Graduate Theses, Dissertations, and Problem Reports

2022

An Examination of Hip Muscle Activation in those with Hip-Related Groin Pain during Single-Legged and Double-Legged Squats

Millissia A. Murro
West Virginia University, mm0044@mix.wvu.edu

Recommended Citation

Murro, Millissia A., "An Examination of Hip Muscle Activation in those with Hip-Related Groin Pain during Single-Legged and Double-Legged Squats" (2022). *Graduate Theses, Dissertations, and Problem Reports*. 11420.
https://researchrepository.wvu.edu/etd/11420

AN EXAMINATION OF HIP MUSCLE ACTIVATION IN THOSE WITH HIP-RELATED GROIN PAIN DURING SINGLE-LEGGED AND DOUBLE-LEGGED SQUATS

Millissia Murro

Thesis submitted to the college of Health Sciences at West Virginia University in partial fulfillment of the requirements for the degree of Master of Science in Exercise Physiology

Jean L. McCrory, PhD, Chair
Yum Nguyen, PhD, ATC
Brian Leary, PhD
Kate Jochimsen, PhD, ATC

Division of Exercise Physiology
Department of Human Performance and Applied Exercise Science

Morgantown, West Virginia
2022

Keywords: Hip-related groin pain, single-legged squat, double-legged squat, sEMG

ABSTRACT

An Examination of Hip Muscle Activation in those with Hip-Related Groin Pain During Single-legged and Double-legged Squats

Millissia Murro

Approximately 60% of young adults who present with chronic hip pain suffer from hip-related groin pain (HRGP). HRGP causes individuals to experience pain, dysfunction, and have a lower quality of life when compared to healthy individuals. The most severe symptoms in these individuals occur during activities that cause the hip to go through a large range of motion, such as a squat. Hip muscle activation during this task may be altered in these individuals, yet we know little about its role in the disease process and pain level in those with HRGP. Current treatment for these individuals includes surgical and non-surgical interventions; however, the effects of both treatments are not effective, and individuals tend to experience symptoms again within 2 years. Understanding muscle activation during squatting tasks may help us to develop a more effective and long-term solution when treating these patients. Therefore, the **purpose** of this study was to examine bilateral hip muscle activity of the tensor fascia latae, rectus femoris, gluteus medius, and gluteus maximus during single- and double-legged squats in individuals with HRGP. Specific Aims 1 and 2 were to compare bilateral differences in hip muscle activation during the double-legged and single-legged squats, respectively. Specific Aim 3 examined differences in muscle activation on the symptomatic side between the double-legged and single-legged squats. **Methods:** Seven individuals (2M/5F, age: 25.83±3.37yrs, BMI: 25.92±4.83kg/m^2) with unilateral HRGP were recruited to participate. Following informed consent, surface EMG sensors were placed bilaterally on the four hip muscles. Individuals were asked to perform maximal voluntary isometric contractions (MVICs) for each muscle. Subsequently, two sets of five double-legged squats and five individual single-legged squats were performed. Average RMS value of each muscle (expressed as %MVIC) during the squats were determined. T-tests were performed to compare between the affected and healthy legs (Specific Aims 1 and 2) or between tasks (Specific Aim 3) when the data were normally distributed. Mann-Whitney U tests were performed when the assumptions of normality were violated. The alpha value for all statistical tests was 0.05. **Results/Conclusions:** No significant differences in hip muscle activation were found bilaterally during double- and single-legged squats for any of the muscles ($p>0.05$). However, when comparing the symptomatic side muscle activation between squat tasks, the gluteus maximus had higher activation during the single-legged squat (single-legged: 25.0 ± 13.5 %MVIC, double-legged: 12.6 ± 7.3 %MVIC, $p<0.001$). No other task differences were found. Synchronous data that were collected as part of a larger study revealed no differences in either hip muscle strength or squat depth between the symptomatic and asymptomatic sides. Thus, the lack of bilateral activation differences is not surprising. Due to the small subject pool, it is hard to determine concrete conclusions concerning activation of the hip musculature. Future studies are needed to better understand these findings in regard to hip pain and functional movement patterns in individuals with HRGP.

CONTENTS

Chapter 1: Introduction

Hip-related groin pain (HRGP) accounts for approximately 60% of chronic hip pain causes in young to middle-aged individuals (26,58,70). HRGP can be caused by a variety of non-arthritic hip conditions including femoroacetabular impingement syndrome, structural instability, labral tears, chondral lesions, and other conditions that occur and cause pain within the hip (22). Individuals with HRGP suffer from pain, dysfunction, and tend to have a lower quality of life (7,22,42). Treatment options for those with HRGP include non-operative (strengthening and range of motion exercise, intra-articular injections, and activity modification) and surgical options; however, none of these interventions achieve sustained symptom improvement (46,48,66). This may be attributed to a lack of scientific consensus on the specific impairments within this population, which prevents the development of effective, targeted long-term treatment for these individuals.

Individuals with HRGP demonstrate significant biomechanical differences of the lower extremity compared to unaffected individuals, particularly at the hip joint (37). A systematic review by King et al. (37) concluded that those with HRGP exhibited altered joint kinetics and kinematics during walking and squatting. Specifically, they had decreased peak hip extension, peak internal rotation, and peak external rotation torques and walk with lower total sagittal range of motion (ROM) at the hip (37). This suggests that those with HRGP tend to have functional movement differences.

Individuals with HRGP also exhibit muscular weakness of the hip flexors, adductors, external rotators, and abductors (8,9,19,59) when compared to healthy controls. The tensor fascia latae (TFL), rectus femoris, gluteus maximus, and gluteus medius muscles surround the hip (53). The TFL is a hip abductor and medial rotator (53). The gluteus maximus is a primary hip extensor (53). The gluteus medius is a primary hip abductor (53). The rectus femoris is a hip flexor (53). Together these muscles help to control the movement at the hip joint. Casartelli et al. (9) examined the function (i.e., activation) of the hip muscles in those with HRGP compared with healthy individuals during maximal strength testing. During the maximal strength testing of the hip flexors, the TFL had decreased muscle activation in those with HRGP compared to healthy controls. They reasoned that those with HRGP may not be able to voluntarily activate TFL effectively due to significant hip flexion muscle weakness (9). The function of the rectus femoris, a hip flexor (53), was also examined (9). In contrast to the TFL, those with HRGP showed comparable rectus femoris muscle activity to normal healthy controls. It is unknown why the muscle activity of the rectus femoris was not different in those with HRGP. Although this study examined muscle activity of these two muscles during a maximal contraction, this information does not provide information as to what these muscles may do in those with HRGP during walking or any functional task which is more relevant to everyday function.

The gluteus maximus and the gluteus medius contribute significantly to hip joint stabilization and function (16,17,22). Studies have reported altered activity of these muscles in individuals with HRGP during different functional tasks and walking (16,17,59). After examining the neuromuscular activation of the hip extensors, Diamond et al. (17) reported that during squatting tasks, the gluteus maximus and the obturator internus activation was greater in those with HRGP compared to healthy controls. They hypothesized the increased activation is a protective mechanism to help stabilize the hip joint and maintain normal functioning during functional tasks. Similarly, both Diamond et al. (16) and Rutherford et al. (59) reported greater gluteus maximus activation during walking in those with HRGP compared to healthy controls. These studies also reported that gluteus medius activation was somewhat increased, although not significantly (16,59). The increased activity of the gluteus maximus and gluteus medius helps confirm that muscles that control hip joint stability function to protect the joint while still performing dynamic movement. However, during walking, no differences in the hip muscle activation in those with HRGP were found between their symptomatic and contralateral limbs (59). Hip muscle activity differences between limbs within an individual with HRGP has not been examined during a squatting task.

A squat is a demanding task done by individuals as a regular daily activity (37). For healthy individuals, this may be done without much thought. For those with chronic hip pain, it may prove to be a more difficult task. Individuals with HRGP squat to a lesser depth and have less sagittal plane pelvic range of motion compared to healthy individuals (10,39,47). The reason behind this is unknown currently but may be due to limitations from fear, pain, or altered muscle activity surrounding the hip joint (10,39,47). Few studies have investigated activation of the hip musculature during squatting tasks in those with HRGP. Available evidence suggests that during squatting, those with HRGP have altered muscle activation patterns compared to healthy individuals. It has been found that they have similar activation patterns during ascent and descent phases of the squat, whereas healthy individuals have variance of activation patterns during squat phases, like decreased activation during the eccentric phase (17). However, the muscle activation differences between the symptomatic and contralateral side hip within an individual with HRGP is still unknown. It is important to understand these differences because examining the hip muscle activity of a double legged squat in those with HRGP will provide information on how the hip joint acts in everyday, common activities. Furthermore, a single-legged squat may exaggerate the potential issues that contribute to hip joint dysfunction. Research on this activity may allow us to understand a potential mechanism on which to intervene and treat this disease.

Purpose

The purposes of this study are to 1) examine the differences in the muscle activation of the TFL, rectus femoris, gluteus medius and gluteus maximus between the symptomatic and the contralateral hip during a single-legged squat and double-legged squat and 2) examine the differences in the muscle activation of the TFL, rectus femoris, gluteus medius, and gluteus maximus of the symptomatic hip between the single-legged and double-legged squats in individuals with HRGP.

Specific Aims

Specific Aim 1, Double-legged squat: To examine the differences in muscle activation of the TFL, rectus femoris, gluteus medius, and gluteus maximus between the symptomatic and contralateral hip of individuals with HRGP during a double-legged squat.

Hypothesis: It is hypothesized that the total activity (quantified as the root mean square) of the gluteus medius and gluteus maximus will be greater, the activity of the TFL will be lower and the activity of the rectus femoris will be the same in the symptomatic side hip when compared to the contralateral side hip.

Specific Aim 2, Single-legged squat: To examine the differences in muscle activation of the TFL, rectus femoris, gluteus medius, and gluteus maximus between the symptomatic and contralateral hip of individuals with HRGP during a single-legged squat.

Hypothesis: It is hypothesized that the total activity (quantified as the root mean square) of the gluteus medius, gluteus maximus, and rectus femoris will be greater and the activity of the TFL will be lower in the symptomatic side hip when compared to the contralateral side hip.

Specific Aim 3, Comparison of tasks: To examine the differences in muscle activation of the TFL, rectus femoris, gluteus medius, and gluteus maximus between the single-legged squat and double-legged squat of the symptomatic side hip in individuals with HRGP.

Hypothesis: It is hypothesized that the muscle activation differences in the symptomatic side hip will be greater in the single-legged squat than in the double-legged squat.

Overall Design

This study is a within-subject, case control study design. To address Specific Aims 1 and 2, we compared the neuromuscular activity of the TFL, rectus femoris, gluteus medius, and gluteus maximus between the symptomatic hip and the contralateral hip during two different squatting tasks: a single-legged squat, and a double-legged squat. To address Specific Aim 3, we evaluated the activation difference between an individual's symptomatic leg during the single-legged squat and double-legged squat. The independent variables in this study are leg (the symptomatic or contralateral hip) for aims 1 and 2 and task (the single-legged squat, and the double-legged squat) for aim 3. The dependent variables arise from the surface electromyography (sEMG) data as assessed via a root mean square on the activation. sEMG was collected bilaterally on the individuals' hips during both squatting tasks, single-legged and double-legged. sEMG was collected on each subject during a maximal voluntary isometric contraction (MVIC) of each muscle. This was used to normalize the EMG data for each subject to be able to compare among subjects, MVIC of each muscle was collected so that the sEMG data can be interpreted as %MVIC.

This study was a part of a larger study with a faculty member. Strength, three-dimensional kinematics, and kinetics were assessed in that study. These data were available for supplementary knowledge for this thesis.

Limitations of the Study

Several study limitations are acknowledged apriori Due to time and funding constraints, a control group was not used as a comparison group in this study. Instead, we evaluated the symptomatic side hip and the contralateral side hip of individuals with HRGP. Another limitation of this study was the use of sEMG. sEMG artifact can interfere with the signal of the muscle and the placement needs to be precise to limit the artifact. The alternative is fine wire EMG, in which the wire-electrodes are placed within the muscle to produce very accurate readings with minimal noise. However, fine-wire EMG method is invasive and requires other EMG technology the lab does not have. This should be kept in mind when examining and interpreting the data.

Glossary of Terms

Surface Electromyography (sEMG): The use of electrode that sit on the surface of the skin, over a muscle, that can detect the electrical activity of the muscle at rest and during activity.

Hip-related groin pain (HRGP): An umbrella term used to describe various conditions that cause non-arthritic pain within the hip joint.

Kinematics: Body motion that pays no regard to the forces that cause the motion (i.e. joint angles, displacement, accelerations).

Kinetics: The forces and torques that cause body movement.

Maximum Voluntary Isometric Contraction (MVIC): The maximal amount of force a muscle is able to generate without the muscle fibers changing length.

Femoroacetabular Impingement Syndrome: A chronic hip-pain syndrome characterized by a triad of symptoms (e.g., position-related hip pain), clinical signs (e.g., positive FADIR test, limited range of motion), and morphologic features (e.g., cam morphology, pincer morphology, labral tear).

Osteoarthritis (OA): Degeneration of the bone and cartilage at joints.

Moment: The tendency of a force to cause an object to rotate around an axis.

Functional Range of Motion: The amount of motion, in degrees, a joint will allow to occur about it without help from an external force.

Chapter 2: Literature Review

Hip-related groin pain

In the United States, chronic hip pain affects approximately 14.3% of adults (1). Hip-related groin pain (HRGP) is a term describing hip pain caused by multiple conditions, including femoroacetabular impingement syndrome, labral tears, chondral lesions, instability, and ligament tears that fall within chronic hip pain (22). HRGP affects at least 60% of young adults presenting with chronic hip pain in the United States (32,72). Individuals with HRGP tend to have pain, dysfunction and decreased quality of life compared to healthy individuals (7,22,42).

