The Effect of Hip Flexor Tightness on Muscle Activity During Functional Movements and the Front Squat

By

Sarah Catherine Martinez

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Dissertation Committee:

Dr. John M. Coons, Chair

Dr. Kelton D. Mehls

Dr. Angela S. Bowman

This work is wholeheartedly dedicated to my life partner, soulmate and the love of my life—Alex Sepanski. I am forever grateful for your unconditional love and support. You were now and forever my greatest source of strength. I would also like to dedicate this paper to my youngest brother, Sean Martinez, for being the best roommate I could ask for while I pursed this degree and always reminding me to never accept defeat so easily. You are my hero and I would not have been able to complete this degree without you. Finally, to my friends and family who believed in me, this is dedicated to all of you.

Love,

Sarah Martinez

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ABSTRACT

Muscular imbalances can be described as altered reciprocal inhibition by which an overactive agonist causes a decrease in neural drive and optimal recruitment to its functional antagonist (Clark et al., 2018), which can lead to synergistic dominance muscles that eventual ends in musculoskeletal injury and impaired performance (Jones & Bampouras, 2010; Kendall et al., 2005). The purpose of this study was to compare muscle activity in the rectus femoris (RF), biceps femoris (BF), semitendinosus (ST), and gluteus maximus (GM) muscles and GM:BF co-activation during the functional movements ($N = 23$) and in the front squat ($N = 16$) in females with and without hip flexor tightness.

Mean muscle activity of the RF, BF, ST, and GM and GM:BF co-activation were not significantly different in females with and without hip flexor tightness during the overhead squat, in-line lunge, and forward step-up. However, individuals with hip flexor tightness displayed higher mean BF activation during the overhead squat, in-line lunge, and forward step-up. Mean ST was also higher in individuals with tight hip flexors during the overhead squat and forward step-up. More investigation on hip flexor tightness and hamstring activity is inquired, as previous literature has shown tight hip flexors may cause changes in the neuromuscular control of the lumbopelvic hip complex, specifically the BF.

During both the ascending and descending phase during a 75% 1RM front squat, peak BF activity was significantly higher ($p < .05$) in resistance trained females with hip flexor tightness compared to those without. During the ascending phase, peak RF ($p < .05$) activity was significantly higher in those with hip flexor tightness compared to those without. Mean BF activity was significantly higher ($p < .05$) during the ascending phase of the front squat in those with hip flexor tightness compared to those without. The GM:BF co-activation ratio was significantly lower ($p < .05$) in those with hip flexor tightness compared to those without during both the ascending and descending phase of the front squat. Fitness professionals should consider providing a hip flexor stretching intervention to prevent over activation of the BF when selecting the front squat as a resistance training exercise. Providing a hip flexor stretching program to individuals who have tight hip flexors may decrease synergistic dominance of the hamstrings.

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CHAPTER I: DISSERTATION INTRODUCTION

All muscles function in unison to produce a desired movement about a joint and generate human movement. Prime movers, agonist, antagonist, synergist, and stabilizer muscles collaborate in order to ensure proper joint movements, while minimizing undesirable motion. Prime movers, agonist, synergist, and stabilizers activate to stabilize and pull a bone or bones in a specific direction, while antagonist muscles relax in order to create a specific movement. Reciprocal inhibition of prime movers and antagonist muscles must exist to ensures proper movement of the human movement system. The National Academy of Sports Medicine (NASM) and the Functional Movement Screen (FMS™) both promotes the focus of neuromuscular control in strength training programs to prevent musculoskeletal injuries from occurring.

According to NASM, a lack of understanding of the synergistic function across all three planes of motion commonly leads to lack of optimal performance and development of muscular imbalances (Clark et al., 2018). Muscular imbalances can be described as altered reciprocal inhibition by which an overactive agonist causes a decrease in neural drive and optimal recruitment to its functional antagonist (Clark et al., 2018). Muscle imbalances have been shown to distort body alignment which can cause undue stress and strain on joints, ligaments and muscles that eventual lead to musculoskeletal injury and impaired performance (Jones & Bampouras, 2010; Kendall et al., 2005). Investigating causes of muscular imbalances allow corrective interventions to be implemented and reestablish optimal neuromuscular control.

The manifestation of noncompliant musculotendinous tissue has been proposed to be related to specific activity patterns, including certain sedentary positions. For example, restricted hip flexor length has been observed in both sedentary and active populations and is commonly considered to be related to excessive amounts of sitting, repetitive uniplanar movements and/or improper movement techniques (Bachrach, 2007; Clark et al. 2014). Ultimately, a tight hip flexor create can create altered reciprocal inhibition and decrease the neural drive to its functional antagonist (gluteus maximus) during hip extension (Clark et al., 2018; Buckthorpe et al., 2019). When this occurs, synergist of the gluteus maximus (hamstring muscle group) must overcompensate in order to complete hip extension. This neuromuscular phenomenon is known as synergistic dominance and can lead to injury of the hamstrings.

Synergistic dominance occurring in the hamstrings due to inhibited or underactive gluteus maximus has shown to leads to arthrokinetic dysfunction during sprinting and jumping movements may increase the risk of hamstring injury (Clark et al., 2014; Aslan et al., 2018; Sahrmann, 2002; Wagner et al., 2010). In resistance train females with tight hip flexors, a decrease in gluteus maximus activity during a bilateral squat has been observed (Mills et al., 2015). However, this study only observed female collegiate soccer players and observed only one functional movement. To better understand the effects of restricted hip extension on muscle activity in the general population during functional movements, further investigation is required.

Not only is neuromuscular efficiency paramount for daily functional tasks, it is required for optimal athletic performance. It has been proposed that synergistic dominance of the hamstrings leads to arthrokinetic dysfunction during sprinting and jumping movements may increase the risk of hamstring injury (Clark et al., 2014; Aslan et al., 2018; Sahrmann, 2002; Wagner et al., 2010). Therefore, muscle imbalances should be identified and addressed during resistance training and performance based programs in order to prevent injury. Maximizing activation of the gluteus maximus allows for proper neuromuscular control during human movements, preventing synergistic dominance (Clark et al. 2014). Yet, the effect of hip flexor tightness on functional movements and a resistance training lift has yet to be investigated.

Title: The effect of hip flexor tightness on muscle activity during functional movements

Purpose of Study 1

The purpose of the first study is to compare surface electromyography (sEMG) in the rectus femoris, gluteus maximus, biceps femoris, and semitendinosus muscles during the over-head squat, in-line lunge, and forward step-up between individuals with and without hip flexor tightness.

Research Questions for Study 1

- What are the differences in muscle activity in the rectus femoris, gluteus maximus, biceps femoris and semitendinosus during the over-head squat, in-line lunge, and step-up in women with and without hip flexor tightness?
- What is the difference between the gluteus maximus: biceps femoris co-contraction ratio during the over-head squat, in-line lunge, and step-up in women with and without hip flexor tightness?

Delimitations

1. The study will target female participants.
2. Participants will be excluded from the study if they report any current illness or musculoskeletal injury.
3. Hip flexor tightness will be measured using a digital inclinometer during the Modified Thomas Test by a Certified Athletic Trainer.
4. A metronome will be used to establish consistent speed during functional movements.
5. The functional movements will be randomized for each participant.
6. The participants will perform 3 repetitions of each movement, with a 1-minute rest period between repetitions to prevent fatigue.

Limitations

1. Participants may have varying fitness levels, which may affect muscle activation.

Basic Assumptions

1. The Modified Thomas Test is a reliable and valid test for measuring hip flexor tightness.
2. Participants will be truthful when disclosing absence of illness or injury.

Significance of Study 1

This study will investigate the effect of hip flexor tightness during daily functional movements. This study will help better understand neuromuscular control and causes of muscular imbalances. Practitioners will be able to better prescribe corrective techniques for
muscle imbalances in order to improve neuromuscular efficiency and prevent injury.

Title: The effect of hip flexor tightness on muscle activity during the front squat

Purpose of Study 2

The purpose of the second study is to compare surface electromyography (sEMG) in the rectus femoris, gluteus maximus, biceps femoris, and semitendinosus muscles during the front squat between resistance trained females with and without hip flexor tightness.

Research Questions for Study 2

- What are the differences in muscle activity in the rectus femoris, gluteus maximus, biceps femoris and semitendinosus during 75% of a one-repetition max (1RM) and 1RM front squat in women with and without hip flexor tightness?
- What is the difference between the gluteus maximus: biceps femoris co-contraction ratio during the front squat in women with and without hip flexor tightness?

Delimitations

1. The study will target resistance trained females classified as intermediately resistance trained by the National Strength and Conditioning Association (NSCA).

2. Participants will complete all front squat repetitions in the presence of a Certified Strength and Conditioning Specialist.

3. The Smith Machine will be used for the front-squat to optimize safety of participant

4. Participants will be required to complete the front squat in agreement with the NSCA guidelines.

5. A metronome will be used to establish a consistent slow and controlled speed

6. Training loads will be randomized for each participant.

7. The participants will perform three repetitions at each load, with a 3-minute rest period between repetitions to prevent fatigue.

8. The participants will be asked to avoid lower body resistance training at least twenty-four hours before a testing session.

Limitations

1. No assurance that the participants provide a maximal effort during one-repetition max.

Basic Assumptions

1. Participants will provide a maximal effort during the lift sessions.

2. Participants will be truthful when disclosing absence of illness or injury and when agreeing to refrain from lifting when the study requires it.

Significance of Study 2

The study will provide information regarding the relationship between hip flexor tightness on muscle activity during the front squat. From this study, practitioners who work female athletes can apply appropriate corrective techniques when needed to optimize target activity during training sessions, thus enhancing program prescription by better target training muscle groups.

CHAPTER II: REVIEW OF LITERATURE

This review of literature begins with defining the roles of agonist, antagonist, synergist, and stabilizer muscles followed by an introduction to muscle imbalances. Addressed next are possible causes for synergistic dominance and how this type of muscular imbalance may lead to changes in muscle activity measured by surface electromyography (EMG). More specifically, the discussion will revolve around existing literature that has addressed muscle activity changes in the lower extremity due to hip flexor tightness. Next, corrective techniques intended to address muscular imbalances, such as synergistic dominance, are discussed. The literature review concludes with examination of synergist muscle activity during functional movements and resistance training exercises.

Prime Movers, Antagonist, Synergist, and Stabilizer Muscles

Motor control is a complex process that demonstrates the centrals nervous system's ability to analyze the information it receives to produce, refine, and create a movement by sending signals to the appropriate skeletal muscles (Clark et al., 2014). Skeletal muscles are responsible for generating movements of the body and appropriate neuromuscular control is crucial to produce proper arthrokinematics (Neumann, 2010). Muscles and muscle groups must work together to ensure proper joint movements, while minimizing undesirable motion. These muscles are often organized into groups that specify roles during movement. Although the exact grouping of muscles may vary across literature, muscles surrounding specific joints are commonly labeled as prime movers, agonists, antagonist, synergist and stabilizers (Clark et al., 2014; Hamill & Knutzen, 2006; Norkin & Levangie, 2005).

Prime movers are muscles that act directly on a joint to bring about a desired movement. There is a general consensus among the rehabilitative and physiotherapy disciplines on which muscles are prime movers during isolated movements. For example, the gluteus maximus and the hamstrings group all assist in hip extension, but the gluteus maximus is commonly recognized as the prime mover for hip extension (Delp et al., 1999; Dostal et al., 1986; Neumann, 2010). There is, however, less agreement on designating prime movers during dynamic movements. Some professionals believe that the level of muscle activity may change depending on the point in range of motion thereby further confounding the issue.

Proper human functional movement requires the symbiosis of prime movers and their synergist and antagonist muscles. A good example of this cooperative relationship is observed when increases in prime mover muscle activity result in notable decreases in antagonist muscle activity. This symbiotic connection is termed reciprocal inhibition, the relaxation of muscles on one side of a joint to accommodate contraction on the other side of that joint. Reciprocal inhibition is necessary to allow normal joint movement (Floyd & Thompson, 1998; Gorkovenko et al., 2012; Iles, 1986). Following the previous example, the psoas major, a hip flexor, is the antagonist muscles to the gluteus maximus during hip extension (Neumann, 2010). Although primary movers dominate a certain plane of motion, the central nervous system will optimize movement through the selection of muscle synergies.

Although the exact role and definition of synergist muscles remains ambiguous, synergist muscles are generally referred to as a group of muscles that work together to produce motion about a joint (Scano et al., 2019). Synergists muscles may assist prime movers by decreasing unwanted motion thereby refining the movement. For example, the hamstring complex and erector spinae act as synergists to the gluteus maximus during hip extension (Clark et al., 2014; Floyd & Thompson, 1998; Tresch & Jarc, 2009). While multiple studies support the existence of synergistic muscles as a strategy employed by the central nervous system to enhance motor control (Alessandro & Nori, 2012; Berger & D'Avella, 2014; Flash & Hochner, 2005; Jacobs & Macpherson, 1996), it has been suggested that the recruitment and activation of synergist muscle may vary across functional- and performance-related tasks depending on the required demands of a specific movement (Alessandro et al., 2013; D'Avella et al., 2006; Delis et al., 2018; Scano et al., 2019; Tamaki, 1998; Tresch & Jarc, 2009).

