<th>P</th>
<th>Non-Dominant r</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gluteus Maximus</td>
<td>MVIC</td>
<td>-0.044</td>
<td>0.800</td>
<td>0.106</td>
<td>0.537</td>
</tr>
<tr>
<td></td>
<td>AMT</td>
<td>-0.047</td>
<td>0.827</td>
<td>0.192</td>
<td>0.477</td>
</tr>
<tr>
<td></td>
<td>MEP</td>
<td>0.562</td>
<td>0.029*</td>
<td>0.326</td>
<td>0.328</td>
</tr>
<tr>
<td>Gluteus Medius</td>
<td>MVIC</td>
<td>0.027</td>
<td>0.877</td>
<td>-0.033</td>
<td>0.849</td>
</tr>
<tr>
<td></td>
<td>AMT</td>
<td>-0.116</td>
<td>0.597</td>
<td>0.136</td>
<td>0.546</td>
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<tr>
<td></td>
<td>MEP</td>
<td>0.167</td>
<td>0.552</td>
<td>-0.366</td>
<td>0.164</td>
</tr>
</tbody>
</table>

Abbreviations: MVIC, maximal voluntary isometric contraction; AMT, active motor threshold; MEP, motor evoked potential at 120% of AMT. * denotes significance at the P ≤ 0.05 level.
Chapter Five
Discussion

Based on previous research of the quadriceps muscle, we hypothesized that gluteal muscle strength and cortical excitability would strongly correlate with jump-landing biomechanics, as measured by the LESS. However, our results show minimal to no correlation between gluteal MVIC and measures of cortical excitability with a clinical measure of jump-landing biomechanics. This suggests that other factors besides strength and cortical excitability of the gluteus maximus and gluteus medius may have a greater influence on overall landing biomechanics in females.

5.1 Gluteal Strength

During jump-landing, increased dynamic knee valgus has been demonstrated to be a risk factor for knee joint injury, specifically of the anterior cruciate ligament. The proximal component of dynamic knee valgus results from internal rotation and adduction of the femur, which are controlled eccentrically by gluteus maximus and gluteus medius function. We found no significant relationship between maximal isometric gluteal strength and performance during dynamic jump-landing tasks, suggesting that gluteal strength alone may not be the determining factor in proper landing mechanics. We had hypothesized that strength, as a gross measure of muscle function, would strongly correlate with an individual's landing mechanics. However, other neuromuscular factors may play a larger role in proper biomechanics during functional tasks, such as correct muscle timing and activation. It is important to note that this investigation only
evaluated MVIC to measure strength. Isometric strength, specifically at one joint angle, may not be a comprehensive evaluation of muscle strength output and performance during functional activities. In addition, we assessed isometric strength, whereas during landing the gluteal musculature is primarily contracting eccentrically to prevent internal rotation and adduction of the femur. An eccentric strength profile of these muscles may yield a relationship with landing mechanics, which warrants further research. Clinically, concentric strengthening of the gluteus maximus and gluteus medius may not be sufficient in improving biomechanical deficits in the lower extremity, specifically in correcting dynamic knee valgus.

5.2 Gluteal Cortical Excitability

Similarly, it does not appear that cortical excitability of the gluteal muscles influences landing biomechanics. Cortical mechanisms have been thought to contribute to neuromuscular function, and insufficiencies in this pathway have been documented following joint injury. While only one measure of cortical excitability was correlated with landing mechanics, these measures were not assessed during the jump-landing itself. Currently, methodological limitations make it unfeasible to measure cortical excitability during dynamic activity. However, it would be ideal to have a snapshot of these measures while the muscle is contracting eccentrically during landing. Although, it is possible that cortical mechanisms do not influence landing mechanics at all rather, individuals may rely on reflexive pathways to alter movement patterns during rapid
movements.