Many researchers have examined kinematic (10,18,31,34,36,37,44,47,54,59,62,65) and kinetic (31,36,47,54,60,61,62,65) biomechanical parameters associated with HRGP and have found those with HRGP have different movement patterns than healthy individuals. Muscle function has been examined in few studies, therefore we have yet to fully understand the impact muscle function in those with HRGP (10,16,17,41,59,65). Understanding how the function of the hip joint is impaired in individuals with HRGP and the potential causes of the symptoms that accompany HRGP is imperative to move forward and provide accurate and effective treatments in these patients.

Factors contributing to HRGP

Much about the risk factors that contribute to the development of HRGP remain unknown. However, potential risk factors have been identified. Genetics, sex, and the type of activity one engages in can increase the risk of HRGP (12,22). Recently, hip muscle function has been investigated to see if it may contribute to the prevalence of HRGP (8,9,19,59). There have been contradictory findings on strength differences between the symptomatic limb and asymptomatic limb in those with HRGP. In some studies, no difference in hip strength has been found between the symptomatic and asymptomatic limb in those with HRGP (59). In others, there has been found to be strength differences where the symptomatic limb is weaker than the asymptomatic side limb (35,52). When comparing hip strength to healthy individuals, similar results are seen. The hip flexors: the iliacus, psoas major, and the rectus femoris (8,9); external rotators: piriformis, superior and inferior gemelli, obturator internus, and quadratus femoris (9); adductors: pectineus, adductor longus, gracilis, adductor brevis, and adductor magnus (9); and abductors: gluteus medius, gluteus minimus, and tensor fasciae latae (9,19), have been found to be weak in those with HRGP when compared to healthy individuals.

This hip muscle weakness may influence the motion of the hip. The muscles controlling hip function provide joint stabilization and influence hip movement (8,9,32). With hip weakness, joint stabilization will be limited, providing less control over movements of the hip, potentially causing kinematic differences in these individuals. This may contribute to pain and dysfunction at the hip, influencing the risk of HRGP (8,9,32). However, measuring muscle strength alone does not give the full picture of how the muscle contributes to joint function. Some clinicians and researchers focus on strength as a variable to assess and "treat" HRGP in these individuals (22,35,46,66); however, strength may not be the problem. Like stated previously, the current treatment is not effective long-term. Therefore, activation may be more indicative of how the hip muscles function during tasks. The amount of muscle activation may provide more important information than strength regarding function. Increasing the muscle activation recruits more muscle fibers to activate during a task, allowing for the muscle to work at a greater capacity, potentially improving muscle function. Yet few researchers have examined muscle activation in those with HRGP. The pain and dysfunction in the hip contributing to HRGP may be due to deficiencies in muscle activation rather than in muscle strength.

Biomechanical factors related to HRGP

The effect of HRGP on gait biomechanics has been examined extensively by many researchers because of how this condition impacts activities of daily life. Most researchers agree that compared to healthy individuals, those with HRGP either walk at the same speed (16,18,34) or at a slower speed (31,54,62). During gait, various kinematic parameters differ between those with HRGP and those without. Throughout the gait cycle, there is a decrease in hip functional range of motion in all planes (sagittal, frontal, transverse) in individuals with HRGP (18,31,34,44,54,62,65).

Individuals with HRGP also demonstrate kinetic alterations during walking. Hip adduction moments in gait are lower in those with HRGP compared to healthy individuals (62). Some controversy occurs in the sagittal plane findings, as some say there is a decrease in hip flexion moment (31,62) while others claim there is an increase in hip flexion moment (60) during gait. These different findings may be a result of differences between individuals in muscle activation in order to help compensate for the discomfort potentially felt from HRGP.

Women with HRGP exhibit different gait biomechanics than do men with the same condition. Men with HRGP tend to walk with a more severe decrease in hip functional range of motion in all planes compared to women (36). During the early stance phase of gait, men also have lower hip adduction moments compared to women. During 10-13% of stance, men have smaller hip internal rotation moments and during 17-21% of stance they have larger hip internal rotation moments compared to women (36). Lewis et al. (44) reported different lower extremity gain alterations in men vs. women with HRGP. Men with HRGP tend to also have greater anterior pelvic tilt and less posterior pelvic tilt than healthy controls. While women with HRGP tend to walk with more hip adduction than healthy controls. Both men and women with HRGP walk with less peak hip extension compared to healthy controls, however men with HRGP walk with with less peak hip extension than women (44).

Muscle activation during gait has only been examined in a few studies (16,59). Throughout the gait cycle, altered coordination patterns of the hip muscles in those with HRGP have been noted (16). Individuals with HRGP have higher muscle activation of the gluteus maximus compared to healthy individuals (59). Few studies have examined muscle activation in individuals with HRGP during activity other than gait. However, understanding hip muscle activation during gait may not be particularly useful in these patients since this task is not very demanding on the hip joint and may not elicit the action of the muscle potentially contributing to the discomfort and pain felt by these individuals.

Biomechanical factors during squatting activities

Typically, individuals with HRGP do not experience severe symptoms of pain and discomfort while walking (39,40). However, activities that require the hip joint to go through a wide range of motion, like squatting, may cause pain and discomfort in those with HRGP (39,40). Several biomechanical factors have been assessed during a squat in those with HRGP. Inconsistent squat depth and speed are noted between studies. Some have reported no difference in squat depth (17,47) while other findings suggest those with HRGP squat to a lesser depth than healthy individuals (21,39). Individuals with HRGP have been found to either squat at the same speed as healthy individuals (17) or at a slower speed (47). Some findings suggest there are no differences in kinematic variables between healthy individuals and those with HRGP during squatting (37,39,47), however some studies suggest otherwise (10). Peak hip flexion angles and total sagittal plane range of motion are reportedly lower during the ascent phase of the squat in individuals with HRGP (3,10). Few differences in joint kinetics occur in those with HRGP and healthy individuals during a squat. Individuals with HRGP squat with a lower peak hip external rotation moment, hip extension moment and mean hip flexion moment compared to healthy individuals (3,37,47).

Several studies examined the muscle activation differences during a squat in those with HRGP (10,17,41). During a deep squatting task, activation of the semitendinosus during both ascent and descent and the gluteus maximus during ascent were larger in those with HRGP compared to healthy individuals (10). An increase in area under the linear envelope was noted in bicep femoris activity during ascent in those with HRGP (10). No differences in EMG amplitude or time of peak activity occurred for the iliocapsularis, iliacus or the rectus femoris muscles between groups during this same squatting task (41). Individuals with HRGP have displayed altered muscle activation patterns of their deep hip musculature during squatting compared to healthy individuals (17). In a squat, the ascent of the movement causes the deep hip muscles to concentrically contract, where the descent of the movement causes the deep hip muscles to eccentrically contract (17). In healthy individuals, lower amplitudes of EMG are expected during descent phase compared to the ascent phase. However, in individuals with HRGP, the hip muscles EMG amplitude during ascent and descent is similar, meaning the descent phase muscle activation patterns are greater than expected (17). These findings show variation in hip muscle activity in those with HRGP compared to healthy individuals that may be due many things, such as protective mechanisms or physiological means (17). No further studies have examined how the muscle activation of other hip muscles in individuals with HRGP alters compared to healthy controls during a squatting task. Few studies have looked at the muscle activation differences between limbs in those with HRGP. Understanding the effects of this task on the muscles of the hip may help us to better understand the function of the hip joint in those with HRGP and could help provide effective interventions in these individuals.

Hip Muscles

The hip joint is a complex joint that can move in all three cardinal planes: frontal, sagittal and transverse. Proper hip function requires the action of multiple muscles. The hip muscles to examined in this thesis include the TFL, the gluteus medius, the gluteus maximus, and the rectus femoris. The actions of each of these muscles at the hip are slightly different yet are all necessary for normal function.

Gluteus Maximus

The gluteus maximus is a primary, powerful hip extensor (53). The gluteus maximus originates on the posterior inferior surface of the sacrum and coccyx and the posterior aspect of the dorsal ilium posterior to the posterior gluteal line (24). Its insertion point is the iliotibial tract and the gluteal tuberosity of the femur (24). The gluteus maximus lengthens and opens the front of the hip (29,53). Generally, the hip extensors are used in movements requiring forward propulsion, like running (29,53). Additionally, hip extension is seen during the upward movement of the squat phase (53). The ascent phase of the squat is due to the concentric action of the hip muscles and the descent phase of the squat is due to the eccentric action of the hip muscles. During hip extension movements, the gluteus maximus helps stabilize the pelvis as well (29,53).

The gluteus maximus also acts as a primary mover of hip external rotation. External rotation of the hip is when the hip femur gets rotated laterally, pivoting outwards (29,53). Because of its role as an external rotator, it also functions to prevent excessive internal rotation (53). The gluteus maximus helps stabilize the hip joint, particularly during single-legged stance (29,53). It helps to stabilize the femur into the acetabulum, improving single-legged stability (29,53).

Tensor Fascia Latae

The TFL is a primary hip flexor and abductor (53). The TFL originates on the anterior superior iliac spine and the anterior iliac crest. (33). Its distal attachment is on the iliotibial tract (33). One main action of the hip flexor muscles is to bring one's femur forward and up towards the torso (29,53). This movement often occurs during walking when bringing the leg forward, or more significantly when squatting downwards (29,53).

In its role as a hip abductor, the TFL works to keep to the pelvis in a neutral position during single-legged tasks (29,53). The TFL aids the gluteal muscles in hip joint stabilization (53). These muscles help to provide articulation of the femoral head to the acetabulum, particularly during single-legged stance (29,53).

Gluteus Medius

The gluteus medius is a primary hip abductor muscle (53). The muscle originates on the ilium between the posterior and anterior gluteal lines (25). It inserts distally to the lateral and superior posterior aspects of the greater trochanter (25). The gluteus medius has a large role in single-limb support tasks because it functions to stabilize the pelvis in the frontal plane, keeping it in a neutral position when a limb is taken off the ground (29,53). This occurs during walking, running or other single-limb tasks. The gluteus medius also aids the gluteus maximus in hip extension and hip external rotation (29,53). It also aids in stabilizing the pelvis in extension or the hip in external rotation during single-legged stance positions (29,53).

Rectus Femoris

The rectus femoris acts as a primary hip flexor (53) and it acts on the knee as a knee extensor (29). The origins of the rectus femoris are the anterior inferior iliac spine and ilium superior to the acetabulum (29). The insertion point of the rectus femoris is the base of the patella (29). It acts most efficiently when the hip is in flexion and the knee is in extension or the hip is in extension and the knee is in flexion (29,53). The TFL assists the rectus femoris in hip flexion to bring the femur to the torso. This is seen during gait repetitively and is particularly seen during a squatting task (29,53). The rectus femoris also acts as a secondary hip abductor (53), helping the gluteus medius and TFL to keep the pelvis neutral during a single-legged support task (29,53).

Understanding the function of each of these muscles is important in developing treatments for individuals with HRGP, as these individuals have functional problems occurring at the hip. These problems include issues with strength, as well as kinematic, kinetic, and muscle activation differences compared to unaffected hips. Each of these muscles either contribute to the stabilization of the hip or help cause the movement required for a squatting task. Investigating the activation of each of these muscles is helpful in the understanding of how stability and function during squat tasks are affected when severe symptoms occur in individuals with HRGP. Examination of muscle function during a single-legged squatting task, which requires a single-legged base of support, and a double-legged squatting motion should elicit potentially bilateral differences and may help explain the deficits in function in those with HRGP.

Surface Electromyography Methodology

EMG is a method used in order to examine the activity of muscles throughout the body. Fine-wire EMG is known as the gold standard for looking at muscle activity by using a wire that gets inserted within a muscle to examine the activity. However, fine-wire EMG is invasive to subjects and expensive to use in a laboratory setting. sEMG is a method of examining muscle activity by placing electrodes on the skin's surface, making it less invasive and a more feasible option for most laboratories. Although not the gold standard, many researchers have examined the activity of hip musculature using sEMG to help better understand the effects of various diseases and conditions on neuromuscular function (5,6,13,71). The analysis of sEMG can better inform treatment options in patients with hip pathologies.

However, care must be taken prior to and during data collection to ensure quality data. Excess adipose tissue in the pelvic and hip region may cause more distance between the electrode located on the skin and the muscle belly, which is deep to the adipose tissue, thus decreasing the voltage that is read by the electrodes. Other issues such as artifact from the skin or clothing interaction may occur (13). However, previous studies have collected data on these muscles using sEMG (5,6,71). The following studies provide evidence of successful data collection and analysis of the hip musculature.

Bishop et al. (5) examined muscle activation patterns between the same exercises done with elastic resistance versus without elastic resistance. Specifically, the gluteus medius, gluteus maximus and tensor fascia latae were measured using sEMG. Differences in activation were noted between the trials with resistance and without resistance, with muscle activation trending to be greater, although not significantly, during the trials with resistance. Thus, surface EMG can be used to measure gluteus medius, gluteus maximus and tensor fascia latae activation and see differences in activation levels during tasks with different muscle requirements (5).

Borren et al. (6) examine the activations of the gluteus maximus and gluteus medius during a variety of rehabilitation exercises such as a single limb squat, side plank with abduction of the top leg, and a front plank with hip extension, to determine which exercise elicits the greatest percentage of the maximum voluntary isometric contraction (%MVIC) for each muscle (6). Different activation levels were noted during different exercises. This confirms surface EMG can accurately read muscle activation data for these muscles and is capable of detecting activation differences during various exercises dependent on the intensity (6).

Whiteley et al. (71) examined the effects of running incline, percent body weight, and speed on muscle activation of the lower limb during unloaded running. They examined the muscle activation of the rectus femoris across a variety of these variable combinations using surface EMG and reported an increase in rectus femoris muscle activation as the percent body weight increased, as well as when the incline increased. Throughout each progressive increase in body weight and incline, this increase was seen. This indicates that the increase in activity of the rectus femoris could be observed and assessed where expected, such that the EMG activity increased as the task got increasingly more difficult on the muscle (71).