Older studies by Tamaki et al. (1998) and Smith et al. (1980) have also observed different recruitment of muscles synergist depending on a specific task. Tamaki et al. (1998) observed sEMG in the lateral gastrocnemius, medial gastrocnemius, and soleus muscles during prolonged static and dynamic contractions. The results of this study showed different alternating synergist activation patterns during static and dynamic contractions. Smith et al. (1980) examined EMG signals from the soleus and lateral gastrocnemius in six cats during rapid and alternating flexion-extension of the hindlimb. The results showed that the soleus was mainly recruited during the slow movement, whereas the lateral gastrocnemius was active mainly activated during fast movements. This may be due to the different muscle fiber typing between the soleus and gastrocnemius, which suggests that the speed of a movement may cause selective recruitment of motor units from specific synergies to suit the demand of motor tasks.

Several other studies have shown that joint angle and timing of the movement alters recruitment thresholds of human motor units when muscle synergies are utilized to complete a task (D'Avella et al., 2006; Van Zuylen et al. 1988). Van Zuylen et al. (1988) observed motor unit activity of muscles acting at different angles of the elbow joint during combinations of voluntary isometric torques in flexion/extension and supination/pronation. The authors found that changing the elbow angle modified the mechanical advantage of various muscles differently. This implies that the relative activation of muscles depends on joint angle. The timing of movement may also affect muscle synergies. D'Avella and his colleagues (2006) recorded EMG activity for about 19 shoulder and arm muscles during different sets of fast-reaching movements in vertical planes. The authors used an algorithm to identify a set of time-varying muscle synergies and found insight for the mechanisms involved in the mapping of motor goals into muscle patterns. Their results showed that the complexity and variability of motor output is task-dependent. The result of these studies demonstrates that the angle of the joint, speed of movement, and specific movement tasks can dictate which muscles contract and relax to create proper human movement.

Stabilizer muscles support or stabilize the body about a joint while the prime movers and synergist perform the movement patterns (Clark et al., 2018). Stabilizers during hip extension include, but are not limited to, the gastrocnemius, soleus, transverse abdominus, and gluteus medius. Neuromuscular efficiency is known as the central nervous system's ability to recruit prime movers, agonist, antagonist, synergists, and stabilizers, in order to allow proper control of the kinetic chain in all three plans of motion. Since muscles rarely work in isolation, it is important to view muscles functioning in all planes of motion and through entire functional movements (Clark et al., 2014).

To ensure proper joint motion and eliminate unwanted motion, all muscles (prime movers, antagonist, synergist, and stabilizers) must work in unison to produce a desired movement. The synergistic action of muscles generating force around a joint to produce human movement is known as a force-couple. Muscles in a force-couple will activate or inhibit in order pull a bone or bones in a direction to create a specific movement. Proper force-couple relationships must exist to ensure proper movement of the human movement system (Clark et al., 2014).

Reciprocal Inhibition

Reciprocal inhibition is a necessary neuromuscular event in movement coordination and efficiency (Blazevich et al., 2012). As described earlier, reciprocal inhibition is the contraction of a prime mover with simultaneous relaxation of its antagonist surrounding a joint to create movement. Through inhibitory pathways, reciprocal inhibition attempts to inhibit excessive muscle contraction in the antagonist to allow a prime mover to generate a desired movement. When a muscle contracts, the opposing muscles are being actively stretched and the tension in the contracted muscles stimulates the Golgi tendon organs (GTOs); this causes a simultaneous reflexive relaxation of the stretched muscle (Haff & Triplett, 2016; Hirabayashi et al., 2020). This allows for a normal length-tension and force-couple relationships where the amount of tension that can be produced at this resting length is optimal (Clark et al. 2018).

Proper muscle activation of the prime mover paired with a decrease in muscle activation of its functional antagonist is required for voluntary movements (Hirabyashi et al., 2019; Lavoie et al, 1997). Lavoie et al. (1997) found evidence of reciprocal inhibition during co-contraction of the tibialis anterior and soleus during walking and motor tasks. The authors observed EMG activity of the tibialis anterior and soleus during walking, one leg step-up, voluntary dorsiflexion, voluntary tonic tibialis anterior contraction, and backward lean. This study demonstrated that reciprocal inhibition of the soleus was stronger during the swing phase of walking compared to voluntary or postural tasks at matched levels of tibialis anterior EMG activity. Thus, establishing that the strength of reciprocal inhibition can be controlled independently at the level of motor activity of the agonist(s).

The timing of a movement can also affect reciprocal inhibition to optimize proper human movement. A study by Hirabayashi and his colleagues (2020) examined the relationship between reciprocal inhibition and repetitive passive movement speed. Twenty healthy adults performed a repetitive passive movement in the 80°-120° range for the ankle joint for 618 times at 80 deg/sec, 309 times at 160 deg/sec, and 618 times at 160 deg/sec. The authors also had participants complete repetitive passive moment tasks focusing on two ranges of ankle joint motion with a movement time of 10 minutes. The results of this study showed that reciprocal inhibition was enhanced depending on the repetitive passive movement speed. More specifically, faster movement speeds enhanced reciprocal inhibition depending of the number of movements.

The findings of these studies indicate that reciprocal inhibition is an important factor that ensures proper movement. To ensure proper joint motion and eliminate unwanted motion, all muscles must work in unison to produce a desired movement. Proper simultaneous contraction of one muscle or muscle group and the relaxation of its antagonist ensures proper tension development around a joint and create movement. In a situation where the length-tension relationship and reciprocal inhibition of muscles are altered, muscle imbalances can occur.

Muscle Activity

Electromyography

Electromyography (EMG) devices can indicate the initiation of muscle activation and its relationship to the force produced by a muscle, as well as muscular fatigue (De Luca, 1997). This is possible through the use of EMG electrode sensors placed on individual muscles that can detect action potentials of motor units in muscles (Halaki & Ginn, 2012). An EMG signal can provide force contribution of individuals, as well as groups of muscles, and provide timing sequence of one or more muscles performing a task (De Luca, 1997). This has made EMG a popular tool to assess muscle activation during dynamic movement tasks.

Modern technology has allowed for the greater decomposition of EMG signals into its motor unit action trains by using the practical and non-invasive surface EMG (sEMG) sensors placed on the skin above the muscle of interest (Zaheer et al. 2012). A 27mm x 37mm x 13mm surface electrode measures surface EMG signals. The surface electrode has detection surfaces consisting of two parallel bars spaced 10mm that create a fixed inter-electrode spacing; which allows bandwidth of the sEMG signal to remain constant (De Luca et al., 2012). Since surface electrodes are self-referencing, a reference electrode is not required. Moreover, a small inter-electrode spacing is preferable as it will reduce the amount of cross-talk from adjacent muscles. Electromyography data can be transmitted to a wireless surface EMG system (Tringo, Delsys, Natick, MA) up to a nominal distance of 20m (De Luca, 2008). The sampling rate of sEMG is 1926 sa/sec with a bandwidth of 20-450 Hz is recommended (Delsys, 2020). Other recommendations for surface electrode configuration include: common mode rejection ratio greater than 80 db, noise less than 20-400 Hz, and input impedance less than 100 meg ohms (De Luca, 1997). Today, many individual and groups of muscles have been observed using surface sEMG to determine the relationship and role of synergistic muscles during different movements (Delis et al., 2018; Michaud et al., 2020; Hug et al., 2010; Pan et al., 2019)

Processing sEMG Signals

Several extrinsic and intrinsic factors may influence EMG signals (De Luca, 2008). Extrinsic factors that influence sEMG signal are associated with the electrode structure and placement on the surface of the skin above the muscle. (De Luca, 1997). Extrinsic factors are attempted to be controlled by the researcher through proper sensor location and placement. Proper sensor location is important to enhance the clarity of the sEMG signal and decrease physiological cross talk or detected force signals from surrounding muscles. In addition, the operator should be aware of muscle fiber orientation, as the sensor should be placed in parallel with the fiber orientation of the muscle. Intrinsic factors such as the physiological, anatomical and biochemical characteristics of muscle cannot be controlled by the researcher (De Luca, 1997). However, the EMG signal can be improved through proper application of sEMG sensors and proper filtering techniques.

Before applying sEMG sensors to the skin, the user should first shave the participants body hair, if necessary, around the desired sensor location and then remove the dead skin using abrasive paste or fine sand paper. Next, the user should clean the area with alcohol and allow the area to dry before electrode placement. It should be noted that there are multiple sources of noise that may influence sEMG signaling. Noise contamination can be classified as physiological noise, ambient noise, baseline noise, or moment artifact noise (De Luca, 2008). To reduce physiological noise, such as tissues that generate electrical signals, the user should place the sensor away from the source of noise by rotating the sensor so that the electrodes are equidistant from the source. To reduce baseline noise, such as skin-electrode interface and thermal noise, the user should use proper skin preparation techniques. To reduce movement artifact noise, such as the movement of the electrode with respect to the skin, the user should use proper skin preparation and filtering techniques. Much of ambient noise, such as power line noise and cable motion, are reduced due to modern sensory technology. Once the sensor has been properly placed to reduce noise and influencing factors, a raw sEMG signal may be recorded from the chosen muscle (De Luca, 2008).

After completion of data collection, the unfiltered and unprocessed raw sEMG signal needs to be rectified and smoothed. Rectification translates raw sEMG signal to a single polarity (usually positive) and facilitates signal processing. Smoothing is the process of conceptualizing the raw sEMG signal into a pattern than can be used for scientific purpose. Since interference patterns of raw EMG are random and cannot be reproduced, a smoothing algorithm must be applied to interpret EMG signals. Normalization is the process of standardizing a raw EMG value against a maximal effort value in reference to the same muscle. In other words, normalized sEMG data is sub-maximal effort sEMG activity during a specific task divided by a referenced maximal effort sEMG activity of the same muscle (Halaki & Ginn, 2012). This results in a ratio that is a normalized signal and is required for direct comparison of muscle across participants. Once the user has completed the entire data processing procedure, the normalized sEMG signal can be used compare muscle activation among participants, muscles, and contractions (De Luca, 2008; Halaki & Ginn, 2012).

The two primary methods of normalization are maximal isometric voluntary contraction (MVIC) and one-repetition maximum (1RM) dynamic measure. Although no gold standard currently exists for EMG normalization technique, it is generally recommended that isotonic movements be normalized to a dynamic movement methods such as a 1RM or the first set of three repetitions (Korak et al., 2020). In other words, if a dynamic movement can be replicated at maximal intensity, such as traditional lifts, then normalization to a 1RM would be preferred. When measuring a maximal voluntary contraction, it is recommended to choose the greatest sEMG value of three consecutive attempts at reaching maximal value, with a rest period of at least 2 minutes between contractions (De Luca, 1997). Many daily functional tasks, such as walking, lunge and the step-up, are difficult and impractical to re-create at a 1RM effort. Thus, the most common method of normalizing sEMG signals of a specific muscle to its recorded MVIC (Halaki & Ginn, 2012). Usually, the process of obtaining a MVIC involves a manual muscle test to identify the maximal contraction of the muscle of interest. Following the completion of MVIC data collection, these values are rectified and smoothed and then used as a reference value for normalizing sEMG signals for the muscle of interest (Halaki & Ginn, 2012).

Muscle Activity During Functional Movements

The Functional Movement Screen (FMS^{TM}) is a screening tool that is effective in recognizing individuals who may be at risk of injury (Cook et al., 2014; Marques et al., 2017). The FMS is designed to identify functional movement deficits that may predispose individuals to musculoskeletal injuries (Cook et al., 2006). The FMS has been validated as a reliable method to evaluate risk for injury (Teyhen et al., 2012) and consists of seven functional movements: In-line lunge, hurdle step, deep squat, quadruped rotary stability, active straight leg raise, shoulder mobility, and trunk stability push-up. These exercises mimic function during daily activities of living and sport because they require precise motor control and neuromuscular efficiency. The FMS integrated and functional approach to exercise promotes the focus of neuromuscular and strength training programs to prevent musculoskeletal injuries (Cook et al., 2006).

Similarly, the National Academy of Sports Medicine (NASM) emphasizes both a static and movement assessment before partaking in an exercise program. The postural assessment involves a fitness professional assessing an individual in a fixed position to assess stationary alignment of the body. The movement assessment involves the fitness professional assessing an individual during different human movements to observe possible muscle imbalances and altered recruitment strategies that may subject an individual to tissue and/or joint stress, which may eventually lead to injury (Clark et al., 2018). The NASM's movement assessment is further categorized into two types: transitional assessment and dynamic assessment. Movements that involve no change in one's base of support are considered transitional movement assessments, whereas movements that involve a change in one's base of support (walking and jumping) are considered dynamic assessments (Clark et al., 2018). Transitional movement assessments include the overhead squat, single-leg squat, push-up, standing cable row, standing overhead dumbbell press, star balance excursion, and upper extremity assessment. The goal of NASM's movement assessments are to subjectively observe one's functional status to determine potential overactive and underactive muscles in a naturally dynamic setting (Clark et al., 2018).

Movement assessments require the observation of the kinetic chain and NASM has established kinetic chain check-points to allow health and fitness professionals to systemically view the body in motion (Clark et al. 2018). The kinetic chain checkpoints are as followed: 1) foot and ankle; 2) knee; 3) lumbo-pelvic-hip complex (LPHC); and 4) shoulders and head/cervical spine (Clark et al. 2018). Major joint regions of the body are considered kinetic chain checkpoints because each joint, as well as the structures above and below the joints, has a specific biomechanical motion. During a movement assessment, the fitness professional subjectively measures the deviation from normal movement pattern at each of the kinetic check points. When a joint deviates from its normal path, this is presumed to be a possible compensation and resultant of a muscular imbalance (Clark et al. 2018). While NASM provides specific examples of movement assessment patterns as discussed previously, the use of the kinetic chain check-points can be utilized to assess any functional or dynamic movement. Recognizing optimal movement patterns is essential for all exercises to promote a safe and effective exercise regime.