We do report a statistically significant positive correlation between MEP amplitude elicited at 120% of the AMT in the dominant gluteus maximus muscle and LESS scores. This implies that subjects with higher cortical excitability display a greater amount of “errors” when landing, representing poor biomechanics. Inherently, one may infer that an increase in cortical excitability would improve neuromuscular function, thereby that individual would land with fewer “errors”. However, our findings suggest that subjects who have poor jump-landing mechanics may require higher levels of cortical excitability to compensate for a lower level of neuromuscular control. This increase in activity could be seen as inefficiency of the system. These individuals may need to up-regulate cortical mechanisms and allow excess cortical information to that muscle in order to regulate motor control. However, this significant correlation may simply be a type I error due to the multiple correlation analyses conducted in this investigation. Therefore, this significant correlation should be viewed cautiously, with more research needed to determine the true relationship between gluteal cortical excitability and landing biomechanics.

5.3 Limitations

A principal limitation in this study was the inability to record all outcome measures for all subjects. Safety restrictions when using TMS prohibit stimulation above 70% of max intensity. Therefore, individuals who have the highest motor thresholds of >70
(denoting lower cortical excitability), may not have been captured in this study. However, at least 11 participants were able to be included in all analyses and at least 15 participants in all but one analysis (non-dominant gluteus medius MEP). Methodologically, the use of the LESS to assess biomechanics during landing may be a potential reason for insignificant findings. Though both a valid and reliable tool for assessing gross motion during dynamic jump landing,\textsuperscript{15} the LESS may not be sensitive enough to detect smaller biomechanical variation present as a result of influences from cortical mechanisms. Three-dimensional motion analysis testing could help to determine if cortical excitability has influences on specific joint angle or moments, potentially leading to more subtle adjustments in motor control.

5.4 Conclusion

No substantial relationship was found between gluteal MVIC and measures of cortical excitability with a clinical measure of jump-landing biomechanics in healthy, physically active females. Further research is needed to understand the effect cortical level pathways have on neuromuscular control and jump-landing biomechanics. Other factors that may influence poor landing mechanics and dynamic knee valgus warrant further investigation.
References


25. Lehman GJ. Trunk and hip muscle recruitment patterns during the prone leg extension following a lateral ankle sprain: A prospective case study pre and post injury. *Chiropractic & Osteopathy.* 2006;4(14).


### Appendix A

#### Landing Error Scoring System Criteria

Landing Error Scoring System Score Sheet

<table>
<thead>
<tr>
<th>Subject</th>
<th>Pre</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>Post</th>
<th>1</th>
<th>2</th>
<th>3</th>
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<table>
<thead>
<tr>
<th>Item</th>
<th>Correct</th>
<th>Error</th>
</tr>
</thead>
</table>

#### Sagittal View

**Evaluated at IC**
- Knee Flexion: >30 degrees
  - Yes
  - No-1
- Hip Flexion: Hips are flexed
  - Yes
  - No-1
- Trunk Flexion: Trunk is flexed on hips
  - Yes
  - No-1
- Ankle Plantar Flexion: Toes to heel
  - Yes
  - No-1

**Evaluated between IC and moment of MKF**
- Knee Flexion Displacement: > than 45 degrees
  - Yes
  - No-1
- Trunk Flexion: Greater than at contact
  - Yes
  - No-1
- Hip Flexion: Greater than at contact
  - Yes
  - No-1

**Overall**
- Sagittal plane joint displacement
  - Soft
  - Avg-1, Stiff-2

#### Frontal View

**Evaluated at IC**
- Lateral Trunk Flexion: Trunk flexed to left or right
  - No
  - Yes-1
- Knee Valgus: Knees over the midfoot
  - Yes
  - No-1
- Initial Foot Contact: Symmetric
  - Yes
  - No-1

**Evaluated at Entire Foot Contact w/ Ground**
- Foot Position: Toes pointing out >30 degrees
  - No
  - Yes-1
- Foot Position: Toes pointing out <30 degrees
  - No
  - Yes-1
- Stance Width: Less than shoulder width
  - No
  - Yes-1
- Stance Width: Greater than shoulder width
  - No
  - Yes-1

**Evaluated between IC and moment of MKF**
- Knee Valgus Displacement: Knees inside of large toe
  - No
  - Yes-1

**Overall**
- Overall Impression
  - Excellent
  - Avg-1. Poor-2

*Zero points are awarded for an item being performed correctly.
*IC=Initial Contact
*MKF=Maximum Knee Flexion
## Appendix B

### Transcranial Magnetic Stimulation Testing Sheet

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Appendix C
Data Collection Sheet

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Appendix D

Scatterplots