Biomechanics on the hip during a single leg and double leg squat

Single-legged tasks are more demanding than double-legged tasks (9,40,43,49). Single-legged tasks are incorporated frequently in rehabilitation to help stress the body in a controlled environment and build neuromuscular control and strength (43,49). In individuals with HRGP, symptoms such as pain may not be apparent until a demanding task requiring large range of motion at the hip, such as a squat, is performed (40). It is thought that muscle activation patterns will be altered in the symptomatic limb in those with HRGP and that the altered patterns will be more severe in the single-legged squat as compared to a double-legged squat (9,40). The rationale behind this is that when individuals have pain, they may change their movement and activation patterns to compensate or avoid pain and discomfort. A single-legged squat is a more demanding task on the hip and may elicit more severe symptoms, therefore more exaggerated compensation mechanisms should occur (9). Few studies have compared the demand of single-legged tasks and double-legged tasks on the hip in individuals with HRGP, however, some studies have examined the effects on the body of various single-legged tasks on healthy individuals.

Kinematic/Kinetic differences

Some studies looked at impact on the single-legged task on the kinematic and kinetic differences between those with HRGP and healthy individuals. Harris-Hayes et al. (28) examined the kinematic and kinetic differences between those with HRGP and healthy controls performing a single-legged squat. They determined that those with HRGP perform the single-legged squat with smaller hip and knee flexion angles. Contrary to those findings, a study done by Lewis et al. (45) examined the kinematic and kinetic differences between those with HRGP and healthy controls during a single-legged step down. This study concluded that those with HRGP perform the step down with greater hip flexion and anterior pelvic tilt. These variances in conclusions may be due to the different single-legged tasks analyzed, however both shed light on the need to better understand the effect of single-legged tasks on those with HRGP.

Kinematic and kinetic differences have been noted during single-legged and double-legged squats in individuals with HRGP compared to healthy individuals (47). During a single-legged squat, individuals with HRGP demonstrated smaller maximal hip adduction and thigh adduction angles compared to healthy individuals (47). However, during a double-legged squat, maximal hip adduction and thigh adduction angles were similar in the two populations (47). The compensation during the single-legged squat in those with HRGP may be due to an attempt to minimize the pain and other symptoms associated with the disease (47). This may confirm that the added stress on the hip joint during the single-legged squat in those with HRGP may elicit a change in use by these individuals. Hip abduction and extension moments were smaller in those with HRGP during a single leg-squat compared to healthy controls. Hip extension moments were also smaller during a double-legged squat in those with HRGP compared to healthy individuals, but not as much of a decrease as the single-legged squat (47). The reason for the lower moments may also be due to a compensatory mechanism to limit the symptoms occurring during single-legged or high joint force tasks. In healthy individuals, when comparing single-legged and double-legged jump landings with single-legged and double-legged squats, similar differences were found between tasks (21). The double-legged landing and squat had significantly higher maximal knee and hip flexion angles compared to single-legged landings and squats (21). These findings are attributed to the increased demands single-legged tasks make on the body (21). The single-legged tasks limit joint range of motion to maintain stability (21). However, maximal hip adduction angles were significantly smaller in the double-legged tasks compared to the single-legged tasks in healthy individuals (21). This may be a compensatory mechanism to move the leg toward the center of the body so the center of mass can be managed more effectively over the base of support, providing increased stabilization during single-legged tasks (56).

Joint moments have also been examined during single-legged and double-legged tasks. Maximum external knee abduction moments are significantly higher in double-legged tasks compared to the single-legged tasks (21). Taylor et al. (67) examined the differences in moments during double-legged landing jumps and single-legged landing jumps. Maximum hip flexion, hip adduction and hip internal rotation moments were significantly higher in the single-legged jump landings compared to double-legged jump landings (67).

Muscle activation differences

Few studies have directly compared muscle activation differences between a single-legged squat and double-legged squat. In one study, healthy female athletes displayed a significantly greater activation of the gluteus medius and hamstring muscles during a single-legged squat compared to during a double-legged squat (50). Conversely, the quadriceps muscle had significantly higher average and peak activation during the double-legged squat (50). The high activation of the gluteus medius confirms the idea that during a single-legged squat, the activation will be higher due to the higher stress put on the hip joint due to the increased frontal plane moment (50) and the need to stabilize the hip/pelvis complex through the movement.

DeForest et al. (15) looked at muscle activation differences in healthy individuals between a single-legged squat and double-legged squat tasks. Muscle activity of the non-dominant leg muscles (gluteus maximus, bicep femoris, semitendinosus, rectus femoris, vastus lateralis, vastus medialis, tibialis anterior, and medial gastrocnemius of the left leg) was examined in these two squatting tasks. With the exception of the biceps femoris, all of the muscle activity was similar between the two tasks. The bicep femoris had significantly higher activation during the single-legged squat compared to the double-legged squat. This high activation of the bicep femoris during the single-legged task also supports the idea that single-legged tasks increase the load placed on the muscles involved in the single limb squat, potentially increasing the muscle activation needed to help control and/or support the movement.

Other studies have examined the activation of various lower extremity muscles during single-legged tasks (55). The rectus femoris, hamstrings and gastrocnemius were found to have higher muscle activation during a unilateral jump landing compared to a bilateral jump landing (55). This suggests that in order to control the body on a single leg, the muscles need to activate more of the muscle fibers to elicit the desired response (55). Although this does not describe all the muscles at the hip, it can help us understand a bit more of what the lower extremity must do to compensate for the single-legged tasks. With this information, we can infer that the muscles at the hip will have to respond in a similar manner namely with increase activation, to have the needed control of the body during a single-legged task. The muscle activation patterns of the lower extremity change during single-legged tasks.

Van Soest et al. (69) looked at the difference in muscle activity in single-legged versus double-legged countermovement jumps in athletes. They examined the gluteus maximus, semitendinosus, rectus femoris, vastus medialis, gastrocnemius, and soleus muscles. They determined that the only significant difference between the two jumps was the muscle activity of the vastus medialis and gastrocnemius muscles were greater in the single-legged countermovement jump compared to the double-legged countermovement jump (69). Again, demonstrating that during single-legged tasks, the lower extremity is under more stress, increasing the need for increased muscle activity to control the movement. Understanding these changes particularly within patient populations, like people with HRGP, will not only help us understand the compensations used to perform certain tasks but also how we can intervene and treat this disease effectively.

Chapter 3: Methods

Subjects

Subjects were recruited through several methods. Advertisements for the study were placed around West Virginia University (WVU) campus and were sent out through various means to the students and faculty. Individuals were asked to contact the WVU Sports Medicine Research Lab with their interest. Recruitment was also done at the WVU orthopedic clinic at University Town Center. Patients who met the inclusion and exclusion criteria were approached by their orthopedic physician during their routine doctor's appointment and given a flyer about the study with the lab's contact information. Interested individuals were asked to go through with a screening interview where they were asked the inclusion/exclusion criteria listed below. Once eligibility was confirmed, an in-person clinical assessment was performed and Dr. Jochimsen conducted to diagnosis unilateral HRGP. HRGP was confirmed with specific symptoms, including movement accompanied by hip pain, stiffness, and snapping or popping of the hip; or HRGP was confirmed with pain during specific clinical tests, including the hip flexion, adduction, internal rotation (FADIR) test, or the hip flexion, abduction, external rotation (FABER) test (22). Participants were required to meet the following inclusion/exclusion criteria:

Inclusion criteria

- Unilateral hip-related groin pain
- Hip pain for > 3 months
- ≤ 45 years old
- Speak and read fluent English

Exclusion criteria

- Previous hip surgery (i.e. hip arthroscopy, open hip dislocation, periacetabular osteotomy) or previous hip diagnosis of Legg-Calve-Perthes disease or slipped capital femoral epiphysis
- Spine or lower extremity surgery or major injury within the last 3 months (other than current hip pain)

- Involvement in other treatments for the HRGP during the study
- Hip pain from another problem such as a stress fracture

The requirement for individuals to have hip pain which has occurred for more than three months has been used as an inclusion criterion for other similar studies and helped to confirm the pain is chronic (16). There will be a maximum age inclusion of 45 years of age. This is to reduce the likelihood of hip OA (68). This inclusion criterion was used to help specify and narrow down the exact population trying to be examined for this study. The exclusion criteria were designed to limit injury to the subjects and confirm our intervention is the only one at play in treating the injury. These inclusion and exclusion criteria are commonly used for this patient population (27).

To determine our target sample size, we used data from Spiker et al. (65). Within this study, they examined the sEMG of the gluteus medius in those with chronic hip pain and those without chronic hip pain during multiple functional tasks; walking, fast walking, stair ascent, stair descent and sit to stand. Since the sit-to-stand task mimics the same large range of motion that occurs at the hip joint, as the squat causes, we used it for the power analysis. The mean sEMG peak linear envelope of those with chronic hip pain was 8.6 % MVIC and the mean sEMG peak linear envelope for those without was 17.4 % MVIC, the standard deviation was 3.5 (65). From this, we determined apriori that 3 participants will be needed to achieve adequate statistical power.

Procedures

Following confirmation of the subject's eligibility in the study based on the inclusion and exclusion criteria, the subject scheduled an appointment to complete the informed consent and testing session in the Mountaineer Sports Medicine Research Laboratory at WVU. During this session, the experimental procedures were explained thoroughly, and the subject was encouraged to ask questions. Written consent was obtained for this WVU IRB approved study [IRB #2106336942]. The subjects then completed surveys via the REDCap^{TM} database using a laboratory iPad; the surveys included demographics, activity levels for pre-injury and current and symptom duration. Following completion of surveys, the subject was instructed to change into snug fitting shorts and t-shirt, along with lab provided shoes (Nike Air Zoom Pegasus 38 TB). Height and weight of the subject was obtained using a stadiometer and scale in the lab.

This study was a part of a larger study that was using a 3D motion capture lab and cluster markers. The 3D motion capture data will be available for this thesis if needed.

Surface electromyography (sEMG) (Trigno Avanti Sensors and Trigno Sensors, Delsys, Natick, MA) (2000Hz) data were collected on the gluteus medius, gluteus maximus, tensor fascia latae, and rectus femoris. Raw data were sent through an onboard bandwidth filter of 20-450Hz. The skin was shaved if needed and prepped with alcohol to make sure it is clean to minimize the electrical noise. The sEMG was placed on the belly of the muscles. The gluteus medius electrodes were placed at a third of the distance from the iliac crest to the greater trochanter, beginning at the greater trochanter (57,64). The gluteus maximus electrodes were placed at a third of the distance from the second sacral vertebrae to the greater trochanter, starting from the second sacral vertebra (57,64). The tensor fascia latae electrodes were placed on the line from the anterior spina iliaca superior to the lateral femoral condyle in the proximal one sixth (57,64). The rectus femoris electrodes were placed at 50% on the line from the anterior spina iliaca superior to the superior part of the patella (57,64). sEMG was collected during maximal strength testing and then during both the single-legged squat and double-legged squat tasks. The same investigator performed all electrode placements throughout the study to ensure valid and reliable readings.

A MVIC was done for each muscle to allow for a %MVIC to be calculated during each trial to be able to compare muscle activation across subjects. For the gluteus medius and TFL, MVIC was determined while the subjects layed supine with their knees extended; a strap was used and placed on the legs to bind them together, the subject then abducted the leg against strap resistance. A handheld dynamometer was placed under the strap against the lateral malleolus and held in place (Figure 1, 20,30). For the gluteus maximus, MVIC was determined while the subject was prone with their legs off the table. The leg not tested was planted on the ground and the tested leg was strapped around a treatment table. The strap was placed on the inferior femur just superior to the patella with the dynamometer sitting on the back of the leg just above the knee (Figure 2, 20,30). For the rectus femoris, MVIC was determined by having the subject lay with their back on a table; their leg was strapped to the table with a dynamometer above the knee. The subject lifted their leg upward against the strap (Figure 3, 20,30). The MVIC was be held for 5 seconds and done two times. The highest value achieved from the trials was used as the MVIC value. The individuals were instructed to gradually reach their peak force over the 5 seconds. These MVICs were taken for both the symptomatic and asymptomatic side legs. Details of MVIC processing are provided in the data processing section below.

Figure 1. Hip Abduction MVIC Testing

Figure 2. Hip Extension MVIC Testing

Figure 3. Hip Flexion MVIC Testing

Subjects then were instructed to complete five trials of a double-legged squat and five trials of a single-legged squat. For both tasks, the instructor visually showed an example of the task being asked to be performed. With the double-legged squat, the instructor cued the individual to place their feet hip width apart, cross their arms across their chest and to squat down like they are sitting in a chair (Figure 4). For the single-legged squat, the instructor cued the individual to stand upright and flex the knee of their contralateral (non-weight bearing) leg, so their shin was parallel to the ground, and to cross their arms across their chest, and squat down (Figure 5). There was a brief break given between the two squatting types to decrease the risk of fatigue. Timing of each trial was not standardized because it was an outcome variable used in this study.

Figure 4. Double--legged Squat Technique

Figure 5. Single--legged Squat Technique

Data Analysis

Data Extraction

After data collection, the EMG data was exported from TheMotionMonitor software and imported into Matlab software for data processing. Data analysis of both experimental EMG data and MVIC EMG data occurred using similar processing methods. Data analysis of experimental data was conducted for the single-legged squat and double-legged squat for each hip separately.

For both the single-legged squat and the double-legged squat, the sacral marker vertical center of mass (COM) was used to help determine the entirety of the squat. The full squat phase was from when the vertical COM moved more than 2 standard deviations (SD) away from baseline and ended when the vertical COM moved back to being equal or less than 1/2 SD away from baseline (14). The squat was analyzed as the full squat together. It has been found that those with HRGP tend to activate their hip muscles similarly during the ascent and descent phases of a squat (17). This seems to be acceptable and seen in other research, as done by Diamond et al. (17) and McCurdy et al. (50) who examined muscle activation through the entire squat and did not break it into phases. Therefore, we feel comfortable just analyzing this data as the full squat.