During functional movement patterns, muscles work in synergy to eccentrically decelerate and concentrically accelerate. It is important to understand neuromuscular efficiency during functional tasks to enhance the fundamental understanding of factors that affect both injury and rehabilitation mechanisms (Thelen et al., 2006). Structural malalignment from muscular imbalances can lead to altered movement patterns and synergistic dominance (Clark et al., 2018). A case study by Wagner and colleagues (2010) followed an adult triathlete, with recurrent cramping of the right hamstring muscle, through a strengthening and neuromuscular reeducation program of the gluteus maximus. The intervention program was one session for 24 weeks and started with 4 weeks of isolated muscle movements, progressed to 11 weeks of weight-bearing strength exercises, followed by 6 weeks of functional training. Following intervention, the client displayed a 36.4% decrease in hamstring activation during terminal swing and the first half of stance phase of running. Additional studies have detected a relationship between lower back pain, patellofemoral pain, and hamstring injury with altered neuromuscular control of hip musculature during stair stepping, marching, and maximal isometric endurance tasks (Cowan et al., 2009; Kankaanpää et al., 1998; Sole et al., 2012).

Practitioners often choose to incorporate exercises that target the gluteus maximus (GM) in both the rehabilitation and sport settings to correct and/or prevent muscular imbalances (Macadam & Feser, 2019). A recent systematic review by Macadam & Feser (2019) observed sEMG activity of the GM during different variations of the body weight exercises such as the squat, lunge, and step-up. These three exercises are commonly prescribed as therapeutic exercises to strengthen to lower extremity due to their ability to simulate in activities of daily living (Bouillon et al., 2012; Muyor et al. 2020; Myer et al., 2014).

The squat is a functional-multi joint movement that continues to be a prevalent exercise used to target muscle surrounding the lumbo-pelvic hip complex (Eliassen et al., 2018). The single-leg squat is a unilateral exercise that has become popular in the rehabilitative setting because of its ability to activate targeted weak muscles (Boudreau et al., 2009). Many studies have observed muscle activation of lower body musculature during a single and double leg-squat (Eliassen et al., 2018; Caterisano et al., 2002; Muyor et al., 2020; Robertson et al., 2008). To our knowledge, only two studies have observed the relationship between hip flexor tightness and hip sEMG during a squat variation (Chiaia et al., 2009; Mills et al., 2015).

Mills et al. (2015) compared muscle activity using surface electromyography (sEMG) of the gluteus maximus and biceps femoris during a double leg air squat in female soccer players with and without hip flexor tightness. Mills and his colleagues found a decrease in GM activity during a bilateral squat in female collegiate soccer players with tight hip flexors compared to those without hip flexor tightness. The results of this study reveal that peak muscle activation of the gluteus maximus decreases with hip flexor tightness. Chiaia and colleagues (2009) examined lower extremity musculoskeletal characteristics among twenty-six elite female soccer players and assessed numerous variables including, but not limited to, hip muscular flexibility, passive range of motion, abductor torque, and dynamic function via the single leg squat and forward step-down. The study identified participants with hip flexor tightness using the modified Thomas Test and identified the presence or absence of "deviation" from neutral at the hip, knee, and/or foot during dynamic movements by the judgment from two physical therapists. The authors found that individuals with hip flexor tightness displayed "deviations" from neutral alignment during the single leg-squat and forward step-down. These two studies used collegiate female soccer players as participants and there has yet to be as study the exams the effect of restricted hip extension in the general population during the squat. Since it is speculated that prolong periods of sitting also cause hip flexor tightness (Clark et al., 2014), it would be noteworthy observe how tight hip flexors effect the general population during functional/dynamic movements.

Numerous sEMG studies have been completed in an effort to determine hip muscular activity during a lunge and forward step-up (Ayotte et al., 2007; Ekstrom et al., 2007; Farrokhi et al., 2008; Selkowitz et al., 2016). Similar to the unilateral squat, the lunge and forward step-yp are unilateral weight bearing exercises that have become a popular method in both rehabilitative and strength training protocols (Bouillon et al., 2012). Previous studies observing sEMG during the lunge found that the gluteus maximus muscle activity ranged from 14% to 44% of MVIC (Bouillon et al., 2012; Distefano et al., 2009; Ekstrom et al., 2007;). This wide range of sEMG values may be due to several external factors such as differences in sample pool, normalization methods, how the tasks were performed, or possible tightness of muscles. Yet, there is no existing literature investigating the difference between in hip sEMG activity during lunge in those with and without tight hip flexors.

The forward step-up is a common observed task during sEMG of the lower hip muscles because it simulates stair ambulation. Ayotte et al. (2007) found that the forward step-up activated the gluteus maximus more than the lateral step-up and retro-step up. Additional studies have supported this notion, reporting that the step-up is one of the most commonly used weight bearing activity that targets both the gluteus maximus and medius (Macaskill et al., 2014; Mercer et al., 2009). However, to the authors best knowledge, no studies exist that have compared EMG activity of the hip musculature comparing hip flexor tightness during a step-up.

Muscle Activity During the Resistance Exercises

The muscles of the posterior chain, specifically the hip extensors, are important in producing speed and power during sport-specific activities, such as sprinting and jumping (Contreras et al., 2013). The squat, deadlift, and Olympic-style lifts are considered the staple exercises in strength and conditioning program (Conteras et al., 2013; Duehring et al., 2009; Ebben & Blackard, 2001; Ebben et al., 2004). Closed kinetic chain exercises are also popular in the rehabilitative setting because of the demand for exercises that recruit a high number of motor units to correct muscular imbalances and provide stabilization at a joint (Clark et al., 2018). Multijoint, integrated dynamic exercises promote intermuscular coordination and therefore make them useful implements when addressing underactive muscles, specifically at the hip.

When selecting a corrective exercise for the hip, it is paramount to understand the level of muscle activity during movements that are used in an exercise program. Hamlyn et al. (2007) compared sEMG activity of the lower abdominals, external oblique, upper lumbar erector spinae, and lumbar-sacral erector spinae between the body weight squat, superman, side bridge exercise, Olympic free squat, and deadlift in eight men and eight women. The squat and deadlift were performed during one set of 6 repetitions of an 80% of 1-repetition maximum (1RM) load. This study discovered that the lumbar sacral erector spinae sEMG activity during the squat was significantly greater compared to the deadlift by 34.5%. The lumbar sacral erector spinae sEMG activity also significantly exceeded the body weight squat, superman and side bridge by 56, 56.6, 65.6 and 53.1%, respectively. This study observed muscle activity in core stabilizer muscles and did not include musculature of the prime movers. From a prescription stand point, it is important to observe sEMG of hip musculature during these lifts in order to target prime movers.

Delgado and his colleagues (2019) recently compared sEMG activity of the vastus lateralis, biceps femoris, semitendinosus, and gluteus maximus between the back squat, Romanian deadlift, and barbell hip thrust during both an absolute 60kg and 1RM load in eight resistance trained men. The authors found significantly greater gluteus maximus muscle activity in the barbell hip thrust compared to the squat at 60kg load and 1RM. Interestingly, even though the bicep femoris did not display significantly different between the three exercises at 1RM, the biceps femoris did display higher activity during all exercises at maximal loads. The increase in the biceps femoris at higher loads indicates that prime movers for hip extension may have a motor threshold and synergist may be required to complete a movement at higher loads.

A study by Mehls et al. (2019) observed prime mover, synergist, and antagonist muscle activity at varying training loads during the barbell back squat. Muscle activity was observed using sEMG in the gluteus maximus, rectus femoris, vastus lateralis, biceps femoris, vastus medialis, and semitendinosus at 40%, 50%, 60%, 70%, 80%, 90% of 1RM of the back squat. During the ascending phase of the back squat, the authors found that the gluteus maximus produced greater muscle activity at 80% and 90% of 1RM compared to 1RM. The authors also noted that when muscle activity for the GM leveled off at 80% of 1RM, synergist muscles like the BF and ST displayed an increase in muscle activity. In addition, the vastus medialis produced greater muscle activity at 80% of 1RM than at 1RM during both phases of the squat. This further demonstrates the idea of a load threshold where synergist muscles must activate to assist a prime mover in completing a movement.

Yavuz et al. (2017) compared sEMG of the rectus femoris, vastus medialis, vatus lateralis, biceps femoris, semitendinosus, erector spinae and gluteus maximus between the back-squat and front-squat during 1RM load in twelve males. The results of this study revealed significantly higher muscle activation of the vastus medialis during the front squat, with no other differences between muscle activity. An older study by Gullet et al. (2009) also observed the differences of the front squat and back squat, but at a lighter load. Gullet and his associates compared sEMG activity of the rectus femoris, vastus medialis, biceps femoris, semitendinosus, and erector spinae between the front squat and back squat during 2 sets of 3 repetitions of a 70% of 1-repetition maximum (1RM) load in nine men and six women. The authors found that bar position did not influence muscle activity, even though more mass was lifted during the back squat. However, Gullet did not observe the muscle activity in the gluteus maximus during this study.

Contreras et al. (2016) compared mean and peak sEMG of the vastus lateralis, biceps femoris, upper gluteus maximus, and lower gluteus maximus between front, full and parallel squats during a 10-repetition maximum load in thirteen women. Contreras found no differences in muscle activity between bar placement and squat depth. Similar results were seen by Deniz & Ulas (2019) compared sEMG of the rectus femoris, vastus medialis, vastus lateralis, biceps femoris, semitendinosus, gluteus maximus, and erector spinae between the front squat, back squat, hack squat, sumo squat, and zercher squat in fourteen healthy males. All exercises were performed for six repetitions at 60% of the individual participants' 1RM. Almost all exercises revealed to have no difference in muscle activity, with the only statistically significant finding between front- and zercher squat. Deniz & Ulas found that the front squat produced greater muscle activation in the vastus medialis and vastus laterlis compared to the zercher squat. The findings from these studies indicate that there are no significant changes in muscle activity in the gluteus maximus when comparing squat depths during higher repetitions (10RM) and lighter loads (60% of 1RM) of the squat.

A recent study by Korak and his colleagues (2019) compared sEMG of the rectus femoris, vastus medialis, biceps femoris, semitendinosus, and gluteus maximus between the back-squat, front-squat and traditional deadlift during 1 set of 3 repetitions of a 75% of 1RM load in thirteen resistance trained females. The primary finding of this study was that gluteus maximus activity was significantly greater during the front-squat compared to the deadlift; no other muscles showed to have significantly different muscle activity across the lifts. It should be noted that while there were no significant differences in muscle activity between the front squat and back squat, the front squat demonstrated the highest muscle activation in the gluteus maximus of all 3 exercises. The authors suggested that a potential factor in the significant difference in activation of the gluteus maximus between the front squat and deadlift is that front squat requires more depth (resulting in greater knee flexion) and therefore more potential activation through the muscle spindles. Therefore, the front squat may be the most appropriate exercise when targeting the gluteus maximus at a lower absolute load at 75% of 1RM.

To summarize, muscle activity of many muscles have been observed across multiple resistance training exercises. Several studies discussed above noted no statistically significant differences in sEMG when comparing different resistance training exercises that were performed at the same load. However, the studies that compared sEMG of the front squat to various resistance training revealed the front squat to be the most superior exercise for activating the gluteus maximus and quadriceps muscles. This would make the front squat a valuable exercise to prescribe when targeting these muscles. However, literature still lacks the understanding of synergist muscle activity during resistance exercises, specifically in individuals with muscular imbalances. Tight hip flexors may change neuromuscular control at the hip and decrease recruitment of prime movers during the front squat. Observing the relationship between sEMG of hip muscles and hip flexor tightness in the front squat can help better prescribe treatment and corrective exercises for those with a muscular imbalance.

Muscle Imbalances

According to the National Academy of Sports Medicine (NASM), a lack of understanding of the synergistic function across all three planes of motion commonly leads to lack of optimal performance and development of muscular imbalances (Clark et al., 2018). Muscles may change function through different planes of motions to meet the independent functional demands required to enhance stability and neuromuscular control. Depending on the load, movement, and positioning of the joint, different muscles will act as prime movers, antagonist, synergist, and stabilizers (Clark et al., 2014). For example, the hamstrings group includes the semitendinosus, semimembranosus, and biceps femoris muscles. With the exception of the short head of the biceps femoris, all of the hamstring muscles cross both the femoroacetabular and tibiofemoral joints which allows for the hamstring complex to contribute to movement at the hip and knee. The hamstrings are the primary mover during knee flexion, but have been shown to generate hip extension force and resist knee extension at the beginning of the final 25% of swing phase during gate (Rodgers & Raja, 2019). This example shows to the complexity of the musculoskeletal system, as a muscle's primary role can change across planes and movements.

When there is an inappropriate shortening and lengthening of muscles this can compromise the length-tension balance within the muscular system (Arboleda & Frederick, 2008). Altered length-tension relationships can occur from poor static posture, joint dysfunction, and myofascial adhesions that may lead to altered muscle recruitment. This changes normal movements patterns and can lead to structural and functional inefficiency, as well at put individuals at higher risk for sport injury (Clark et al., 2018)

When muscles resting length is consistently shortened or lengthened, there is altered activation of prime movers/antagonist/synergist muscles (Clark et al., 2018). Tight muscles become overactive and cause a decrease neural drive to their optimal recruitment of its opposing muscle. More specifically, muscle imbalances are identified as an overactive agonist paired with an underactive functional antagonist, potentially resulting in changes in neuromuscular control, structural alignment, and movement patterns (Clark et al., 2018).