Data Filtering

Filtering of both experimental sEMG data and MVIC sEMG data occurred using similar processing methods. The data were filtered using a band-pass 20-350Hz, fourth order, zero order, Butterworth filter. This filtered data was then rectified, and the root mean square (RMS) value was determined over a moving window of 25ms (30). Since there were two MVIC trials, the average RMS of both trials was determined and then the peak RMS value of the two trials was used for the MVIC (63). The average RMS value was determined for each individual squat and then the average RMS of the last 3 single-legged squats (49,51) and 5 double-legged squats (10) was determined. These data were normalized to the MVIC EMG data, this will occur using *100*RMS of Squatting Task / MVIC*, to give % MVIC. This normalization helped to create a relative variable that can be compared across subjects, with minimal data bias. We determined the average activation throughout the trial (30).

Statistical Analysis

All statistical analyses were performed in SPSS software (IBM, version 21, Armonk, NY). Demographics (i.e. age, sex, height, weight, BMI) of the population were determined. Descriptive statistics, including measures of central tendency (means, medians, other percentiles) and dispersion (standard deviations, ranges) were computed for continuous data such as age. For the sEMG data for each of the muscles during the two squatting tasks, graphical displays including histograms, box plots, and Q-Q plots were produced to observe the distribution of the data. Prior to any of the statistical tests, the ShapiroWilk test of normality assumptions were used on all dependent variables with an alpha level set of 0.05.

Specific aim 1 looked at the bilateral muscle activation differences of the four hip muscles (TFL, rectus femoris, gluteus medius, and gluteus maximus) between the symptomatic side hip and contralateral side hip in those with HRGP during a double-legged squat. It was hypothesized that the total activity of the gluteus medius and gluteus maximus will be greater, the total activity of the TFL will be lower, and the total activity of the rectus femoris will be the same in the symptomatic side hip when compared to the contralateral side hip. Specific aim 2 looked at the bilateral muscle activation differences of the four hip muscles between the symptomatic side hip and contralateral side hip in those with HRGP during a single-legged squat. It was hypothesized that the total activity of the gluteus medius, gluteus maximus, and rectus femoris will be greater and the total activity of the TFL will be lower in the symptomatic side hip when compared to the contralateral side hip. Lastly, Specific aim 3 looked at the hip muscle activation differences between the single-legged squat and double-legged squat of the symptomatic side hip in those with HRGP. It was hypothesized that the muscle activation differences between the symptomatic and contralateral sides will be greater in the single-legged squat compared to the double-legged squat.

For specific aim 1, the ShapiroWilk test determined that the data of the TFL, rectus femoris, and gluteus medius were non-normally distributed, while the gluteus maximus was normally distributed. An independent T-test was used to examine the differences in muscle activation of the gluteus medius between the symptomatic and contralateral side hips during a double-legged squat. A Mann-Whitney U test was used to examine the differences in the muscle activation of the TFL, rectus femoris, and gluteus maximus between the symptomatic and contralateral limbs during the double-legged squat. For specific aim 2, the ShapiroWilk test determined that data of all four muscles were normally distributed. An independent T-test was used to examine the differences in muscle activation of the TFL, rectus femoris, gluteus medius and gluteus maximus between the symptomatic and contralateral side hips during a single-legged squat.

For specific aim 3, the ShapiroWilk test determined the TFL data were non-normally distributed, while the rectus femoris, gluteus medius, and gluteus maximus were normally distributed. An independent T-test was used to examine the differences in hip muscle activity of the rectus femoris, gluteus medius, and gluteus maximus between tasks (double-legged and single-legged) in the symptomatic side hip. A Mann-Whitney U test was used to examine the differences in muscle activation of the TFL between tasks (double-legged and single-legged) in the symptomatic side hip. The alpha was set to 0.05 for all analyses.

Chapter 4: Results

Seven individuals with unilateral hip-related groin pain between the ages of 23 and 31 (1M/6F) were recruited from the Morgantown area (Table 1). Individual subject data is available via appendices A and B. Scatter plots of each individuals data are located in appendices C and D.

Table 1. Subject demographics.

Age (yrs)	Height (cm)	Mass (kg)	BMI (kg/m^2)
25.83±3.37	166±9.74	72.57±12.48	25.92±4.83

Specific Aim 1: Double-legged squat

Specific Aim 1 was to examine the differences in muscle activation of the TFL, rectus femoris, gluteus medius, and gluteus maximus between the symptomatic and contralateral hips of an individual with HRGP during a double-legged squat. During the double-legged squat, there were no significant activation differences found between sides for the TFL (p=.277; Figure 6), rectus femoris (p=.317; Figure 6), gluteus medius (p=.974; Figure 7), gluteus maximus (p=.848; Figure 6). The data are provided on separate figures because medians are shown in Figure 6 due to the data being not normally distributed; whereas means are shown in Figure 7 because the data was normally distributed.

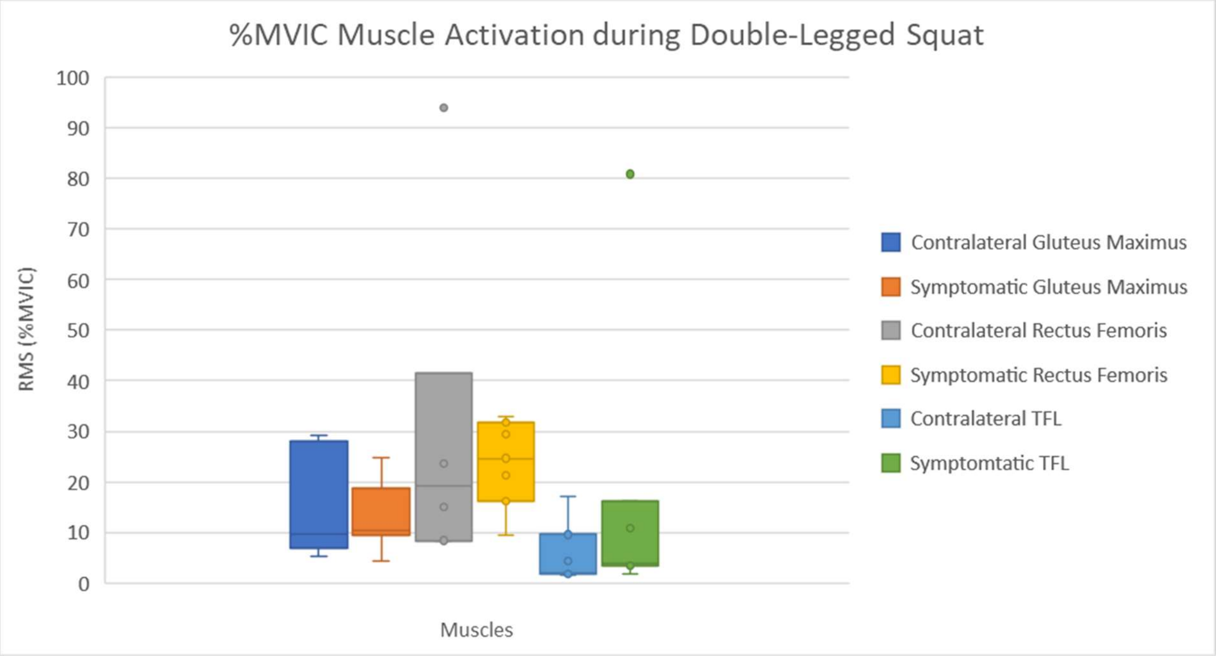


Figure 6. Bilateral hip muscle activation during a double-legged squat. The medians and interquartile ranges (IQR) are presented for the TFL, rectus femoris, and gluteus maximus. No significant differences were found.

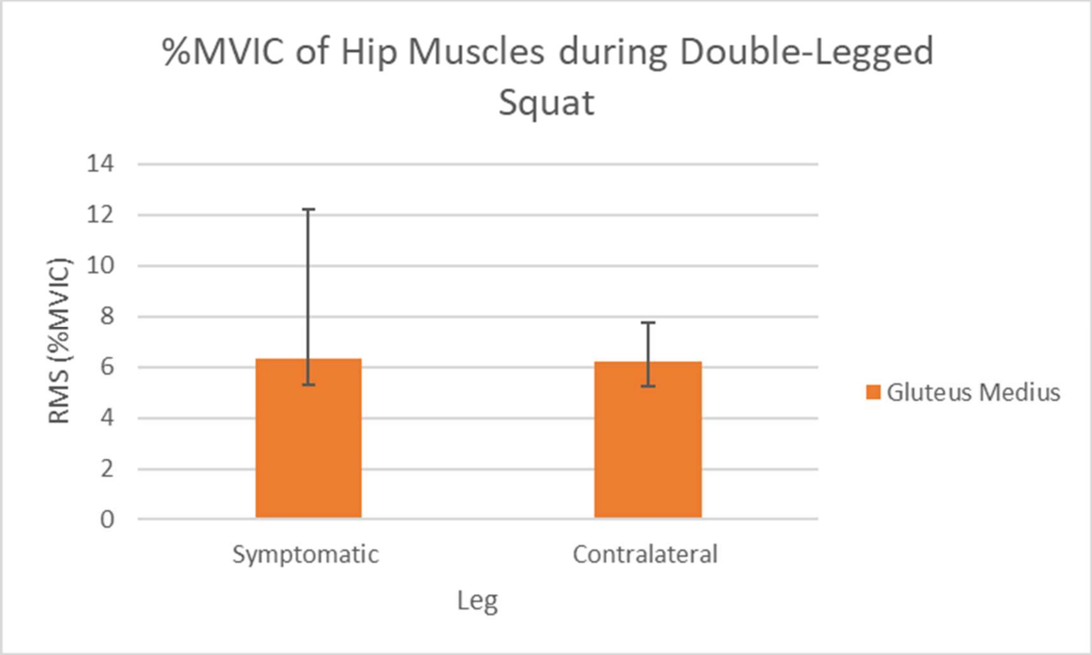


Figure 7. Bilateral hip muscle activation during a double-legged squat. The mean and standard deviation (SD) is presented for the gluteus medius. No significant differences were found.

Specific Aim 2: Single-legged squat

Specific Aim 2 was to examine the differences in muscle activation of the TFL, rectus femoris, gluteus medius, and gluteus maximus between the symptomatic and contralateral hip of an individuals with HRGP during a single-legged squat. During the single-legged squat (Figure 8), there were no activation differences found between sides for the TFL (p=.928), rectus femoris (p=.566) gluteus medius (p=.891), gluteus maximus (p=.982).

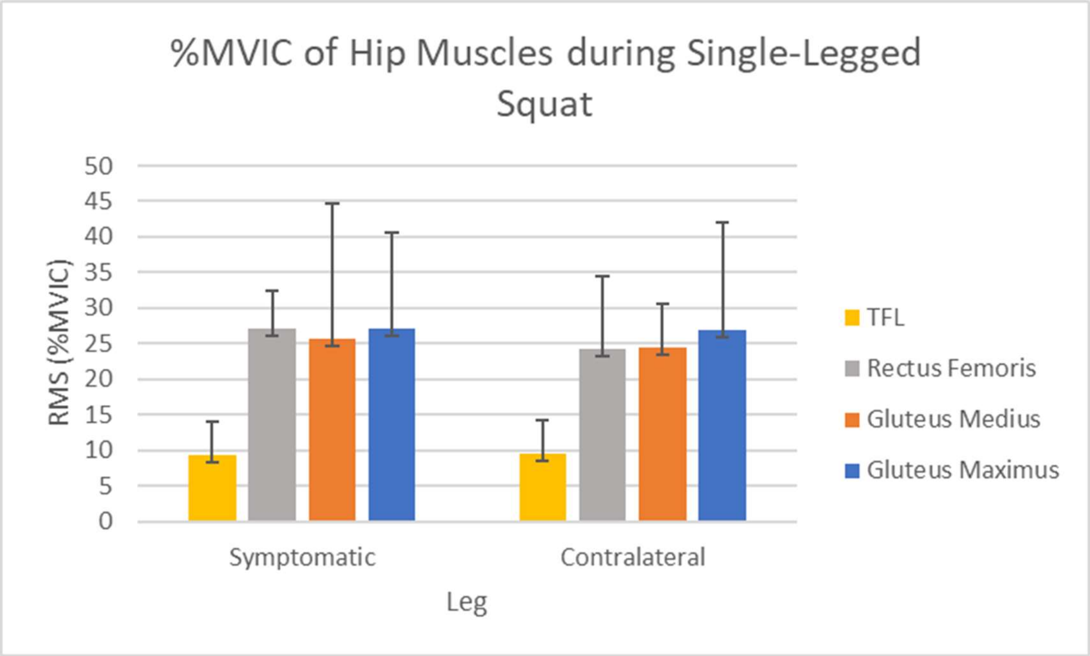


Figure 8. Bilateral hip muscle activation during a single-legged squat. The means and standard deviations (SD) are presented here for the TFL, rectus femoris, gluteus medius, and gluteus maximus. No significant differences were found.

Specific Aim 3: Comparison of tasks

Specific Aim 3 was to examine the muscle activation differences between muscle activity of the symptomatic side TFL, rectus femoris, gluteus medius, and gluteus maximus between the single-legged squat and double-legged squat in those with HRGP. In the symptomatic hip, gluteus maximus activation was higher in the single-legged squat than the double-legged squat (p =.036; Figure 10). Activation of the symptomatic side TFL (p=0.749; Figure 11), the rectus femoris (p=0.390; Figure 10) and the gluteus medius (p=.057; Figure 10) were not significantly different between the single-legged squat and double-legged squat. The data are provided on separate figures because medians are shown in Figure 11 due to the data being not normally distributed; whereas means are shown in Figure 10 because the data was normally distributed.