Muscle imbalances have shown to distort body alignment which can cause undue stress and strain on joints, ligaments and muscles that eventual lead to musculoskeletal injury and impaired performance (Jones & Bampouras, 2010; Kendall et al., 2005). The complexity of the musculoskeletal system makes the exact cause of muscle imbalances difficult to identify, but possible mechanisms include improper habitual patterns, chronic repetition of a movement, and altered movement due to previous injury (Clark et al., 2018; Clark et al., 2014; Janda et al., 1996). A popular theory underpinning muscular imbalance is altered reciprocal inhibition which is instigated by shortened muscles on one side of the joint causing muscles on the opposing side to become lengthened. An overactive short and tight muscle will reciprocally inhibit its functional antagonist. The decrease in neural drive and optimal recruitment to the joints functional antagonist, caused by a tight agonist, is known as altered reciprocal inhibition (Clark et al., 2018). Altered reciprocal inhibition may also lead to the occurrence of autogenic inhibition during movement. Autogenic inhibition can be described as a muscle inhibited by its own Golgi tendon organs (GTOs) from static tension placed on the musculotendinous unit (Clark et al., 2018). Autogenic inhibition is commonly applied during passive stretching techniques to reduce stiffness in a tight/shortened muscle (Kim & Lee, 2018), but may also serve as a neurological model for explaining the lack of activation that normally occurs in antagonist muscle groups in the presence of muscular imbalance. When a muscle is lengthened, there is a stretch placed on the muscle that activates GTOs and further decrease neural drive to the lengthened antagonist. A study by Lunnen et al. (1981) found that sEMG activity of the biceps femoris muscle decreases as the muscle is lengthened. From these findings, one could conclude that prolonged lengthening of the GTOs in a lengthened/weak muscle may prohibit the muscle from activating. When altered reciprocal inhibition or autogenic inhibition occurs, a synergist muscle may need to compensate for a prime mover to maintain force production (Clark et al., 2018; Edgerton et al., 1996; Sahramnn, 2002).

One proposed specific cause of muscle imbalances is prolonged sitting (Clark et. al., 2014; Sahramnn, 2002). Several studies have shown sitting for prolonged periods of time throughout the day can result in hip flexor tightness (rectus femoris, tensor fascia latae, iliopsoas) and postural imbalances (Clark et al., 2018; Clark et al., 2014). Kendall et al. (2005) has defined hip flexor tightness as the inability to achieve full hip extension when in the modified Thomas test position (Kendall et al., 2005; Winters et al., 2004). When controlling for lumbopelvic movement, the modified Thomas test has proven to be a valid test in measuring hip extension (Vigotsky et al., 2016). To allow for optimal neuromuscular efficiency, individuals need to have proper flexibility to provide freedom of movement during multiple planes of motions. Thus, individuals with tight hip flexors have demonstrated poor neuromuscular efficiency and distorted normal movements patterns (Clark at al., 2014; Krivickas & Feinberg, 1996). This altered reciprocal inhibition modifies the agonist-antagonist relationship and a tight hip flexor may decrease the neural drive to its antagonist (gluteus maximus) during hip extension (Clark et al., 2018; Buckthorpe et al., 2019). This can alter the force-coupling and length tension relationship between hip flexors and hip extenders. This specific example of muscular imbalance at the hip joint can cause the synergistic pair (hamstring complex) to become over active— a theory better known as synergistic dominance (Clark et al., 2018; Janda, 1993).

Synergistic Dominance

Synergistic dominance is a neuromuscular phenomenon in which a synergist muscle becomes over active to compensate for a weak or inhibited prime mover (Clark et al., 2018; Clark et al., 2014). As previously described, movement occurs about a joint when a prime mover activates and reciprocal inhibition occurs in its functional antagonist. However, when tight hip flexors become overactive, there may be altered recruitment and autogenic inhibition to the prime mover (gluteus maximus) during hip extension. When the gluteus maximus is underactive, there is a greater reliance on the synergist, hamstrings, to move the body through hip extension (Clark et al., 2018; Clark et al., 2014; Kisner, 2012). It has been postulated that synergistic dominance of the hamstrings leads to arthrokinetic dysfunction during sprinting and jumping movements may increase the risk of hamstring injury (Clark et al., 2014; Aslan et al., 2018; Sahrmann, 2002; Wagner et al., 2010). Gabbe et al. (2006) measured hip flexibility using the modified Thomas Test and found that tight hip flexors were an independent risk factor for self-reported hamstrings injuries in adults older than 25 years of age. Several older studies have also found an increased risk of hamstring injury due to increased hip flexor tightness in professional male soccer players (Bradley & Portas, 2007; Henderson et al., 2009; Witvrouw et al., 2003). Current studies have also supported the concept of altered reciprocal inhibition in the hip due to tight hip flexors (Aali et al., 2017; Mills et al., 2015; Van Gelder et al., 2015).

Mills and colleagues (2015) used the modified Thomas Test to measure hip flexor tightness to assign the athletes into ‘restricted’ or normal hip flexion. The authors compared muscle activity using surface electromyography (sEMG) of the gluteus maximus and biceps femoris during a double leg air squat in female soccer players with and without hip flexor tightness. Gluteus maximus: biceps femoris co-activation ratio was also observed, which was calculated by dividing the mean gluteus activity by the mean biceps femoris activity during the descending phase of the squat. The results of this study showed that peak muscle activation of the gluteus maximus was significantly less than the restricted group compared to the normal group. The results also showed the gluteus maximus: biceps femoris co-activation ratio was lower than one in the restricted group, indicating a greater activation of the biceps femoris relative to the gluteus maximus. Interestingly however, there was no difference in muscle activation or amplitude of the bicep femoris between groups. From these findings, the authors concluded that individuals with restricted hip flexor length may use less muscle activation of the gluteus maximus and greater relative activation of the hamstrings to achieve the same net hip extension.

Another recent study by Aali et al. (2017) compared muscle activity using sEMG of the gluteus maximus, biceps femoris, and adductor magnus during stance phase of walking gait in healthy adolescents with and without hip flexor tightness. The modified Thomas Test was used to categorize into those with and without iliopsoas tightness. The results of this study showed that there was greater muscle activity of the gluteus maximus, biceps femoris, and adductor magnus in individuals with iliopsoas tightness compared to without during middle and late stance phase of walking gait. The authors infer that individuals with hip flexor tightness appear to utilize different neuromuscular control in the lower extremities.

Additionally, Van Gelder and associates (2015) compared muscle activity using surface electromyography (sEMG) of the gluteus maximus, gluteus medias and biceps femoris during a two-handed kettlebell swing and single-handed kettlebell swing in healthy adults. The authors used the modified Thomas Test to measure hip flexor tightness of twenty-three healthy college age participants to investigate whether or not hip flexor length was related to muscular activation during both kettlebell exercises. A multi-linear regression analyses revealed a positive correlation between peak gluteus maximus activity and Thomas test measurements. Based on these findings, the authors concluded that greater passive or active hip extension (or less "tight" or "short" the hip flexor), the greater the gluteus maximus muscle activity.

Altered reciprocal inhibition, caused by tight hip flexors, decreases neural drive and optimal recruitment of the gluteus maximus which is theorized to cause synergistic dominance of the hamstrings (Clark et al., 2018; Buckthorpe et al., 2019). Subsequently, synergistic dominance can lead to movement compensation patterns that may result in injury. It is speculated that synergistic dominance of the hamstrings may lead to hamstring strains and lower back pain (Clark et al., 2014; Clark et al., 2018). Therefore, an intervention from a fitness professional to correct synergistic dominance is currently recommended (Clark et al., 2018; Kendall et al., 2005).

Correcting Muscular Imbalances

The National Academy of Sports Medicine (NASM) currently has a multi-step approach to correcting muscular imbalances. This corrective continuum involves inhibitory, lengthening, activation, and integration techniques to address muscles that are tight/short and weak/lengthened (Clark et al., 2014; Clark et al., 2018). The first step of correcting muscular imbalances starts with self-myofascial release of tight muscles to improve the muscle tissue's ability lengthen (Clark et al., 2018). Restoration of optimal function and appropriate balance between agonist and antagonist muscles cannot be completed unless the release of tension and stretching of the shortened agonist group is completed with appropriate strengthening of the weak antagonist group (Arboleda & Frederick, 2008). This can be done through the use of a variety of tools such as foam rollers, hand-rollers, PVC pipes and other objects of various size and material. Several studies have analyzed different myofascial release techniques that target tight hip flexors in hopes to increase hip range of motion (Bushell et al., 2015; Mohr et al., 2014). Mohr et al. (2014) conducted a study to determine if foam rolling before static stretching produced increases in passive hip-flexion range of motion. The authors concluded that foam rolling with a combination of static stretching allowed for an increase in hip-flexion range of motion. Bushell et al. (2015) also observed the effects of foam rolling on increasing hip extension and found similar results for the effectiveness of foam rolling on hip extension angles in a dynamic lunge position. The results showed consistent foam rolling produced increased hip extension during a dynamic lunge, indicating that foam rolling is beneficial for increasing range of motion.

The next step in the corrective continuum involves lengthening mechanically shortened muscle to increase range of motion (ROM) at the tissue and joint (Clark et al., 2018). This step is accomplished through several stretching methods such as static and neuromuscular stretching. A variety of stretching techniques have been described in the literature to address tight hip flexors to increase limited hip extension (Aslan et al., 2018). Static (active or passive), dynamic, and proprioceptive neuromuscular facilitation (PNF) stretching have shown to increase hip extension by targeting hip tight flexors (Watt et al., 2011; Winters et al., 2004). Winters et al. (2004) found both active and passive stretching of the hip flexor muscles to improve hip extension range of motion. Watt et al. (2011) observed the effectiveness of a 10-week supervised hip flexor stretching program in frail elderly adults. The results of the hip-flexor stretching program showed to increase the walking speed and stride-length in older adults.

The final steps of NASM's corrective exercise continuum are activation and integration techniques to address the underactive myofascial tissue and re-establishment of proper neuromuscular control. The activation stage applies isolated strengthening exercises for muscles that are under active or “weak”. A few examples of active isolated exercises for muscles surrounding the hip are bridges, standing hip extension, side-lying hip abduction, and positional isometric exercises (Clark et al., 2018). Once appropriate muscles have been activated, integrated dynamic movements are utilized to enhance functional capacity. This final integration stage focuses highly on synergistic function to enhance neuromuscular control. During the final stage, it is imperative to select exercises that that continue to emphasize underactive muscles. The gluteus maximus is one of the most commonly targeted muscles to improve muscular imbalances in the lower body (Clark et al., 2014; Clark et al., 2018). A variety of exercises, such as the squat, deadlift, bridge, kettle-bell swing, forward-lunge, side-lunge, step-up have been suggested to strengthen the gluteus maximus (Distefano et al., 2009; McGill & Marshall, 2012; Patel, 2014; Reiman et al., 2012). When comparing the front squat, back squat, and deadlift, Korak and colleagues (2019) found the front squat activated the highest amount of gluteus maximus activity. Training loads less than 1RM seem to be sufficient in maximizing motor recruitment of the gluteus maximus during a squat (Korak et al., 2019; Mehls et al. 2019). The premise of the dynamic integrated movements is to promote high levels neuromuscular efficiency to simulate daily functional activities, thus reestablishing motor control and decreasing reliance on synergy muscles (Clark et al., 2018). Therefore, understanding which muscles produce the highest activation during functional and dynamic movement is paramount when targeting prime movers.

Conclusions

Muscles and muscle groups must work together to ensure proper joint movements, while also minimizing undesirable motion. The National Academy of Sports Medicine emphasizes movement assessments before partaking in an exercise program to identify possible altered recruitment strategies that may subject an individual to injury (Clark et al., 2018). Muscular imbalances can lead to altered neuromuscular efficiency during movement and lead to synergistic dominance. It is important to investigate possible causes of muscle imbalances, such as hip flexor tightness, and how this changes motor control. Existing literature suggests that tight hip flexors may cause reciprocal inhibition of the gluteus maximus and place greater stress on the hamstrings during functional movements. However, no study has compared sEMG in the hip musculature in the general population during the over-head squat, in-line lunge, step-up or in the resistance trained population during the front squat in those with and without hip flexor tightness.

CHAPTER III

THE EFFECT OF RESTRICTED HIP EXTENSION ON MUSCLE ACTIVITY DURING FUNCTIONAL MOVEMENTS

Introduction

Poor flexibility has long been suggested to affect a person's functional movement capacity. For instance, several authors have noted that restricted hip extension is associated with poor neuromuscular efficiency and distorted movements patterns (Bachrach, 2007; Clark at al., 2014; Krivickas & Feinberg, 1996). The manifestation of noncompliant musculotendinous tissue has been proposed to be related to specific activity patterns, including certain sedentary positions. For example, restricted hip flexor length has been observed in both sedentary and active populations and is commonly considered to be related to excessive amounts of sitting, repetitive uniplanar movements, and/or improper movement techniques (Bachrach, 2007; Clark et al. 2014).

A restricted muscle can alter the length-tension relationships surrounding a joint and lead to altered muscle recruitment patterns (Clark et al., 2014). For example, tight hip flexors can create altered reciprocal inhibition which modifies the agonist-antagonist relationship at the hip joint. Shortened, overactive hip flexors can cause a decrease in neural drive to its functional agonist (gluteus maximus) during hip extension (Clark et al., 2018; Buckthorpe et al., 2019). When the gluteus maximus is underactive, there is a greater reliance on the synergist, hamstrings, to move the body through hip extension, a syndrome termed synergistic dominance (Clark et al., 2018; Clark et al., 2014; Kisner, 2017). It has been proposed that synergistic dominance of the hamstrings leads to arthrokinetic dysfunction during sprinting and jumping movements, thus increasing the risk of hamstring injury (Clark et al., 2014; Aslan et al., 2018; Sahrmann, 2002; Wagner et al., 2010).

Functional movements are often used to assess arthrokinetic dysfunction to identify altered muscle recruitment patterns and muscular imbalances (Clark et al. 2014; Janda 1996). The squat, lunge, and step-up are common functional movements used to observe human movement impairments that may lead to potential risk for injury (Clark et al. 2014; Cook et al. 2014; Marques et al., 2017; Muyor et al. 2020). By identifying muscular imbalances, such as synergistic dominance, specific corrective exercises can be prescribed to enhance one's functionality and decrease risk of future injuries (Blazevich et al., 2012; Bouillon et al., 2012; Clark et al. 2014; Myer et al., 2014).

To the author's knowledge, only one study has observed the effects of restricted hip extensor on muscle activity during a bilateral air squat (Mills et al. 2015). However, this study only observed female collegiate soccer players and observed only one functional movement. To better understand the effects of restricted hip extension on muscle activity in the general population during functional movements, further investigation is required. The purpose of the study was to compare surface electromyography (sEMG) in the rectus femoris (RF), gluteus maximus (GM), biceps femoris (BF), and semitendinosus (ST) muscles and GM:BF co-activation ratio during the over-head squat, in-line lunge, and step-up between resistance trained with and without hip flexor tightness. It was hypothesized that trained females without hip flexor tightness will have higher peak muscle activation of the gluteus maximus compared to those with hip flexor tightness

Methods

Participants

Twenty-three apparently healthy trained females (age: 22.00 ± 2.62 years; height: 162.84 ± 4.98 cm; body mass: 70.47 ± 14.84 kg; BMI: 26.48 ± 4.91) were assigned either to a control (n = 12) or experimental (n = 11) group determined from the modified Thomas Test. All participants were free of any lower body musculoskeletal injury within the past three months. After the participants were informed of the benefits and possible risks of the protocol, all participants read and signed a written informed consent and PAR-Q+ pre-health screening prior to participation. Participants were recruited from the surrounding community via word of mouth. The Institutional Review Board at Middle Tennessee State University approved this study prior to data collection.

The modified Thomas Test was used to assess hip flexor length. Previous studies have also shown that this method of hip extension range of motion (ROM) assessment has good inter-rater reliability (Clapis et al., 2008; Peeler & Anderson, 2007; Mills et al. 2015). A digital inclinometer (Model #12-1057, Fabrication Enterprise Inc. – Baseline Evaluation Instruments, White Plains, New York) was used to measure hip extension ROM during the modified Thomas Test. Inclinometer values greater than 0° (+) indicate that the thigh was positioned above parallel and relatively flexed. Inclinometer values below 0° (-) indicate that the thigh was below parallel and relatively extended (Ferber, 2010). Inclusion criteria for the normal group was defined as hip extension ROM greater than 15° below parallel. Inclusion criteria for the experimental (tight hip flexor) group was defined as hip extension greater than 0° above parallel (Mill et al., 2015). The tightest leg was the experimental leg observed during the study for individuals with tight hip flexors, whereas the most flexible leg was the control leg observed for individuals without tight hip flexors in the study.

Procedures

Participants were required to attend a single session at the university muscle physiology laboratory. Upon attending the session, participants completed the informed consent and pre-health screening questionnaire (PAR-Q+) and were screened for inclusion criteria. If inclusion criteria were met into either group, participant's age, height, and body were measured and recorded. Height was measured to the nearest 0.1 cm using a stadiometer (SECA Corporation, Model 222, Germany) and body mass was assessed using a digital scale (Tanita Worldwide, Model BF 522, Arlington Heights, Illinois) to the nearest 0.1 kg.

Muscle activity and kinematic data were measured using the Trigno wireless electromyographic (EMG) system (Delsys; Natick, MA). The system contained Trigno Flex EMG sensors that are placed directly on the skin surface over the mid-belly of indicated muscles. Prior to placing EMG sensors, hair was shaved with a safety razor, exfoliated with Redux paste, and cleaned with isopropyl alcohol to reduce signal impedance. The underside of the sensors was attached to the skin with double-sided adhesive tape and then the outside of the sensor was further secured with adhesive stretch tape. Location and procedures for placement of sensors on the RF, GM, BF, and ST muscles was implemented in accordance with the SENIAM project guidelines (SENIAM group).

Kinematic data (angular movement) was measured using wireless goniometers (Biometrics, Newport, UK) that were connected to Trigno Goniometer Adapters both of which were fixated to the skin in the same fashion described for the Trigno Flex sensors. The primary purpose of the kinematic data was to identify ascending and descending phases of movements. For knee joint angle, the proximal arm was aligned along the femur to the greater trochanter and the distal arm was aligned to the lateral tibia in line with lateral malleolus. All muscle activity and kinematic data was integrated directly into the EMGworks software via wireless adapters provided by the manufacture to ensure proper timing during recording. An external trigger device (Delsys, Natick, MA) was used to initiate and cease data collection. Prior to performing functional movements, participants performed three trials of maximal voluntary isometric contractions (MVIC). For each MVIC movement, participants were positioned to generate maximal force (Kendall, McCreary, & Provance 1993). Participants performed one practice trial, followed by three MVIC trials for each movement. Participants were instructed to hold the MVICs for 5 seconds and allotted 60 second rest between each trial. The highest peak MVIC per muscle was used for normalization of muscle activity during the functional movements.

Functional Movements

Prior to testing, participants were permitted to practice each functional movement to familiarize themselves until they performed each movement in a controlled manner and completed a 5-minute warm-up on a stationary cycle ergometer. For each functional movement, participants were instructed to perform at least 3 repetitions with a 1- minute rest period between each repetition to prevent fatigue. To establish a controlled and consistent speed, a digital metronome was set 60 beats per minute for each functional movement. The participants were asked to perform a three second eccentric phase and a two second concentric phase for overhead squat and in-line lunge. For the forward step-up, participants were instructed to step at a two second concentric phase.

Over-head squat. The over-head squat was performed in a manner originally described by the National Academy of Sports Medicine (NASM) movement assessment (Clark et al. 2014). The participants were instructed to stand with their feet shoulder-width apart and pointed straight ahead on a stable surface. Participants then raised their arms overhead with elbows fully extended and were instructed to squat to roughly the height of a chair seat and return to a starting position.

In-line lunge. The in-line lunge was performed in a similar manner originally described by the Functional Movement Screen (FMS™) (Cook et al., 2014). An athletic trainer attained the participants' tibia length by measuring from the floor to the tibial tuberosity. The participant was then asked to place the end of their heel on a tape measure taped to the floor. The previous tibial measurement was then applied from the end of the toes of the foot on the floor and a mark was made. Finally, the participants were instructed to lower the back knee enough to touch the ground surface behind the heel of the front foot, while maintaining an upright posture, and then return to the starting position. The participants were informed to perform the in-lunge in a slow controlled fashion with both toes pointing forward and feet remaining flat. Participants were instructed to keep their hands on their hips.

Forward Step-up. Participants were asked to step-up onto a step (20cm) with their tested foot, with their opposite foot trailing until both feet were firmly planted on top of the step. The participants were instructed to start the test directly in front of the step while keep their hands on their waist and knees straight. The non-tested leg was positioned over the floor adjacent to the step with the knee extended, while the tested leg was used to step-up until both feet were planted on top of the step.

Data Processing

All EMG data was normalized to maximal voluntary isometric contraction (MVIC) data collected for each participant to represent muscle activation of each muscle as a percent of peak muscle activity. Surface EMG data were initially processed using a Nyquist resampling equation at 1000Hz. Data was initially filtered with a Butterworth band-pass filter at 20Hz and 450Hz. A root-mean-square algorithm with a 200ms window was then applied to the filtered data. Goniometer data was to mark and differentiate directional phases during the overhead squat and in-line lunge. The ascending phase of the forward step-up was the only phase observed because the purpose was to simulate the concentric nature of stepping up stairs. All data processing was performed using EMGworks analysis software (Delsys, Model SC-S08-4.5.3, Natick, MA) and exported to Microsoft excel (2016). The gluteus maximus: biceps femoris co-contraction ratio was calculated by dividing the mean gluteus maximus activity by the mean biceps femoris activity (gluteus maximus: biceps femoris), as described by Mills et al. (2015). A gluteus maximus: biceps femoris co-activation ratio of 1.0 indicates balanced muscular activation, whereas a ratio less than one 1.0 indicates greater activation of the biceps femoris relative to the gluteus maximus.

Statistical Analyses

The IBM© SPSS© Statistics (IBM Corp. Released 2016. IBM SPSS Statistics for Windows, Version 24.0. Armonk, NY: IBM Corp) was used for the statistical analysis. Descriptive statistics was provided for each participant and be expressed in means $\pm$ standard deviations. Independent samples t-tests were conducted to compare participants with hip flexor tightness (n = 12) and without hip flexor tightness (n = 11) RF, BF, ST and GM mean muscle activity and GM:BF co-activation ratio during the overhead squat and in-line lunge, and forward step-up. Mean muscle activation was analyzed during the ascending and descending phases for the over-head squat and in-line lunge, whereas the only the ascending phase was observed during the forward step-up. Effect sizes were calculated using Hedges' *g*. The alpha level was set at .004 using the Bonferroni correction for all statistical procedures.

Results

Results of the independent samples *t*-test comparing mean muscle activity of the muscles used in the study (RF, BF, ST, and GM) and GM:BF co-activation ratio during the ascending and descending phase of the overhead squat are displayed in Table 1. Mean muscle activity in the RF, BF, ST, and GM were not significantly different in female participants with and without hip flexor tightness during the descending and ascending phases of the overhead squat. Although, mean BF muscle activity in participants with tight hip flexors (M = .27, SD = .33) was higher compared to participants without tight hip flexors (M = .13, SD = .08) during the descending phase of the overhead squat, but was not statistically significant (p = .18). Similar results were seen during the ascending phase of the overhead squat where individuals with tight hip flexors displayed higher mean BF (M = .33, SD = .31) and higher mean ST (M = .24, SD = .36) compared to mean BF activity (M = .23, SD = .19) and mean ST activity (M = .12, SD = .17) in those without hip flexor tightness. However, there was no statistical difference between mean BF (p = .31) and mean ST (p = .26) activity in those with and without hip flexor tightness during the ascending phase of the overhead squat.

Results of the independent samples *t*-test comparing mean muscle activity of the RF, BF, ST, and GM and GM:BF co-activation ratio during the ascending and descending phase of the in-line lunge are displayed in Table 2. Mean muscle activity in the RF, BF, ST, and GM were not significantly different in female participants with and without hip flexor tightness during the descending and ascending phases of the in-line lunge. During the ascending phase of the in-line lunge, individuals with tight flexors also displayed higher mean BF activity (*M* = .28, *SD* = .21) compared to individuals without tight hip flexors (*M* = .18, *SD* = .09), but was not statistically significant (*p* = .16).

Results of the independent samples *t*-test comparing for mean muscle activity of the RF, BF, ST, and GM and GM:BF co-activation ratio in those with and without hip flexor tightness during the ascending of the in-line lunge are displayed in Table 3. Mean muscle activity in the RF, BF, ST, and GM were not significantly different in female participants with and without hip flexor tightness during the descending and ascending phases of the forward step-up. During the ascending phase of the forward step-up, individuals with hip flexor tightness displayed higher mean BF (*M* = .30, *SD* = .41) activity and ST (*M* = .27, *SD* = .43) activity compared to mean BF (*M* = .10, *SD* = .06) and ST (*M* = .14, *SD* = .43) activity in those without hip flexor tightness. However, there was no statistical difference between mean BF (*p* = .13) and mean ST (*p* = .41) activity in those with and without hip flexor tightness during the ascending phase of the forward step-up.

Table 1.

Normalized Mean Muscle Activity and GM:BF Co-Activation during the Overhead Squat.

	Non-Tight Hip Flexors		Tight Hip Flexors						
Variable	M	SD	M	SD	*t*	*p*	Mean Difference	95% CI	Hedges' *g*
DSC RF	.53	.40	.51	.23	.21	.86	.03	[-0.26, 0.31]	.83
DSC BF	.13	.08	.27	.33	1.42	.184	.22	[-0.56, 0.87]	.58
DSC ST	.06	.09	.09	.02	.28	.79	.01	[-0.07, 0.05]	.59
DSC GM	.09	.03	.09	.05	.57	.58	.02	[-0.04, 0.07]	.22
DSC GM:BF Co-A	.75	.50	.56	.40	1.01	.32	.19	[-0.20, 0.58]	.41
ASC RF	.67	.54	.50	.24	.97	.35	.17	[-0.20, 0.53]	.42
ASC BF	.23	.19	.33	.31	1.04	.31	.14	[-0.41, 0.13]	.37
ASC ST	.12	.17	.24	.36	1.13	.26	.19	[-0.55, 0.17]	.43
ASC GM	.13	.08	.15	.06	.58	.57	.02	[-0.08, 0.05]	.23
ASC GM:BF Co-A	.70	.36	.73	.47	.18	.86	.03	[-0.39, 0.32]	.07

* DSC descending, ASC ascending, RF rectus femoris, BF biceps femoris, ST semitendinosus, GM gluteus maximus, Co-A co-activation.

Table 2.

Normalized Mean Muscle Activity and GM:BF Co-Activation during the In-line Lunge.