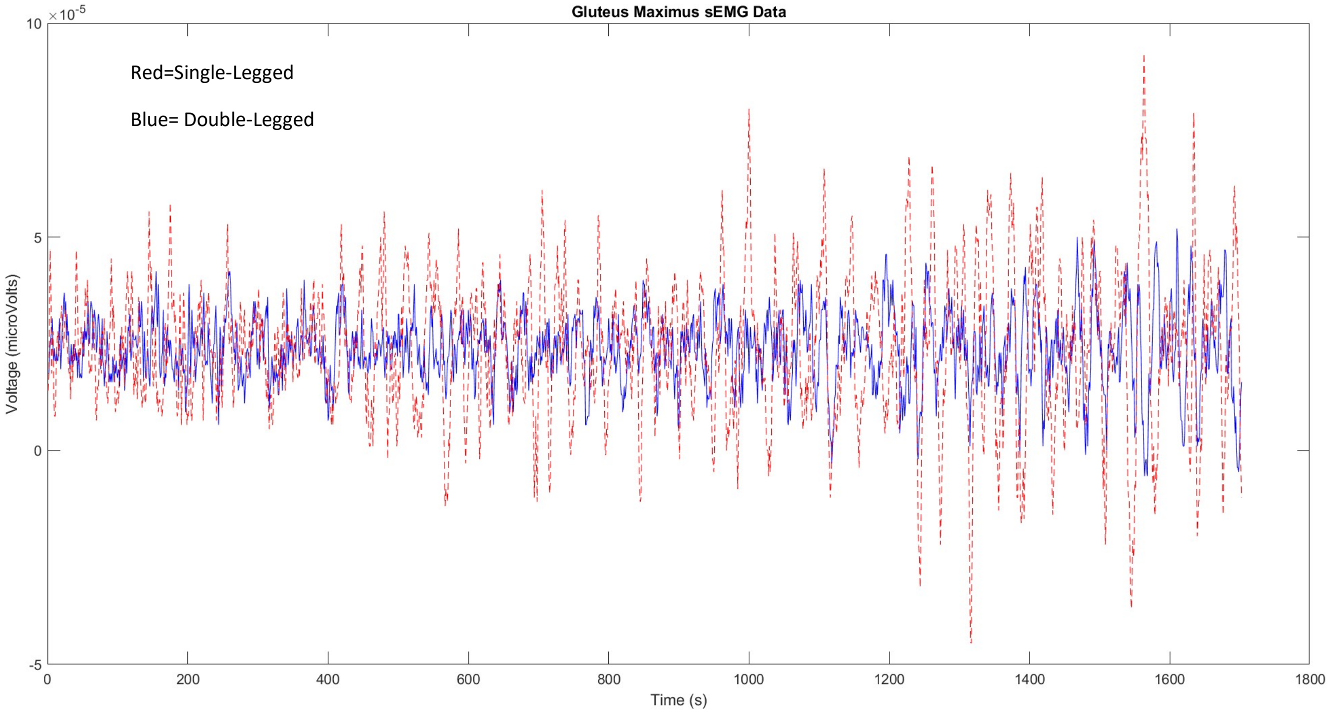


Figure 9. Raw sEMG signal of the gluteus maximus during a single-legged and double-legged squat. The red line indicated the single-legged squat, and the blue line indicated the double-legged squat. The gluteus maximus activation during the single-legged squat was significantly greater than during double-legged squat (p=.036).

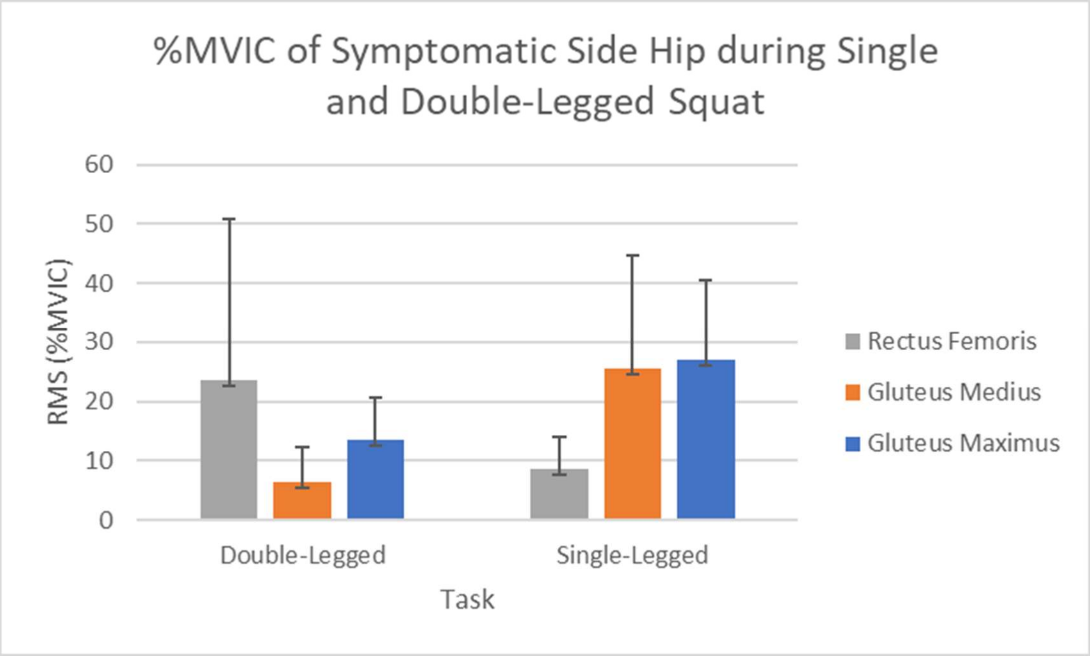


Figure 10. Symptomatic side hip muscle activation during a single and double-legged squat. The means and standard deviations (SD) are presented for the rectus femoris, gluteus medius, and gluteus maximus. The gluteus maximus had higher activation (p=.036) during the single-legged squat. No other differences were found.

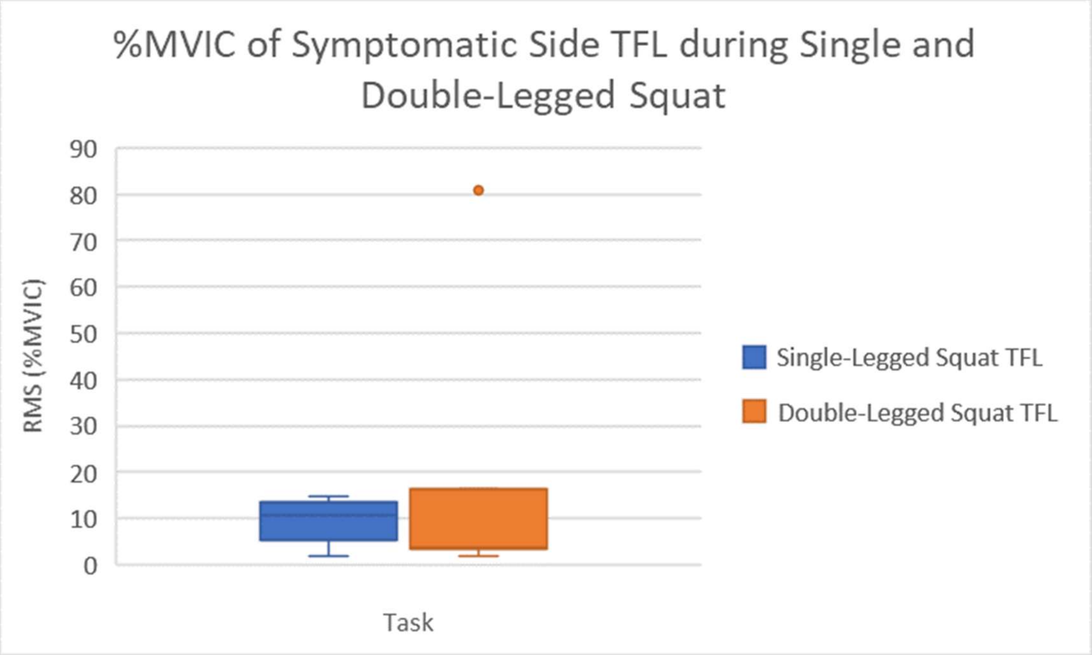


Figure 11. Symptomatic side hip muscle activation during a single and double-legged squat. The medians and interquartile ranges (IQR) are presented for the TFL. No differences were found.

Chapter 5: Discussion

The purpose of this study was to assess the hip muscle activation differences during squatting tasks in those with unilateral HRGP. Individuals with HRGP tend to experience severe symptoms of pain and dysfunction during activities like squatting tasks that require large range of motion of the hip joint. Little is known regarding treatment for this pain and dysfunction that these individuals feel. There is a need to better understand how the body functions in those with HRGP so that we can move forward with effective and long-term solutions for these individuals. This is one of the first studies to have investigated the role of the hip muscles during squatting in these individuals, particularly within the symptomatic and contralateral limb. This information may provide imperative insight, clinically, so that the neuromuscular function of the hips in those with HRGP is understood. Our hypothesis was that the hip muscles in the symptomatic side hip in those with HRGP would perform differently during squatting tasks than in the non-symptomatic side hip.

Specific Aim 1: Double-legged squat

Specific Aim 1 was to examine the differences in muscle activation of the TFL, rectus femoris, gluteus medius, and gluteus maximus between the symptomatic and contralateral hip of individuals with HRGP during a double-legged squat. We hypothesized that the total activity of the gluteus medius and gluteus maximus will be greater, the activity of the TFL would be lower and the activity of the rectus femoris will be the same in the symptomatic side hip when compared to the contralateral side hip.

Our hypotheses were partially supported. Rectus femoris activation was not different between the symptomatic and contralateral legs in our participants with HRGP during the double-legged squat task. Similar to our findings, Casartelli et al. (9) reported similar rectus femoris muscle activity between their healthy participants and those with HRGP. This result may be attributable to the rectus femoris' dual roles at the hip and the knee joints. With its primary role being at the knee for knee extension (29,53), its role at the hip is small (29,53) and may not be impacted by HRGP.

In contrast to our hypothesis, the activation of the TFL muscle was found to have no differences between the symptomatic side hip and contralateral side hip in our participants. Casartelli et al. (9) found that those with HRGP had lower muscle activity of the TFL during flexion tasks compared to healthy control subjects, and suggested that this finding is due to the limited ability of those with HRGP to fully activate their TFL muscle. We wanted to examine if the TFL continued to have a decreased ability to activate during more functional activities, such as squatting. We hypothesized that this decreased ability of the TFL to activate would continue during squatting. One reason for the contrast in our findings may be because the primary muscle involved during a squatting task is the gluteus maximus. During a double-legged squat, it is responsible for the ascent and descent phases of the squat and the TFL does not really have to fire or turn on. Therefore, we may not see differences in TFL activity because it is not required to activate anyway (17,33). Another reason for the contrast in our findings may be due to Casartelli et al. (9) not loading the TFL with body weight when they had their subjects flex their hip, instead they just flexed their hip using a dynamometer, which may not tell us how the TFL will function during real-time, functional activities. During double-legged squatting, when adding the load of one's body, which was not done in the study by Casartelli et al. (9), the TFL may have to increase its activation to help control the movement at the hip. Therefore, not showing any differences in the symptomatic side and contralateral side muscle activity.

Contrary to our hypotheses, we found no difference in the gluteus medius and the gluteus maximus muscle activity between the symptomatic and contralateral legs in those with HRGP. Our hypothesis for the increased activation of the gluteus medius and maximus came from a study done by Diamond et al. (17). In Diamond et al. (17) compared symptomatic side gluteus medius and gluteus maximus activity in those with HRGP to healthy controls during a double-legged squat. They reported greater gluteus maximus activity in those with HRGP compared to controls during a double-legged squat. The thought behind this is the increased activation of the hip muscles, was to increase the stability of the femoral head within the acetabulum. This would be a potential protective mechanism to keep the hip from moving into a position that may be more painful to those with HRGP (17). Our results may be different than those of Diamond et al. (17) because our study did not include a comparison to healthy controls. The changes that accompany HRGP may be seen bilaterally even if the symptoms of pain are primarily felt unilaterally. Seventy-eight percent of patients that present with symptomatic, unilateral HRGP, are found to have bilateral non-symptomatic clinical signs or morphology of HRGP (2). This similarity in muscle activation bilaterally may be purely due to similar structural and neuromuscular changes that follow HRGP.

Specific Aim 2: Single-legged Squat

Specific Aim 2 was to examine the differences in muscle activation of the TFL, rectus femoris, gluteus medius, and gluteus maximus between the symptomatic and contralateral hip of individuals with HRGP during a single-legged squat. We hypothesized that the total activity of the gluteus medius, gluteus maximus, and rectus femoris will be greater and the activity of the TFL will be lower in the symptomatic side hip when compared to the contralateral side hip.

The findings did not support our hypothesis. There were not differences in any of the hip muscle activity between symptomatic and non-symptomatic sides during a single-legged squat. One reason for this may be due to our lack of understanding of the kinematics of the subjects, primarily their trunk kinematics. Farrokhi et al. (23) and Kraus et al. (38) found changes in hip muscle activity dependent on the positioning of the individuals trunk. The more flexed an individual's trunk, the greater the hip muscle activation. Our subjects may be altering their movement patterns in order to compensate for the symptoms associated with HRGP. Therefore, if there were changes in hip muscle activity, the alteration in their movement patterns, particularly trunk position, may be hiding this difference. For the purposes of this discussion, we compared the squat depth on the symptomatic and contralateral limbs to see if it could help explain these results. We found no differences in squat depth between sides (Symptomatic limb: .19 ± .06m; Contralateral limb: .19 ± .057m; p=.950). The body was working similarly during the single-legged squat on each side. Another hypothesis for not seeing any differences between limbs may be due to existence of HRGP morphology bilaterally, even though they are only presenting with unilateral pain. As stated above, this occurs in about 78% of individuals who present with unilateral HRGP (2). This similar morphology bilaterally may contribute to similar neuromuscular patterns that occur during the single-legged squat. Another hypothesis could be that these patients have had this pain chronically. We know that the body adapts to chronic stimuli, and we may be seeing bilateral neuromuscular adaptations to this chronic hip pain (4). Since we do not have a control group, we are unable to tell what the muscle activity changes may be in those with HRGP compared to a healthy individual.