	Non-Tight Hip Flexors		Tight Hip Flexors						
Variable	M	SD	M	SD	*t*	*p*	Mean Difference	95% CI	Hedges' *g*
DSC RF	.44	.31	.44	.18	.04	.97	.004	[-0.23, 0.22]	.02
DSC BF	.13	.07	.27	.28	1.52	.16	.14	[-0.24, 0.04]	.69
DSC ST	.12	.18	.11	.08	.26	.80	.01	[-013, 0.21]	.10
DSC GM	.10	.03	.09	.03	.35	.73	.008	[-0.04, 0.06]	.14
DSC GM:BF Co-A	.72	.30	.63	.56	.49	.63	.09	[-0.29, 047]	.20
ASC RF	.57	.48	.46	.17	.71	.49	.10	[-0.21, 0.42]	.28
ASC BF	.18	.09	.28	.21	1.43	.16	.10	[-0.25, 0.08]	.59
ASC ST	.15	.10	.14	.10	.09	.93	.005	[-0.10, 0.05]	.04
ASC GM	.18	.11	.18	.09	.24	.81	.01	[-0.09, 0.08]	.09
ASC GM:BF Co-A	.97	.38	.99	.41	.06	.95	.02	[-0.55, 0.58]	.04

* DSC descending, ASC ascending, RF rectus femoris, BF biceps femoris, ST semitendinosus, GM gluteus maximus, Co-A co-activation.

Table 3.

Normalized Mean Muscle Activity and GM:BF Co-Activation during the Forward Step-up.

	Non-Tight Hip Flexors		Tight Hip Flexors						
Variable	M	SD	M ± SD	M ± SD	*t*	*p*	Mean Difference	95% CI	Hedges' *g*
ASC RF	.26	.20	.25	.12	.10	.92	.007	[-0.13, 0.15]	.04
ASC BF	.10	.06	.30	.23	1.73	.11	.12	[-0.48, 0.07]	.73
ASC ST	.14	.26	.17	.15	.37	.71	.03	[-0.43, 0.18]	.15
ASC GM	.10	.07	.10	.04	.035	.97	<.001	[-0.05, 0.51]	.01
ASC GM:BF Co-A	.96	.41	.80	.61	.89	.39	.18	[-0.25, 0.64]	.35

*DSC descending, ASC ascending, RF rectus femoris, BF biceps femoris, ST semitendinosus, GM gluteus maximus, Co-A co-activation

Discussion

The purpose of this study was to compare mean muscle activity of the RF, BF, ST, and GM and GM:BF co-activation ratio between females with and without hip flexor tightness during the overhead squat, in-line lunge, and forward step-up. Contrary to our hypothesis, no statistical differences were found in mean muscle activation of the RF, BF, ST, and GM and GM:BF co-activation ratio. Mean GM activity was similar in those with and without hip flexor tightness during all three functional movements. However, individuals with hip flexor tightness displayed higher mean BF activation during the overhead squat, in-line lunge, and forward step-up. Mean ST was also higher in individuals with tight hip flexors during the overhead squat and forward step-up.

To our knowledge, there is only one study that has observed mean GM and BF activity during an overhead squat. The authors compared muscle activity using surface electromyography (sEMG) of the gluteus maximus and biceps femoris during a double leg air squat in female soccer players with and without hip flexor tightness. Gluteus maximus: biceps femoris co-activation ratio was also observed, which was calculated by dividing the mean gluteus activity by the mean biceps femoris activity during the descending phase of the squat. Mills et al. (2015) found that peak muscle activation of the gluteus maximus was significantly less than the restricted group compared to the normal group. The authors also found that the GM:BF co-activation ratio was lower than 1.0 in the restricted group, indicating a greater activation of the biceps femoris relative to the gluteus maximus. However, there was no difference in muscle activation or amplitude of the bicep femoris between groups. In the current study, there was no significant difference between mean GM and BF activity during the overhead squat and GM:BF co-activation ratio. This may due Mills et al. (2015) using collegiate soccer females and therefore an active population, whereas this study did not consider activity level in the sample. It is well established that individuals who are resistance trained and physically active have greater motor unit activation and neuromuscular control compared to their untrained counterparts (Aagaard et al., 2002; Pensini et al. 2002; Sale, 1987). However, the sample in this study had individuals who were both active and non-active, which may influence mean EMG muscle activity during functional movements more than hip flexor tightness.

Numerous sEMG studies have been completed to determine hip muscular activity during a lunge (Ekstrom et al., 2007; Farrokhi et al., 2008; Selkowitz et al., 2016). Previous studies observing sEMG during the lunge found that the gluteus maximus muscle activity ranged from 10% to 44% of MVIC (Bouillon et al., 2012; Distefano et al., 2009; Ekstrom et al., 2007; Selkowitz et al., 2016). This wide range of sEMG values may be due to several external factors such as differences in sample pool, normalization methods, how the tasks were performed, or possible tightness of muscles. To the authors best knowledge, the current study is the first study to investigate hip sEMG activity during the in-lunge in those with and without tight hip flexors. The results of this study revealed no significant difference in mean RF, BF, ST, or GM between individuals with and without hip flexor tightness during the in-line lunge. The mean GM activity during the ascending phase of the in-line lunge in those with hip flexor tightness and without were comparable. Interesting, however, during the ascending phase of the in-line lunge mean BF activity was higher in those with hip flexor tightness compared to those without, but was not statistically significant. Similar patterns were seen during the descending phase of the in-line lunge where participants with hip flexor tightness displayed higher mean BF activity during the in-line lunge compared to those without. Individuals with hip flexor tightness may display overactive BF during the in-line lunge due to a change in dynamic movement, such as excessive forward lean, to compensate for tight hip flexors (Clark et al., 2014). While, was not found during the in-line lunge in the current study, there was a large effect size in ascending BF. Potentially, a low absolute load on the muscle may not activate enough of a motor unit pool of the synergist BF to see statistical significant differences. Another reason for not seeing statistical significance may possibly be due to activity level not being considered in the participant sample. Proper form and greater neuromuscular activation is more likely to be seen in individuals who are physically active and resistance trained, regardless of hip flexor tightness. Muscle imbalances caused by hip flexor tightness may affect a physically active and inactive population differently. More specifically, the mechanism that instates a muscular imbalance in a specific population may cause distinct changes in muscular activation.

The complexity of the musculoskeletal system makes the exact cause of muscle imbalances difficult to identify, but possible mechanisms include improper habitual patterns, chronic repetition of a movement, and altered movement due to previous injury (Clark et al., 2018; Clark et al., 2014; Janda et al., 1996). The mechanism that causes hip flexor tightness may impact the musculoskeletal compensations and therefore influence muscular activity differently. Mills et al. (2015) used female soccer players who were thought to obtain hip flexor tightness from chronic repetitive hip flexion. In the current study, both active and inactive participants who partook in the study may have obtained hip flexor tightness from other types of mechanisms. Therefore, the mechanism itself that caused hip flexor tightness may influence muscle activity during functional movements.

The forward step-up has been observed using sEMG of the lower hip muscles because it simulates stair ambulation and is one of the most used weight bearing activity that targets the gluteus maximus (Ayotte et al., 2007; Macaskill et al., 2014; Mercer et al., 2009; Selkowitz et al., 2016). However, these previous studies are comparative studies between the forward step-up and other popular exercises and no literature exists that compared EMG activity of the hip musculature comparing hip flexor tightness during a forward step-up. In this study, individuals with and without hip flexor tightness produced similar mean GM activity. However, participants with hip flexor tightness generated greater mean BF activity compared to those without hip flexor tightness during the forward step-up, but was not statistically significant. Moreover, individuals with hip flexor tightness displayed a lower GM:BF co-activation during the forward step-up compared to those without, but this was also not statically significant. This indicates that those with hip flexor tightness may have overactive hamstrings activity relative to the gluteus maximus. It is again possible that a low absolute load may have been the reason that statistical significance was not found, yet a large effect size is apparent.

It has been speculated that tight hip flexors may cause reliance on secondary hip extensors, which may provoke greater stress on the hamstrings (Daly et al., 2016; Franklyn-Miller et al., 2014; Mills et al., 2015; Renström & Johnson, 1985). Over activation of the hamstrings has been linked to those with lower extremities injuries (Besier et al., 2009; Emami et al., 2014; Sharma et al., 2017). Sharma et al. 2017 and colleagues found that participants with osteoarthritis displayed increased semitendinosus

(SMT) and BF muscle activity during mid-stance, late stance and early swing phase of a gait cycle (Sharma et al., 2017). Similar results were seen in those with patellofemoral pain syndrome (PPS) where those with PPS generated greater BF activity during walking gait (Besier et al., 2009). In addition, Emami et al. 2014 observed greater mean BF activity in those with hamstring injury compared to those without during a prone hip extension test. A study by Daly et al. (2016) compared BF:GM muscle activation in male athletes with and without a previous hamstring injury during running gait. Daly and his team found that individuals with a previous hamstring injury had greater BF:GM muscle activation compared to those without a previous hamstring injury, indicating greater BF muscle activity compared to the GM. In the current study, mean BF activity was higher in those with hip flexor tightness during the over-head squat, in-line lunge, and forward step-up, but was not statistically significant. Therefore, more investigation on hip flexor tightness and hamstring activity is inquired, as previous literature has shown tight hip flexors may cause changes in the neuromuscular control of the lumbopelvic hip complex, specifically the BF.

Only one study (Mills et al., 2015) has investigated the effect of hip flexor tightness on muscle activity during the air squat, which showed significantly higher peak GM and GM:BF co-activation in those without hip flexor tightness. However, the results of this study showed that individuals with hip flexor tightness generated greater mean BF during the overhead squat, in-line lunge, and forward step-up compared to those without, although it was not statistically different. This may have been due to Mills et al. (2015) and his colleagues observing female collegiate soccer players, an active population, whereas this study did not control for physical activity level. This suggests that muscular imbalances caused by hip flexor tightness may affect a physically active and inactive population differently due to different causational mechanisms that lead to hip flexor tightness, and eventually muscular imbalances surrounding the hip.

The main limitation of this study was low sample size and unequal groups, increasing the likelihood of type II error. Another limitation to this study was the calculation of the GM:H ratio only considered the BF (Mills et al., 2015), which may not fully represent the function of the hamstring muscle group during hip extension. An additional limitation is that activity level was not controlled for, which may have been the reason that there was no difference between groups. The findings of this study call for further investigation on the effect if hip flexor tightness of muscle activity during functional movements. Future studies should investigate muscle activation in those with and without hip flexor tightness under different external loads while controlling for activity level. Future research should also aim to confirm the effect of hip flexor tightness on muscle activity and its relationship to hamstring injury.

Chapter III References

Aagaard, P., Simonsen, E. B., Andersen, J. L., Magnusson, P., & Dyhre-Poulsen, P. (2002). Increased rate of force development and neural drive of human skeletal muscle following resistance training. *Journal of Applied Physiology*, *93*(4), 1318-1326.

Aslan, H., Buddhadev, H. H., Suprak, D. N., & San Juan, J. G. (2018). Acute effects of two hip flexor stretching techniques on knee joint position sense and balance. *International Journal of Sports Physical Therapy*, *13*(5), 846–859.

Ayotte, N. W., Stetts, D. M., Keenan, G., & Greenway, E. H. (2007). Electromyographical analysis of selected lower extremity muscles during 5 unilateral weight-bearing exercises. *Journal of Orthopaedic & Sports Physical Therapy*, *37*(2), 48-55.

Bachrach, R. M., Micelotta, J., & Winuk, C. (2007). The relationship of low back pain to psoas insufficiency. *Journal of Orthopaedic Medicine*, *29*(3), 98-104.

Besier, T. F., Fredericson, M., Gold, G. E., Beaupré, G. S., & Delp, S. L. (2009). Knee muscle forces during walking and running in patellofemoral pain patients and pain-free controls. *Journal of Biomechanics*, 42(7), 898–905. https://doi.org/10.1016/j.jbiomech.2009.01.032

Blazevich, A. J., Kay, A. D., Waugh, C., Fath, F., Miller, S., & Cannavan, D. (2012). Plantarflexor stretch training increases reciprocal inhibition measured during voluntary dorsiflexion. *Journal of Neurophysiology*, *107*(1), 250–256.

Bouillon, L. E., Wilhelm, J., Eisel, P., Wiesner, J., Rachow, M., & Hatteberg, L. (2012). Electromyographic assessment of muscle activity between genders during unilateral weight-bearing tasks using adjusted distances. *International Journal of Sports Physical Therapy*, *7*(6), 595.

Buckthorpe, M., Stride, M., & Villa, F. D. (2019). Assessing and treating gluteus maximus weakness - a clinical commentary. *International Journal of Sports Physical Therapy*, *14*(4), 655–669.

Clapis, P. A., Davis, S. M., & Davis, R. O. (2008). Reliability of inclinometer and goniometric measurements of hip extension flexibility using the modified Thomas test. *Physiotherapy Theory and Practice*, *24*(2), 135-141.

Clark, M.A., Lucett, S.C., McGill, E., Montel, I., & Sutton, B. (2018). *National Academy of Sports Medicine Essentials of Personal Fitness Training.* Jones & Bartlett Learning.

Clark, M., Sutton, B. G., & Lucett, S. (2014). *NASM Essentials of Sports Performance Training.* Jones & Bartlett Learning.

Cook, G., Burton, L., Hoogenboom, B. J., & Voight, M. (2014). Functional movement screening: the use of fundamental movements as an assessment of function-part 2. *International Journal of Sports Physical Therapy*, *9*(4), 549–563.