For the purposes of this discussion, we also ran a regression between squat depth and muscle activity. We found significant relationships between rectus femoris muscle activity and squat depth (R=.599, p=.030), as well as between gluteus maximus muscle activity and squat depth (R=.474, p=.087). The deeper the squat, the greater the EMG activity of the rectus femoris and gluteus maximus produced. This relationship was only seen in sagittal plane muscles and not the frontal plane muscles (TFL, gluteus medius). This relationship has been seen in prior studies as well. Gorsuch et al. (26) found that the deeper one squat the higher the rectus femoris activation. Caterisano et al. (11) found this same relationship with the gluteus maximus. This helps to show us that those with HRGP may actually be activating similarly to healthy individuals. Thus, the deeper the squat, the greater the EMG RMS of the sagittal plane muscles; No difference in squat depth was noted between the painful and asymptomatic hips, no difference in hip strength was noted between the painful and asymptomatic hips, and no differences in EMG activity were found.

Specific Aim 3: Comparison of Tasks

Specific Aim 3 was to examine the differences in muscle activation of the TFL, rectus femoris, gluteus medius, and gluteus maximus between the single-legged squat and double-legged squat of the symptomatic side hip in individuals with HRGP. We hypothesized that the muscle activation differences in the symptomatic side hip will be greater in the single-legged squat than in the double-legged squat.

Our hypotheses were partially supported. The symptomatic side hip in individuals with HRGP had greater gluteus maximus muscle activity during the single-legged squat than during the double-legged squat. Like our findings, other studies have reported increased activation of the lower extremity muscles during single-legged tasks (15,55). The reasoning for this increase in activation comes from the increased stress put on the hip joint and muscles during a single-legged task. The increased stress put on the unilateral hip joint requires the muscles to increase the activity to control the unilateral movement and the pelvis itself (50). The gluteus medius during the double-legged squat had a mean of 6.31 %MVIC and during the single-legged squat had a mean of 25.58 %MVIC. When just looking at the means, it appears there should be a significant difference. Yet there is no significance, likely due to the large standard deviations in these variables. We had a very small subject pool, with an N=7. It is believed that if we had a larger sample size, the difference in activation of the symptomatic side gluteus medius during a single and double-legged squat would have been significant.

Contrary to what we hypothesized, we found no significant differences in symptomatic side muscle activation between a double and single-legged squat for the rectus femoris. This finding can be confirmed with a study done by DeForest et al. (15), where they looked at a healthy population during double and single-legged tasks. They found no difference in the rectus femoris activity during the two squatting tasks. Our original thought regarding the increase in rectus femoris activity during a single-legged squat came from the idea that individuals with HRGP tend to feel unstable in their hip (40). It was thought they would attempt to combat the instability, particularly in a single-legged high stress task, by increasing the activity of the muscles contributing to the hip stability. Therefore, recruiting multiple muscles around the hip to assist with stabilizing, including the rectus femoris. With these findings, we can conclude that the rectus femoris may not be contributing to stabilization during these tasks.

No significant difference in TFL activation between tasks was found. Not much research has examined this muscle during squatting tasks, primarily due to the difficulty of the target EMG placement. Prior research done by Casartelli et al. (9), found that those with HRGP tended to have decreased TFL activation during maximal hip flexion. This combined with the knowledge of the increased stress we see on the hip joint during single-legged tasks (15,55,69), it was thought we would see this decreased activation to a greater extent in the single-legged task. Our results did not conclude this and could be because of a few reasons. One of which is that the increased stress on the hip increased the muscle activity of the TFL to help compensate for the decreased stability of the single-legged task. This could be the body's response to increase control of the body. Another reason could be lack of correct placement of the electrode for the TFL muscle. Given that the TFL is a difficult muscle to find and potentially place, there is always the chance that during collection, we had misplaced the TFL EMG electrode. This would skew the data we received from the TFL activity, giving us false conclusions.

Although not part of our main purpose, we examined the differences in muscle activation between phases of the squat (ascent, descent) in those with HRGP. We found no differences in muscle activation of any of the muscles between ascent and descent in this subject pool. This is interesting because this is a similar finding as Diamond et al. (17) who examined the activation differences in those with HRGP between ascent and descent of the squat and found no differences in hip muscle activation. In healthy individuals, there should be variation in muscle activity during the ascent and descent, with descent having lower hip muscle activity compared to descent. This tells us that those with HRGP have altered patterns of activation during squatting. This may be due to many things, like the attempt of the body to protect itself from entering a position of pain and hip impingement. The increase in activation during descent helps to stabilize and try to prevent entering that impingement, or painful position.

Few studies have a direct comparison of muscle activation means to our study. However, we can use activities that have similar movement patterns in order to infer if our means are similar. Spiker et al. (65) had individuals with HRGP perform a sit-to-stand task, which can be comparable to a double-legged squat and measured gluteus medius activity during the task. They determined the mean gluteus medius activation during a sit-to-stand task was 8.6% of their MVIC. During our study, when those with HRGP performed a double-legged squat their gluteus medius had an activation of 6.31% of their MVIC. Spiker et al. (65) and Hammond et al. (27) examined the gluteus medius muscle activation during stair climbing, which can be comparable to a single-legged squat. Spiker et al. (65) determined those with HRGP have a gluteus medius %MVIC of 29.8% and Hammond et al. (27) found they had a %MVIC of 30.5%. In our study, when those with HRGP performed a single-legged squat, their gluteus medius had an activation of 25.6%. These variations in means are minimal and can be purely due to differences in the tasks the individuals are performing. However, they are similar enough that we can infer our gluteus medius data are comparable to others who have examined muscle activation in those with HRGP. Hammond et al. (27) also examined the rectus femoris during a stair climbing task and determined those with HRGP have a %MVIC of 17.1%. During our study, with the comparable single-legged squat, our subjects had a %MVIC of 27.1% in their rectus femoris muscle. There is a bit of variance in our means of the rectus femoris activation. This can be due to how those with HRGP alter their movement and activation patterns to complete tasks. Therefore, even though the movement of a single-legged squat and stair step-up is similar, those with HRGP may be completing each task using different muscles. Therefore, our rectus femoris activation during this task is not comparable to the rectus femoris activation during a stair step-up. From previous research done in these individuals, we can determine that our muscle activation data may be comparable to other studies and we can potentially use our data on those with HRGP to move forward with potential treatments to aid these individuals in moving and feeling better.

Several limitations exist within this study. One limitation this study had was the small sample size due to time constraints, issues with recruitment and exclusion of many participants.

Thus, it is hard to conclude if the results of the study happened by chance is a true result. Some of our results indicate that with a bigger sample size, they would be significant but with the current sample, these significances are not there. This makes it difficult to generalize to a bigger population along with comparing to other studies looking at individuals with HRGP.

The use of sEMG was a limitation of this study. The use of sEMG was done due to the ease of use and access to the device. The alternative would have been fine-wire EMG. However, this EMG method is invasive and requires equipment that our lab does not have. The use of sEMG may have skewed the accuracy of the data. It is harder to ensure the muscle activity detected is the desired musclee. We also encountered significantly more artifact and issues with the device falling off, etc. This should be kept in mind when examining the muscle activity data in this study.

Another limitation this study faced was broken EMG sensors. The use of broken EMG sensors occurred for some of the participants. This then gave us partial data for an individual. For example, we would have data for only three out of the four muscles, making it difficult to have full datasets and decreased our sample size again. Although this only occurred for some of the participants and we were able to get new sensors, the lack of data for some muscles may have influenced our results. We are missing the gluteus medius muscles activation for four subjects.

Although kinematic data were collected, they were not examined for this study, with the exception of squat depth. Therefore, we cannot know how differences in body movement between the affected and contralateral legs may have influenced these results. For example, how each subject may have positioned their torso, or angle of hips or ankles, in order to accomplish the squatting tasks. We understand from research done by Farrokhi et al. (23) and Kraus et al. (38) that trunk position impacts the activation of the hip muscles. The more flexed an individual's trunk, the greater the hip muscle activation. So, subjects may be altering their movement patterns in order to compensate for the symptoms associated with HRGP. If there were changes in hip muscle activity, body movement, particularly trunk position, may be hiding this difference. We also did not account for pain in these participants. We were comparing between legs and did not have pain rating for both legs, therefore we could not account for pain during the squatting tasks.

Lastly, a limitation we experienced was a lack of control group for this study. We did not use a control group due to lack of resources to fund a control group, along with limited time and low levels of recruitment. The use of a control group could have given us a true comparison in muscle activation between healthy individuals and those with HRGP and how it may be different. However, with the issues we had, using the participant as their own control worked to give us a relatively good comparison.

Future Research

In those with HRGP, the understanding of how the body is affected by HRGP and how it responds to these effects requires further exploration. The more we know and understand about HRGP and its effects on the body, the better we can move forward with a more effective treatment. Research looking at the relationship between body movement or kinematics and muscle activation should be examined in depth. This issue has been looked at secondarily in some research studies however, the relationship between muscle activation and kinematics itself has not been examined primarily. The reason this may be important in this population is because of the potential "give and take" these mechanisms may have with each other. An individual with HRGP may move differently to compensate for many things like pain, functional barriers, or fear of movement. This change of movement can then influence how the muscles are working and could exacerbate the issue at hand. This relationship could also function in the opposite way. Determining if this relationship exist could help us to intervene in a manner that teaches them to move their body or activate their muscles differently and could help us see changes in pain or function.

Another place for future research includes limiting the variability and noise in individuals' movement strategies. For example, there is typically much inter-subject variability in performing a single-legged squat, due to the increased difficulty of the task. In order to combat this, we could have individuals preform different tasks that would elicit similar movements about the hip joint, such as height-based stair climbs or step-ups. These movements can decrease the variability of the movement strategies used for a few reasons. One could be due to it being an easier task. Another is that we can help standardize it by altering the height of each box to be a fair height for each individual and we do not have to account for other factors that may be influencing our findings such as squat depth, unweighted leg position, or trunk position.

We did not look at the relationship between duration of symptoms and muscle activation levels. This could help to separate the individuals who have had these symptoms for a long duration from those with low duration of symptoms. Pain duration may have a relationship to muscle activation levels or patterns. This could tell us how individuals adapt to HRGP. Understanding if this relationship exists would not only tell us more about HRGP, but could help tell us how to intervene and help these individuals. We also did not look at the relationship between pain levels and muscle activation. Pain has been seen to influence how individuals move (1,2). Understanding if this relationship exists, would tell us the influence pain has on the variations in function we see in those with HRGP. This would provide insight into care and treatment as well. In conclusion, looking at these relationships may help with better understanding what occurs in those with HRGP and should be examined in the future.

Conclusion

Minimal differences are seen bilaterally during a single and double-legged squat in those with HRGP. However, when just examining the symptomatic side hip, we see increased activity during the single-legged squat in the posterior muscles, gluteus maximus and gluteus medius, in those with HRGP. This data should be examined with caution due to the extremely small subject pool. The data we have received may be skewed from the N=7. However, this information helps us to understand that bigger studies with more participants are needed to come to any further conclusions.

References

1. Ahuja V, Thapa D, Patial S, Chander A, Ahuja A. Chronic Hip Pain in Adults: Current Knowledge and Future Prospective. J Anaesthesiol Clin Pharmacol. 2020 Oct-Dec;36(4):450-457. doi: 10.4103/joacp.JOACP_170_19. Epub 2020 Sep 26. PMID: 33840922; PMCID: PMC8022067.
2. Allen D, Beaulé PE, Ramadan O, Doucette S. Prevalence of Associated Deformities and Hip Pain in Patients With Cam-Type Femoroacetabular Impingement. The Journal of Bone and Joint Surgery British volume. 2009;91-B(5):589-594. doi:10.1302/0301-620X.91B5.22028
3. Bagwell JJ, Snibbe J, Gerhardt M, Powers CM. Hip Kinematics and Kinetics in Persons With and Without Cam Femoroacetabular Impingement During a Deep Squat Task. Clinical Biomechanics. 2016;31:87-92. doi:10.1016/j.clinbiomech.2015.09.016
4. Bartsch RP, Liu KK, Bashan A, Ivanov PC. Network Physiology: How Organ Systems Dynamically Interact. PloS one. 2015;10(11):e0142143.
5. Bishop BN, Greenstein J, Etnoyer-Slaski JL, Sterling H, Topp R. Electromyographic Analysis of Gluteus Maximus, Gluteus Medius, and Tensor Fascia Latae During Therapeutic Exercises With and Without Elastic Resistance. Int J Sports Phys Ther. 2018 Aug;13(4):668-675.
6. Boren K, Conrey C, Le Coguic J, Paprocki L, Voight M, Robinson TK. Electromyographic Analysis of Gluteus Medius and Gluteus Maximus During Rehabilitation Exercises. Int J Sports Phys Ther. 2011;6(3):206-223.
7. Callhoff J, Albrecht K, Redeker I, Lange T, Goronzy J, Günther KP, Zink A, Schmitt J, Saam J, Postler A. Disease Burden of Patients With Osteoarthritis: Results of a Cross-Sectional Survey Linked to Claims Data. Arthritis Care Res (Hoboken). 2020 Feb;72(2):193-200. doi: 10.1002/acr.24058.
8. Casartelli NC, Leunig M, Item-Glatthorn JF, Lepers R, Maffiuletti NA. Hip Flexor Muscle Fatigue in Patients With Symptomatic Femoroacetabular Impingement. Int Orthop. 2012 May;36(5):967-73. doi: 10.1007/s00264-011-1385-5. Epub 2011 Oct 26. PMID: 22038443; PMCID: PMC3337110.
9. Casartelli NC, Maffiuletti NA, Item-Glatthorn JF, Staehli S, Bizzini M, Impellizzeri FM, Leunig M. Hip Muscle Weakness in Patients With Symptomatic Femoroacetabular Impingement. Osteoarthritis Cartilage. 2011 Jul;19(7):816-21. doi: 10.1016/j.joca.2011.04.001. Epub 2011 Apr 12. PMID: 21515390.
10. Catelli DS, Kowalski E, Beaulé PE, Smit K, Lamontagne M. Asymptomatic Participants With a Femoroacetabular Deformity Demonstrate Stronger Hip Extensors and Greater Pelvis Mobility During the Deep Squat Task. Orthop J Sports Med. 2018 Jul 17;6(7):2325967118782484. doi: 10.1177/2325967118782484. PMID: 30038915; PMCID: PMC6050869.
11. Caterisano A, Moss RE, Pellinger TK, et al. The Effect of Back Squat Depth on the EMG Activity of 4 Superficial Hip and Thigh Muscles. The Journal of Strength & Conditioning Research. 2002;16(3):428-432.

12. Clohisy JC, Baca G, Beaulé PE, et al. Descriptive Epidemiology of Femoroacetabular Impingement: A North American Cohort of Patients Undergoing Surgery. Am J Sports Med. 2013;41(6):1348-1356. doi:10.1177/0363546513488861
13. Cram JR Kasman, Glenn S, Holtz, Jonathan,. Introduction to Surface Electromyography. Aspen Publishers; 1998.
14. Cvetanovich GL, Farkas GJ, Beck EC, Malloy P, Jan K, Espinoza-Orias A, Nho SJ. Squat and Gait Biomechanics 6 Months Following Hip Arthroscopy for Femoroacetabular Impingement Syndrome. J Hip Preserv Surg. 2020 Feb 18;7(1):27-37. doi: 10.1093/jhps/hnaa004.
15. DeFOREST BA, Cantrell GS, Schilling BK. Muscle Activity in Single- vs. Double-legged Squats. Int J Exerc Sci. 2014 Oct 1;7(4):302-310.
16. Diamond LE, Van den Hoorn W, Bennell KL, et al. Coordination of Deep Hip Muscle Activity is Altered in Symptomatic Femoroacetabular Impingement. Journal of Orthopaedic Research. 2017;35(7):1494-1504. doi:10.1002/jor.23391
17. Diamond LE, van den Hoorn W, Bennell KL, et al. Deep Hip Muscle Activation During Squatting in Femoroacetabular Impingement Syndrome. Clinical Biomechanics. 2019;69:141-147. doi:10.1016/j.clinbiomech.2019.07.017
18. Diamond LE, Wrigley TV, Bennell KL, Hinman RS, O'Donnell J, Hodges PW. Hip Joint Biomechanics During Gait in People With and Without Symptomatic Femoroacetabular impingement. Gait & Posture. 2016;43:198-203. doi:10.1016/j.gaitpost.2015.09.023
19. Diamond LE, Wrigley TV, Hinman RS, et al. Isometric and Isokinetic Hip Strength and Agonist/Antagonist Ratios in Symptomatic Femoroacetabular Impingement. Journal of Science and Medicine in Sport. 2016;19(9):696-701. doi:10.1016/j.jsams.2015.10.002
20. DiStefano LJ, Martinez JC, Crowley E, Matteau E, Kerner MS, Boling MC, Nguyen AD, Trojian TH. Maturation and Sex Differences in Neuromuscular Characteristics of Youth Athletes. J Strength Cond Res. 2015 Sep;29(9):2465-73. doi: 10.1519/JSC.0000000000001052. PMID: 26313573.
21. Donohue MR, Ellis SM, Heinbaugh EM, Stephenson ML, Zhu Q, Dai B. Differences and Correlations in Knee and Hip Mechanics During Single-Legged Landing, Single-Legged Squat, Double-Legged Landing, and Double-Legged Squat Tasks. Res Sports Med. 2015;23(4):394-411. doi: 10.1080/15438627.2015.1076413.
22. Enseki K, Harris-Hayes M, White DM, et al. Nonarthritic Hip Joint Pain. J Orthop Sports Phys Ther. 2014;44(6):A1-A32. doi:10.2519/jospt.2014.0302
23. Farrokhi S, Pollard CD, Souza RB, Chen YJ, Reischl S, Powers CM. Trunk Position Influences the Kinematics, Kinetics, and Muscle Activity of the Lead Lower Extremity During the Forward Lunge Exercise. Journal of Orthopaedic & Sports Physical Therapy. 2008;38(7):403-409.
24. Gluteus Maximus. UW Radiology. https://rad.washington.edu/muscle-atlas/gluteus-maximus/. Accessed January 15, 2022.
25. Gluteus Medius - Attachments, Actions &Amp; Innervation. GetBodySmart. https://www.getbodysmart.com/posterior-thigh-muscles/gluteus-medius-muscle. Published April 16, 2020. Accessed January 15, 2022.

26. Gorsuch J, Long J, Miller K, et al. The Effect of Squat Depth on Muscle Activation in Male and Female Cross-Country Runners. In: ; 2010.
27. Hammond CA, Hatfield GL, Gilbart MK, Garland SJ, Hunt MA. Trunk and Lower Limb Biomechanics During Stair Climbing in People With and Without Symptomatic Femoroacetabular Impingement. Clinical Biomechanics. 2017;42:108-114. doi:10.1016/j.clinbiomech.2017.01.015
28. Harris-Hayes M, Hillen TJ, Commean PK, et al. Hip Kinematics During Single-Leg Tasks in People With and Without Hip-Related Groin Pain and the Association Among Kinematics, Hip Muscle Strength, and Bony Morphology. Journal of Orthopaedic & Sports Physical Therapy. 2020;50(5):243-251. doi:10.2519/jospt.2020.9150
29. Hip Anatomy. Physiopedia. 2021. Retrieved 18:15, December 12, 2021 from https://www.physio-pedia.com/index.php?title=Hip_Anatomy&oldid=265100.
30. Hogg JA, Ackerman T, Nguyen AD, Ross SE, Schmitz RJ, Vanrenterghem J, Shultz SJ. The Effects of Gluteal Strength and Activation on the Relationship Between Femoral Alignment and Functional Valgus Collapse During a Single-legged Landing. J Sport Rehabil. 2021 Mar 3;30(6):942-951. doi: 10.1123/jsr.2019-0528.
31. Hunt MA, Gunether JR, Gilbart MK. Kinematic and Kinetic Differences During Walking in Patients With and Without Symptomatic Femoroacetabular Impingement. Clinical Biomechanics. 2013;28(5):519-523. doi:10.1016/j.clinbiomech.2013.05.002
32. Jauregui JJ, Salmons HI, Meredith SJ, Oster B, Gopinath R, Adib F. Prevalence of Femoro-Acetabular Impingement in Non-Arthritic Patients With Hip Pain: A Meta-Analysis. Int Orthop. 2020 Dec;44(12):2559-2566. doi: 10.1007/s00264-020-04857-7. Epub 2020 Oct 22. PMID: 33094401.
33. Karunaharamoorthy A. Tensor Fasciae Latae Muscle. Kenhub. https://www.kenhub.com/en/library/anatomy/tensor-fasciae-latae-muscle. Published January 10, 2022. Accessed January 15, 2022.
34. Kennedy MJ, Lamontagne M, Beaulé PE. Femoroacetabular Impingement Alters Hip and Pelvic Biomechanics During Gait: Walking Biomechanics of FAI. Gait & Posture. 2009;30(1):41-44. doi:10.1016/j.gaitpost.2009.02.008
35. Kierkegaard S, Mechlenburg I, Lund B, Søballe K, Dalgas U. Impaired Hip Muscle Strength in Patients With Femoroacetabular Impingement Syndrome. Journal of Science and Medicine in Sport. 2017;20(12):1062-1067. doi:https://doi.org/10.1016/j.jsams.2017.05.008
36. King MG, Heerey JJ, Schache AG, Semciw AI, Middleton KJ, Sritharan P, Lawrenson PR, Crossley KM. Lower Limb Biomechanics During Low- and High-Impact Functional Tasks Differ Between Men and Women with Hip-Related Groin Pain. Clin Biomech (Bristol, Avon). 2019 Aug;68:96-103. doi: 10.1016/j.clinbiomech.2019.06.001.
37. King MG, Lawrenson PR, Semciw AI, Middleton KJ, Crossley KM. Lower Limb Biomechanics in Femoroacetabular Impingement Syndrome: A Systematic Review and Meta-Analysis. British Journal of Sports Medicine. 2018;52(9):566-580. doi:10.1136/bjsports-2017-097839

38. Krause DA, Hollman JH. Electromyographic Analysis of Hip Muscle Activation During a Single Limb Squat Lateral Slide Exercise. International Journal of Sports Physical Therapy. 2020;15(5):755.
39. Lamontagne, M., Kennedy, M.J. & Beaulé, P.E. The Effect of Cam FAI on Hip and Pelvic Motion During Maximum Squat. Clin Orthop Relat Res. 2009;467: 645–650. https://doi.org/10.1007/s11999-008-0620-x
40. Laude F, Boyer T, Nogier A. Anterior Femoroacetabular Impingement. Joint Bone Spine. 2007;74(2):127-132. doi:10.1016/j.jbspin.2007.01.001
41. Lawrenson P, Hodges P, Crossley K, Vicenzino B, McGorm M, Semciw A. The Effect of Altered Stride Length on Iliocapsularis and Pericapsular Muscles of the Anterior Hip: An Electromyography Investigation During Asymptomatic Gait. Gait Posture. 2019 Jun;71:26-31. doi: 10.1016/j.gaitpost.2019.04.003. Epub 2019 Apr 10.
42. Levy DM, Kuhns BD, Chahal J, Philippon MJ, Kelly BT, Nho SJ. Hip Arthroscopy Outcomes With Respect to Patient Acceptable Symptomatic State and Minimal Clinically Important Difference. Arthroscopy. 2016 Sep;32(9):1877-86. doi: 10.1016/j.arthro.2016.05.014.
43. Lewis CL, Foch E, Luko MM, Loverro KL, Khuu A. Differences in Lower Extremity and Trunk Kinematics between Single Leg Squat and Step Down Tasks. PLOS ONE. 2015;10(5):e0126258. doi:10.1371/journal.pone.0126258
44. Lewis CL, Khuu A, Loverro KL. Gait Alterations in Femoroacetabular Impingement Syndrome Differ by Sex. Journal of Orthopaedic & Sports Physical Therapy. 2018;48(8):649-658. doi:10.2519/jospt.2018.7913
45. Lewis CL, Loverro KL, Khuu A. Kinematic Differences During Single-Leg Step-Down Between Individuals With Femoroacetabular Impingement Syndrome and Individuals Without Hip Pain. Journal of Orthopaedic & Sports Physical Therapy. 2018;48(4):270-279. doi:10.2519/jospt.2018.7794
46. Mallets E, Turner A, Durbin J, Bader A, Murray L. Short-Term Outcomes of Conservative Treatment for Femoroacetabular Impingement: A Systematic Review and Meta-Analysis. Int J Sports Phys Ther. 2019 Jul;14(4):514-524.
47. Malloy P, Neumann DA, Kipp K. Hip Biomechanics During a Single-legged Squat: 5 Key Differences Between People With Femoroacetabular Impingement Syndrome and Those Without Hip Pain. J Orthop Sports Phys Ther. 2019;49(12):908-916. doi:10.2519/jospt.2019.8356
48. Mansell NS, Rhon DI, Meyer J, Slevin JM, Marchant BG. Arthroscopic Surgery or Physical Therapy for Patients With Femoroacetabular Impingement Syndrome: A Randomized Controlled Trial With 2-Year Follow-up. The American Journal of Sports Medicine. 2018;46(6):1306-1314. doi:10.1177/0363546517751912
49. Mauntel TC, Begalle RL, Cram TR, Frank BS, Hirth CJ, Blackburn T, Padua DA. The Effects of Lower Extremity Muscle Activation and Passive Range of Motion on Single Leg Squat Performance. J Strength Cond Res. 2013 Jul;27(7):1813-23. doi: 10.1519/JSC.0b013e318276b886.
50. McCurdy K, O'Kelley E, Kutz M, Langford G, Ernest J, Torres M. Comparison of Lower Extremity EMG Between the 2-Leg Squat and Modified Single-Legged Squat in Female

Athletes. Journal of Sport Rehabilitation. 2010 Feb; 19(1):57–70. Available from: https://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=48074528&site=ehost-live&scope=site