Daly, C., Persson, U. M., Twycross-Lewis, R., Woledge, R. C., & Morrissey, D. (2016). The biomechanics of running in athletes with previous hamstring injury: A case-control study. *Scandinavian Journal of Medicine & Science in Sports*, *26*(4), 413–420. https://doi.org/10.1111/sms.12464

Emami, M., Arab, A. M., & Ghamkhar, L. (2014). The activity pattern of the lumbo-pelvic muscles during prone hip extension in athletes with and without hamstring strain injury. *International Journal of Sports Physical Therapy*, *9*(3), 312.

Farrokhi, S., Pollard, C. D., Souza, R. B., Chen, Y. J., Reischl, S., & Powers, C. M. (2008). Trunk position influences the kinematics, kinetics, and muscle activity of the lead lower extremity during the forward lunge exercise. *The Journal of Orthopaedic and Sports Physical Therapy*, *38*(7), 403–409.

Ferber, R., Kendall, K. D., & McElroy, L. (2010). Normative and critical criteria for iliotibial band and iliopsoas muscle flexibility. *Journal of Athletic Training*, *45*(4), 344-348.

Franklyn-Miller, A., Roberts, A., Hulse, D., & Foster, J. (2014). Biomechanical overload syndrome: defining a new diagnosis. *British Journal of Sports Medicine*, *48*(6), 415-416.

Janda, V., Frank, C., & Liebenson, C. (1996). Evaluation of muscular imbalance. *Rehabilitation of the Spine: A Practitioner's Manual*, *6*, 97-112. Lippincott Williams & Wilkins.

Kisner, C., Colby, L. A., & Borstad, J. (2017). *Therapeutic Exercise: Foundations and Techniques*. F.A. Davis Company.

Krivickas, L. S., & Feinberg, J. H. (1996). Lower extremity injuries in college athletes: relation between ligamentous laxity and lower extremity muscle tightness. *Archives of Physical Medicine and Rehabilitation*, *77*(11), 1139–1143.

Marques, V. B., Medeiros, T. M., de Souza Stigger, F., Nakamura, F. Y., & Baroni, B. M. (2017). The functional movement screen (FMS™) in elite young soccer players between 14 and 20 years: composite score, individual-test scores and asymmetries. *International Journal of Sports Physical Therapy*, *12*(6), 977–985.

Mills, M., Frank, B., Goto, S., Blackburn, T., Cates, S., Clark, M., Aguilar, A., Fava, N., & Padua, D. (2015). Effect of restricted hip flexor muscle length on hip extensor muscle actvity and lower extremity biomechanics in college-aged female soccer players. *International Journal of Sports Physical Therapy*, *10*(7), 946–954.

Muyor, J. M., Martín-Fuentes, I., Rodríguez-Ridao, D., & Antequera-Vique, J. A. (2020). Electromyographic activity in the gluteus medius, gluteus maximus, biceps femoris, vastus lateralis, vastus medialis and rectus femoris during the monopodal squat, forward lunge and lateral step-up exercises. *PloS One*, *15*(4).

Myer, G. D., Kushner, A. M., Brent, J. L., Schoenfeld, B. J., Hugentobler, J., Lloyd, R. S., Vermeil, A., Chu, D. A., Harbin, J., & McGill, S. M. (2014). The back squat: A proposed assessment of functional deficits and technical factors that limit performance. *Strength and Conditioning Journal*, *36*(6), 4–27.

Peeler, J., & Anderson, J. E. (2007). Reliability of the Thomas test for assessing range of motion about the hip. *Physical Therapy in Sport*, *8*(1), 14-21.

Pensini, M., Martin, A., & Maffiuletti, N. A. (2002). Central versus peripheral adaptations following eccentric resistance training. *International Journal of Sports Medicine*, *23*(08), 567-574.

Renström, P., & Johnson, R. J. (1985). Overuse injuries in sports. *Sports Medicine*, *2*(5), 316-333.

Sale, D. G. (1987). Influence of exercise and training on motor unit activation. *Exercise and Sport Sciences Reviews*, *15*, 95-151.

Sahrmann, S. (2002). *Diagnosis and Treatment of Movement Impairment Syndromes.* Mosby St. Louis.

SENIAM The SENIAM Project Retrieved January 2021, from http://wwwseniamorg/

Sharma, S. K., Yadav, S. L., Singh, U., & Wadhwa, S. (2017). Muscle Activation Profiles and Co-Activation of Quadriceps and Hamstring Muscles around Knee Joint in Indian Primary Osteoarthritis Knee Patients. *Journal of Clinical and Diagnostic Research*, *11*(5), RC09–RC14. https://doi.org/10.7860/JCDR/2017/26975.9870

Wagner, T., Behnia, N., Ancheta, W. K., Shen, R., Farrokhi, S., & Powers, C. M. (2010). Strengthening and neuromuscular reeducation of the gluteus maximus in a triathlete with exercise-associated cramping of the hamstrings. *The Journal of Orthopaedic and Sports Physical Therapy*, *40*(2), 112–119.

CHAPTER IV

THE EFFECT OF HIP FLEXOR TIGHTNESS ON MUSCLE ACTIVITY DURING THE FRONT SQUAT

Introduction

Resistance training exercises have long been utilized to target muscles groups to address weakness. To optimize resistance training exercises, the maximal recruitment of motor units in a targeted muscle is warranted. Many recent studies have compared muscle activity during resistance training exercises such as the back squat, deadlift, hip thrust, and front squat (Contreras et al., 2015; Deniz & Ulas, 2019; Delgado et al., 2019; Korak et al., 2019; Mehls et al., 2019; Simenz et al., 2012; Yavuz et al., 2017) to help improve exercise prescription of commonly targeted muscles, particularly for the gluteus maximus.

When selecting a resistance exercise to train the gluteus maximus (GM), it is paramount to understand the level of muscle activity during resistance training lifts. Korak and his colleagues (2019) found that GM was highest in the front squat compared to the back-squat and dead-lift at 75% of a one-repetition maximum (1RM). The authors believed that the front squat displayed greater activation of the gluteus maximus compared to the deadlift due the front squat allowing greater hip flexion of the lift. Whereas greater gluteus maximus muscle activity during the front squat compared to the back squat was thought to be associated to the frontal bar placement, allowing for a deeper squat position. Maximal activation of the gluteus maximus is customarily emphasized during resistance training programs because it is considered the prime mover at the hip during various weight-bearing activities (McCurdy et al., 2018; Okkonen & Hakkinen, 2013). Correspondingly, activation of the gluteus maximus allows for proper neuromuscular control during human movements, thus preventing lower extremity movement impairments that may lead to injury (Clark et al. 2014).

As mentioned above, appropriate muscle activation patterns of GM is essential for proper human movement. However, poor flexibility has been noted to alter muscle recruitment patterns and distort normal human movement patterns. Specifically, restricted hip extension caused by tight hip flexors can inhibit neural drive to the gluteus maximus (Aali et al., 2017, Clark et al., 2018; Buckthorpe et al., 2019). Tight and overactive hip flexors can cause altered reciprocal inhibition, where the gluteus maximus is lengthened and underactive during hip extension. This may lead to muscular imbalances where there is a greater reliance on the synergist, hamstrings, to move the body through hip extension (Clark et al., 2018; Clark et al., 2014; Kisner, 2012) otherwise known as synergistic dominance. It has been proposed that synergistic dominance of the hamstrings leads to arthrokinetic dysfunction during sprinting and jumping movements may increase the risk of hamstring injury (Clark et al., 2014; Aslan et al., 2018; Sahrmann, 2002; Wagner et al., 2010).

To the authors knowledge, only one study has observed the possible effects of restricted hip extension on muscle activity in the GM (Mills et al., 2015). While the authors noted a decrease in gluteus maximus activity in individuals this with hip flexor tightness compared to those without, the only exercise observed was the bilateral air squat. Thus, there has yet to be a study that investigates the effect of tight hip flexors on muscle activation during a resistance training exercise. Therefore, the aim of this study was to compare sEMG in the rectus femoris (RF), gluteus maximus (GM), biceps femoris (BF), and semitendinosus (ST) muscles during front squat between resistance trained females with and without hip flexor tightness. It was hypothesized that individuals without hip flexor tightness will have higher peak muscle activation of the gluteus maximus compared to those with hip flexor tightness.

Methods

Participants

Sixteen apparently healthy trained females (age: 22.19 ± 2.28 years; height: 163.54 ± 6.82 cm; body mass: 69.02 ± 9.66 kg; 1RM: 70.44 ± 17.01 kg) were assigned either to a control (n = 9) or experimental (n = 7) group determined from the modified Thomas Test. All participants were free of any lower body musculoskeletal injury within the past three months and categorized as moderately resistance trained where they have been currently training for the past 3-6 months at a minimum of 2 times per week (Haff & Triplett, 2016). After the participants were informed of the benefits and possible risks of the protocol, all participants read and signed a written informed consent and PAR-Q+ pre-health screening prior to participation. Participants were recruited from the surrounding community via word of mouth The Institutional Review Board at Middle Tennessee State University approved this study prior to data collection.

The modified Thomas Test was used to assess hip flexor length. Previous studies have shown that this method of hip extension range of motion (ROM) assessment has good inter-rater reliability (Clapis et al., 2008; Peeler & Anderson, 2007; Mills et al. 2015). A digital inclinometer (Model #12-1057, Fabrication Enterprise Inc. – Baseline Evaluation Instruments, White Plains, New York) was used to measure hip extension ROM during the modified Thomas Test. Inclinometer values greater than 0° (+) indicate that the thigh was positioned above parallel and relatively flexed. Inclinometer values below 0° (-) indicate that the thigh was below parallel and relatively extended (Ferber, 2010). Inclusion criteria for the control group was defined as hip extension ROM greater than 15° below parallel. Inclusion criteria for the experimental (tight hip flexor) group was defined as hip extension greater than 0° above parallel (Mill et al., 2015). The tightest leg was the experimental leg observed during the study. The modified Thomas Test was performed by the by the leader investigator, a certified athletic trainer.

Procedures

Participants were required to attend two sessions session at the university muscle physiology laboratory. Upon attending the first session, participants completed the informed consent and PAR-Q+ pre-health screening questionnaire and were screened for inclusion criteria. If inclusion criteria were met into either group, participant's age, height, and body were measured and recorded. Height was measured to the nearest 0.1 cm using a stadiometer (SECA Corporation, Model 222, Germany) and body mass was assessed using a digital scale (Tanita Worldwide, Model BF 522, Arlington Heights, Illinois) to the nearest 0.1 kg. All testing procedures were performed by a certified athletic trainer.

Next, the participants were asked warm-up using a row on a row ergometer (Concept II) at a self-selected pace for 3-5 minutes. Participants then performed 15 repetitions of the front squat using the Smith Machine at a self-selected load where 15-repetitions could be easily completed. Following practice repetitions, the participants one-repetition max (1RM) was assessed following the National Strength and Conditioning Guidelines (NSCA) (Haff & Triplett, 2016). All testing procedures were performed by the primary investigator, a certified athletic trainer and certified strength and conditioning specialist.

Participants returned for the second session a minimum of 48 hours later to assess muscle activity during the front squat. Kinematic data (angular movement) was measured using wireless goniometers (Biometrics, Newport, UK) that were connected to Trigno Goniometer Adapters both of which were fixated to the skin in the same fashion described for the Trigno Flex sensors.

The primary purpose of the kinematic data was to identify ascending and descending phases of the front squat. For knee joint angle, the proximal arm was aligned along the femur to the greater trochanter and the distal arm was aligned to the lateral tibia in line with lateral malleolus. All muscle activity and kinematic data was integrated directly into the EMGworks software via wireless adapters provided by the manufacture to ensure proper timing during recording. An external trigger device (Delsys, Natick, MA) was used to initiate and cease data collection. The sEMG data that was collected during the 1RM was used for normalization of muscle activity during the front squat.

Participants performed the same warm-up they were asked to complete during session 1. Following the warm-up, the participants completed a 1RM, followed by 75% of 1RM front squat. Participants were given 5 minutes of rest between the 1RM and performing 3 repetitions at 75% 1RM. The participants performed the front squat using a two second eccentric phase and one second concentric phase. A level was placed on the participants thigh to ensure parallel squat depth on each repetition before ascending during all testing procedures.

Data Processing

All EMG data was normalized to peak muscle activity during 1RM data collected for each participant to represent muscle activation of each muscle as a percent of peak muscle activity during a 1RM. Surface EMG data were initially processed using a Nyquist resampling equation at 1000Hz. Data was initially filtered with a 2^{nd} order Butterworth band-pass filter at 20Hz and 450Hz. A root-mean-square algorithm with a 200 ms window was then applied to the filtered data. Goniometer data was to mark and differentiate directional phases during each movement. The described data processing was performed through EMGworks analysis software (Delsys, Model SC-S08-4.5.3, Natick, MA). All data was then imported into IBM© SPSS©

Statistics (IBM Corp. Released 2016. IBM SPSS Statistics for Windows, Version 24.0. Armonk, NY: IBM Corp) where the data was normalized to the peak 1RM values The gluteus maximus: biceps femoris co-activation ratio was analyzed as described by Mills et al. (2015), which is calculated during the descending phase by dividing the mean gluteus maximus activity by the mean biceps femoris activity (gluteus maximus: biceps femoris). A gluteus maximus: biceps femoris ratio of 1.0 indicates balanced muscular activation, whereas a ratio less than one 1.0 indicates greater activation of the biceps femoris relative to the gluteus maximus.