51. Nakagawa TH, Moriya ÉTU, Maciel CD, SerrãO FV. Trunk, Pelvis, Hip, and Knee Kinematics, Hip Strength, and Gluteal Muscle Activation During a Single-Leg Squat in Males and Females With and Without Patellofemoral Pain Syndrome. Journal of Orthopaedic & Sports Physical Therapy. 2012;42(6):491-501. doi:10.2519/jospt.2012.3987
52. Nepple JJ, Goljan P, Briggs KK, Garvey SE, Ryan M, Philippon MJ. Hip Strength Deficits in Patients With Symptomatic Femoroacetabular Impingement and Labral Tears. Arthroscopy: The Journal of Arthroscopic & Related Surgery. 2015;31(11):2106-2111. doi:https://doi.org/10.1016/j.arthro.2015.04.095
53. Neumann D. Kinesiology of the Hip: A focus on Muscular Actions. Journal of Orthopedic and Sports Physical Therapy. 2010;40(2):82-94.
54. Ng KCG, Mantovani G, Modenese L, Beaulé PE, Lamontagne M. Altered Walking and Muscle Patterns Reduce Hip Contact Forces in Individuals With Symptomatic Cam Femoroacetabular Impingement. Am J Sports Med. 2018 Sep;46(11):2615-2623. doi: 10.1177/0363546518787518.
55. Pappas E, Hagins M, Sheikhzadeh A, Nordin M, Rose D. Biomechanical Differences Between Unilateral and Bilateral Landings From a Jump: Gender Differences. Clin J Sport Med. 2007 Jul;17(4):263-8. doi: 10.1097/JSM.0b013e31811f415b.
56. Powers CM. The Influence of Abnormal Hip Mechanics on Knee Injury: A Biomechanical Perspective. J Orthop Sports Phys Ther. 2010 Feb;40(2):42-51. doi: 10.2519/jospt.2010.3337.
57. Rainoldi A, Melchiorri G, Caruso I. A Method for Positioning Electrodes During Surface EMG Recordings in Lower Limb Muscles. Journal of Neuroscience Methods. 2004;134(1):37-43. doi:10.1016/j.jneumeth.2003.10.014
58. Reiman MP, Agricola R, Kemp JL, et al. Consensus Recommendations On The Classification, Definition and Diagnostic Criteria of Hip-Related Pain in Young and Middle-Aged Active Adults From the International Hip-Related Pain Research Network, Zurich 2018. Br J Sports Med. 2020;54(11):631. doi:10.1136/bjsports-2019-101453
59. Rutherford DJ, Moreside J, Wong I. Differences in Hip Joint Biomechanics and Muscle Activation in Individuals With Femoroacetabular Impingement Compared With Healthy, Asymptomatic Individuals: Is Level-Ground Gait Analysis Enough? Orthopaedic Journal of Sports Medicine. 2018;6(5):2325967118769829. doi:10.1177/2325967118769829
60. Samaan MA, Schwaiger BJ, Gallo MC, Sada K, Link TM, Zhang AL, Majumdar S, Souza RB. Joint Loading in the Sagittal Plane During Gait Is Associated With Hip Joint Abnormalities in Patients With Femoroacetabular Impingement. Am J Sports Med. 2017 Mar;45(4):810-818. doi: 10.1177/0363546516677727.
61. Samaan MA, Zhang AL, Popovic T, Pedoia V, Majumdar S, Souza RB. Hip Joint Muscle Forces During Gait in Patients with Femoroacetabular Impingement Syndrome are Associated with Patient Reported Outcomes and Cartilage Composition. J Biomech. 2019 Feb 14;84:138-146. doi: 10.1016/j.jbiomech.2018.12.026.

62. Savage TN, Saxby DJ, Pizzolato C, et al. Trunk, Pelvis and Lower Limb Walking Biomechanics are Similarly Altered in Those With Femoroacetabular Impingement Syndrome Regardless of Cam Morphology Size. Gait & Posture. 2021;83:26-34. doi:10.1016/j.gaitpost.2020.10.002
63. Selkowitz DM, Beneck GJ, Powers CM. Comparison of Electromyographic Activity of the Superior and Inferior Portions of the Gluteus Maximus Muscle During Common Therapeutic Exercises. Journal of Orthopaedic & Sports Physical Therapy. 2016;46(9):794-799. doi:10.2519/jospt.2016.6493
64. Sensor Locations. http://seniam.org/sensor_location.htm. Accessed January 15, 2022.
65. Spiker AM, Kraszewski AP, Maak TG, Nwachukwu BU, Backus SI, Hillstrom HJ, Kelly BT, Ranawat AS. Dynamic Assessment of Femoroacetabular Impingement Syndrome Hips. Arthroscopy. 2021 Jun 12:S0749-8063(21)00575-2. doi: 10.1016/j.arthro.2021.05.062.
66. Stone AV, Malloy P, Beck EC, et al. Predictors of Persistent Postoperative Pain at Minimum 2 Years After Arthroscopic Treatment of Femoroacetabular Impingement. Am J Sports Med. 2019;47(3):552- 559. doi:10.1177/0363546518817538
67. Taylor JB, Ford KR, Nguyen AD, Shultz SJ. Biomechanical Comparison of Single- and Double-legged Jump Landings in the Sagittal and Frontal Plane. Orthop J Sports Med. 2016 Jun 28;4(6):2325967116655158. doi: 10.1177/2325967116655158.
68. Turkiewicz A, Petersson IF, Björk J, et al. Current and Future Impact of Osteoarthritis On Health Care: A Population-Based Study With Projections to Year 2032. Osteoarthritis and Cartilage. 2014;22(11):1826-1832. doi:10.1016/j.joca.2014.07.015
69. van Soest AJ, Roebroeck ME, Bobbert MF, Huijing PA, van Ingen Schenau GJ. A Comparison of One-Legged and Two-Legged Countermovement Jumps. Med Sci Sports Exerc. 1985 Dec;17(6):635-9. doi: 10.1249/00005768-198512000-00002.
70. Weir A, Brukner P, Delahunt E, et al. Doha Agreement Meeting On Terminology and Definitions In Groin Pain in Athletes. Br J Sports Med. 2015;49(12):768. doi:10.1136/bjsports-2015-094869
71. Whiteley R, Hansen C, Thomson A, Sideris V, Wilson MG. Lower Limb EMG Activation During Reduced Gravity Running On An Incline. Speed Matters More Than Hills Irrespective of Indicated Bodyweight. Gait Posture. 2021 Jan;83:52-59. doi: 10.1016/j.gaitpost.2020.09.029.
72. Zhou J, Melugin HP, Hale RF, Leland DP, Bernard CD, Levy BA, Krych AJ. The Prevalence of Radiographic Findings of Structural Hip Deformities for Femoroacetabular Impingement in Patients With Hip Pain. Am J Sports Med. 2020 Mar;48(3):647-653. doi: 10.1177/0363546519896355.

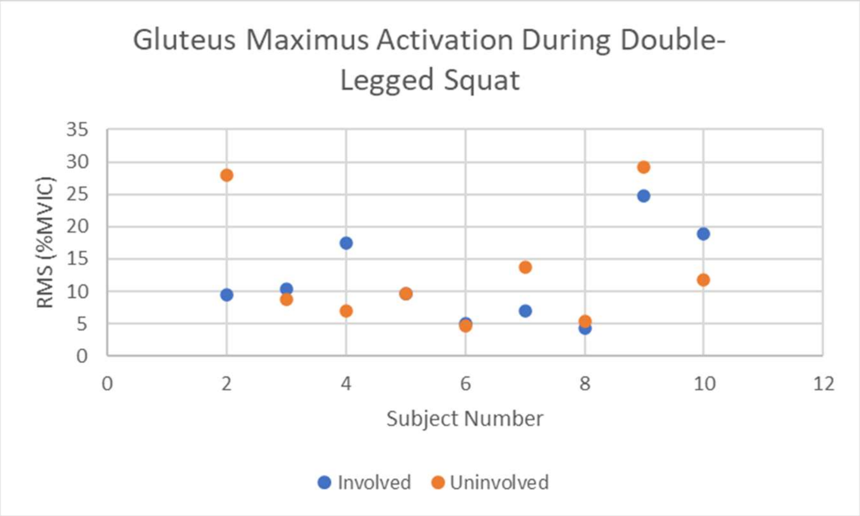
Appendix A: For each subject, %MVIC sEMG values of each muscle during a double-legged squat

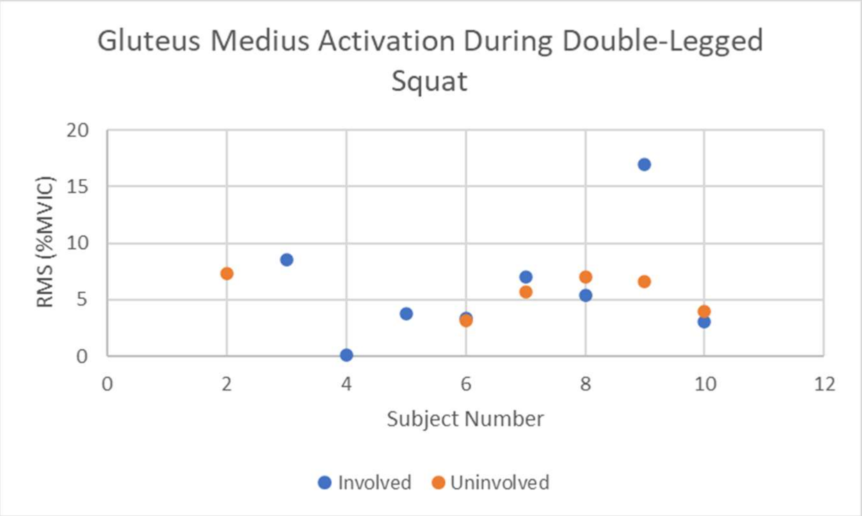
	Double-Legged Squat							
	Involved Side				Uninvolved Side			
Subject Number	Gluteus Maximus	Gluteus Medius	Rectus Femoris	TFL	Gluteus Maximus	Gluteus Medius	Rectus Femoris	TFL
2	9.41		32.97	10.96	27.93	7.31	93.83	17.12
3	10.37	8.52	16.15	3.40	8.82		15.00	2.09
4	17.48	0.11	29.43	3.53	6.92		23.64	4.31
5	9.64	3.79	31.71	3.96	9.61			1.89
6	5.02	3.37	4.39	2.99	4.67	3.12	12.03	1.50
7	6.94	7.02	4.59	2.54	13.80	5.74	7.86	20.60
8	4.40	5.40	9.48	80.81	5.36	7.00	8.29	1.60
9	24.75	17.01	24.65	16.23	29.14	6.60	8.45	9.62
10	18.82	3.01	21.25	1.89	11.81	3.98	24.09	1.81

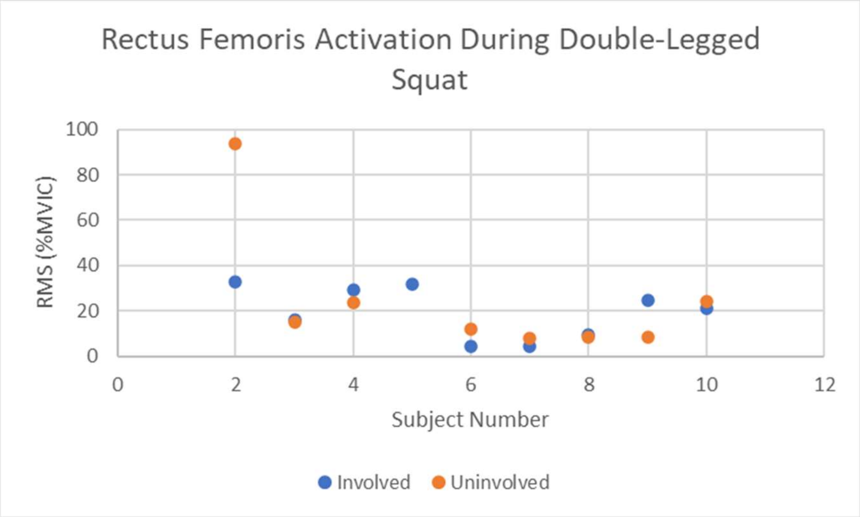
Appendix B: For each subject, %MVIC sEMG values for all the muscles during a single-legged squat

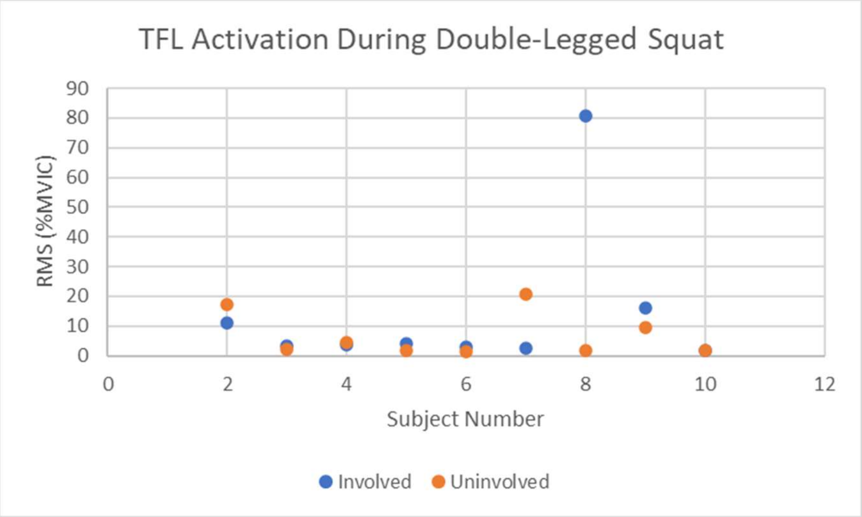
	Single-Legged Squat							
	Involved Side				Uninvolved Side			
Subject Number	Gluteus Maximus	Gluteus Medius	Rectus Femoris	TFL	Gluteus Maximus	Gluteus Medius	Rectus Femoris	TFL
2	19.52		29.96	6.81	55.90	24.24	40.50	15.18
3	18.63	25.59	20.82	11.45	13.54		18.68	14.72
4	46.32	0.37	26.98	13.54	19.62		26.36	12.95
5	27.39	24.34	34.30	10.83	24.63			5.42
6	8.65	11.26	8.82	3.51	9.07	8.13	8.93	4.27
7	11.93	25.31	7.24	4.16	41.45	33.94	11.15	17.15
8	6.58	17.94	20.52	1.85	10.85	15.51	20.34	2.97
9	31.67	59.45	31.61	5.54	30.98	28.82	10.83	7.09
10	39.58	25.81	25.36	14.91	32.95	28.94	29.14	8.23

Appendix C: Scatter plots for each muscle with all the %MVIC sEMG values during a double-legged squat









Appendix D: Scatter plots for each muscle with all the %MVIC sEMG values during a single-legged squat