Statistical Analyses

The IBM© SPSS© Statistics (IBM Corp. Released 2016. IBM SPSS Statistics for Windows, Version 24.0. Armonk, NY: IBM Corp) was used for the statistical analysis. Average peak and mean muscle activity across 3 reps at 75% 1RM was calculated in SPSS. Descriptive statistics were provided for each participant and be expressed in means $\pm$ standard deviations. Independent samples t-tests were conducted to compare participants without hip flexor tightness (n = 9) and participants with hip flexor tightness (n = 7) RF, BF, ST and GM peak and mean muscle activity and gluteus maximus: biceps femoris co-activation ratio during 75% 1RM of the front squat. Peak and mean muscle activation were analyzed during the ascending and descending phases of the front squat. Effect sizes were calculated using Hedges' g. The alpha level was set at .05 for all statistical procedures.

Results

The result of the independent samples t-test indicated a statistically significant difference in peak RF and BF between those with and without hip flexor tightness during 75% 1RM of the front squat. Results of the independent t-test comparing peak muscle activity of the RF, BF, ST, GM those with and without hip flexor tightness can be found in Table 1. During the ascending phase, peak RF activity (*M* = .86, *SD* = .12) was significantly higher *(p* = .013) for participants with tight hip flexors compared to those without tight hip flexors (*M* = .58, *SD* = .23). Peak BF muscle activity (*M* = .74, *SD* = .20) in those with hip flexor tightness was also significantly higher (*p* = .001) during the ascending phase compared the those without hip flexor tightness (*M* = .46, *SD* = .27). Peak ST and GM activity did not show significant differences between groups during neither the ascending or descending phase of the front squat.

Results of the independent samples *t*-tests comparing mean muscle activity of the RF, BF, ST, GM in those with and without hip flexor tightness can be found in Table 2. Mean muscle activity of the RF (*M* = .55, *SD* = .15) was higher in those with hip flexor tightness compared to those without hip flexor tightness (*M* = .39, *SD* = 18), but was not statistically significant (*p* = .076). During the ascending phase of the front squat, participants with hip flexor tightness displayed significantly higher (*p* = .045) mean BF activity (*M* = .50, *SD* = .18) compared to participants without hip flexor tightness (*M* = .30, *SD* = .17). Mean ST and GM activity did not show significant differences during neither the ascending or descending phase of the front squat.

Results of the independent samples *t*-test comparing GM:BF co-activation during the descending and ascending phases of a back squat can be found in Figure 1. During the descending phase of front squat, GM:BF co-activation was significantly lower higher (*p* = .042) in those with hip flexor tightness (*M* = .63, *SD* = .34) compared to those without hip flexor tightness (*M* = 1.52, *SD* = .36). During the ascending phase of the front squat, GM:BF co-activation was also significantly lower (*p* = .035) in those with hip flexor tightness (*M* = 1.05, *SD* = .36) compared to those without hip flexor tightness (*M* = 2.86, *SD* = 2.12).

Table 1.

Normalized Peak Muscle Activity during 75% 1RM of the Front Squat

Variable	Non-Tight Hip flexors M	Non-Tight Hip flexors SD	Tight Hip Flexors M	Tight Hip Flexors SD	*t*	*p*	Mean Difference	95% CI	Hedges' *g*
DSC RF	.50	.15	.62	.15	.1.28	.22	.12	[-0.33, 0.08]	.61
DSC BF	.23	.17	.54	.12	4.01	.001*	.30	[-0.47, -0.14]	1.91
DSC ST	.55	.30	.58	.14	.32	.77	.03	[-0.30, 0.23]	.14
DSC GM	.43	.17	.35	.16	.830	.42	.07	[-0.11, 0.26]	.40
ASC RF	.59	.23	.86	.12	2.86	.01*	.28	[-0.48, 0.07]	1.36
ASC BF	.45	.28	.74	.21	2.27	.040*	.28	[-0.55, -0.02]	1.08
ASC ST	.56	.16	.63	.27	.60	.32	.06	[-0.29, 0.16]	.29
ASC GM	.81	.14	.69	.22	1.27	.23	.11	[-0.07, 0.31]	.60

*denotes a significant difference between individuals with and without hip flexor tightness; $p < .05$. DSC descending, ASC ascending, RF rectus femoris, BF biceps femoris, ST semitendinosus, GM gluteus maximus, Co-A co-activation.

Table 2.

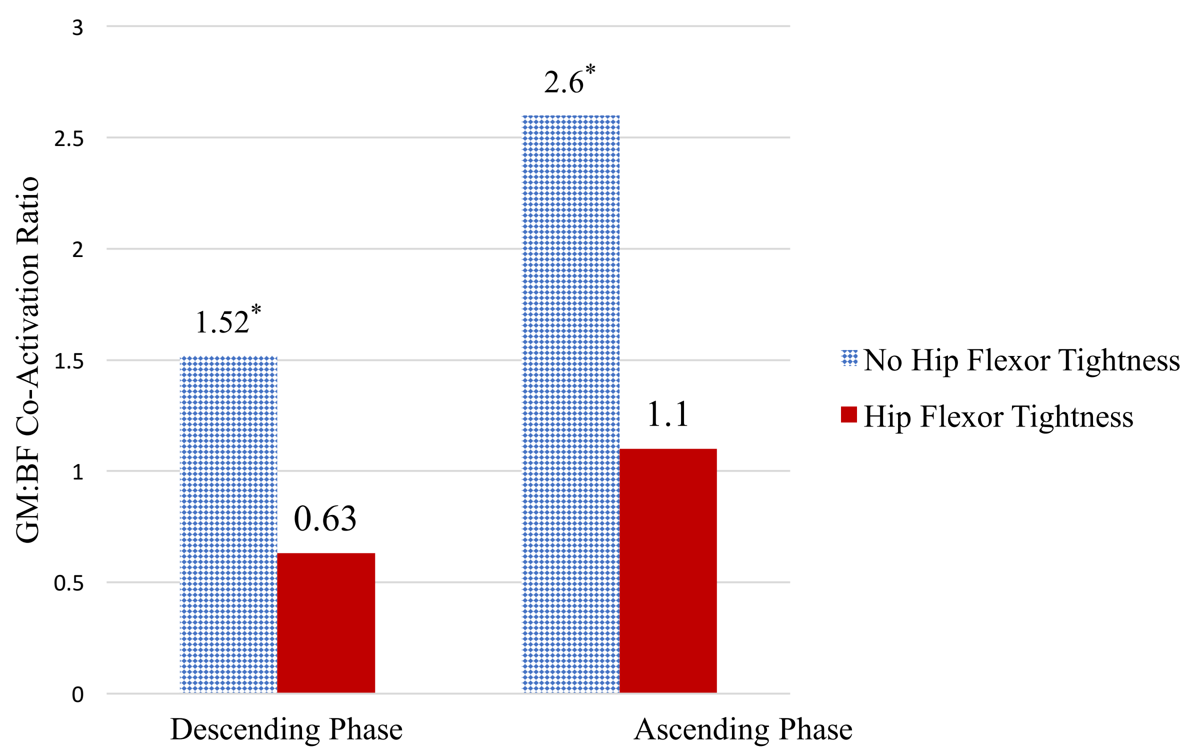
Normalized Mean Muscle Activity during 75% 1RM of the Front Squat

Variable	Non-Tight Hip flexors		Tight Hip Flexors		*t*	*p*	Mean Difference	95% CI	Hedges' *g*
	M	SD	M	SD					
DSC RF	.26	.10	.36	.22	1.10	.25	.10	[-0.28, 0.78]	.58
DSC BF	.23	.19	.31	.09	1.03	.32	.08	[-0.25, 0.09]	.49
DSC ST	.32	.19	.31	.07	.194	.85	.01	[-0.14, 0.17]	.09
DSC GM	.20	.08	.17	.06	.83	.44	.03	[-0.04, 0.11]	.38
ASC RF	.39	.15	.55	.15	1.92	.07	.15	[-0.32, 0.02]	.91
ASC BF	.30	.17	.50	.18	2.24	.04*	.20	[-0.39, -0.01]	1.07
ASC ST	.39	.18	.48	.14	1.01	.32	.09	[-0.27, 0.10]	.49
ASC GM	.56	.20	.48	.10	1.12	.33	.08	[-0.09, 0.26]	.49

*denotes a significant difference between individuals with and without hip flexor tightness; $p < .05$. DSC descending, ASC ascending, RF rectus femoris, BF biceps femoris, ST semitendinosus, GM gluteus maximus, Co-A co-activation.

Figure 1.

GM:BF Co-Activation Ratio during the Descending and Ascending Phases of 75% 1RM of the Front Squat.



Note. *denotes a significant difference between individuals with and without hip flexor tightness; $p < .05$ DSC descending, ASC ascending, RF rectus femoris, BF biceps femoris, ST semitendinosus, GM gluteus maximus, Co-A co-activation.

Discussion

The purpose of this study was to compare peak and mean RF, BF, ST, GM, and GM:BF co-activation in resistance trained females with and without hip flexor tightness during 75% 1RM of the front squat. During both the ascending and descending phase, peak BF activity was significantly higher ($p < .05$) in those with hip flexor tightness compared to those without. During the ascending phase, peak RF ($p < .05$) activity was significantly higher in those with hip flexor tightness compared to those without. Mean BF activity was significantly higher ($p < .05$) during the ascending phase of the front squat in those with hip flexor tightness compared to those without. The GM:BF co-activation ratio was significantly lower ($p < .05$) in those with hip flexor tightness compared to those without during both the ascending and descending phase of the front squat, indicating that those with hip flexor tightness generate less muscle activity in the GM relative to the BF during the front squat. This partially supports the hypothesis that the GM would be more activated in those without hip flexor tightness.

The results in this study align with Mills et al. (2015) who found significantly greater GM:BF co-activation ratio in female soccer players without hip flexor tightness during the descending phase of an overhead air squat. Mills and colleagues (2015) used the modified Thomas Test to measure hip flexor tightness to assign the athletes into ‘restricted’ or normal hip flexion. The authors compared muscle activity using surface electromyography (sEMG) of the GM and BF during a double leg air squat in female soccer players with and without hip flexor tightness. Gluteus maximus: biceps femoris co-activation ratio was also observed Mills and his colleagues (2015) found that that peak muscle activation of the gluteus maximus was significantly less than the restricted group compared to the normal group. These findings align with the current study and suggest that hip flexor tightness may affect muscle activity during hip extension.

Significant overactivity in the RF and BF are indicators of muscle imbalance in the tight hip flexor group (Clark et al., 2018; Buckthorpe et al., 2019). Mills and his colleagues (2015) found that those with tight hip flexors demonstrated significantly less peak GM muscle activation compared to those without tight hip flexors during the bilateral air squat. However, this current study did not show significant differences in peak or mean GM during the front squat. Additionally, the current study found that females with tight hip flexors displayed significantly greater BF activity, whereas Mills et al. (2015) did not find significant differences in the BF. The results of Mills et al. (2015) combined with the findings of the present study may suggest that the mechanism of the muscular imbalance at the hip and length of exposure to a repetitive movement may affect muscle activation in those with tight hip flexors. Possible mechanisms believed to cause muscular imbalances include improper habitual patterns, chronic repetition of a movement, and altered movement due to previous injury (Clark et al., 2018; Clark et al., 2014; Janda et al., 1996). Mills et al. (2015) used female soccer players who were thought to develop hip flexor tightness through the repetitive hip flexion that is required in the sport. A plausible explanation for the decreased GM activity in the tight hip flexor group of the Mills et al. (2015) study is that chronic hip flexion activity with shortened hip flexors contributed to the GM becoming underactive. While the current study used similar criteria for determining hip flexor tightness, it is unlikely that the population of the current study was exposed to the same amount of repetitive hip flexion as the population used by Mills et al. (2015). Therefore, the lack of congruity in the GM findings between the current study and Mills et al. (2015) may be explained by activities performed while having tight hip flexors.

A greater GM:H co-activation is believed to prevent muscular imbalances that lead to synergistic dominance and thereby reduce the risk of hamstring injury (Clark et al., 2014; Mills et al., 2015; Wagner et al., 2010). However, when tight hip flexors become overactive, hip extensor prime mover (GM) muscle recruitment and autogenic inhibition may be altered. When the GM is underactive, there is a greater reliance on the synergist (BF and ST) to move through hip extension (Clark et al., 2018; Clark et al., 2014; Kisner, 2012). The results of the present study showed that individuals with hip flexor tightness displayed significantly lower GM:BF co-activation ratio compared to those without hip flexor tightness. Individuals with tight hip flexors had a GM:BF co-activation lower than 1.0 during both the ascending and descending phase of the front squat, whereas those without tight hip flexor tightness generated a GM:BF co-activation ratio greater than 1.0 during both phases. In fact, individuals without hip flexor tightness displayed almost twice the amount of GM activity compared those with tight hip flexors during the ascending phase of the front squat.

Mills et al. (2015) also found the GM:BF co-activation ratio was significantly higher than 1.0 in those without hip flexor tightness, indicating a greater activation of the GM relative to the BF. Interestingly however, there was no difference in muscle activation or amplitude of the BF between groups. In the current study, resistance trained females without hip flexor tightness displayed great GM:BF co-activation ratio during both the ascending and descending phase during a 75% 1RM front squat, whereas Mills et al. (2015) only found a greater GM:BF during the descending phase of an air squat.

Thus, a greater external load may cause a greater change in muscle activity during the ascending phase of hip extension in those who experience hip flexor tightness. This indicates that activity may be more heavily affected under a higher load and individuals who squat at 75% 1RM should be aware of hip mobility to obtain greater GM activation relative to the BF.

A tight overactive hip flexor may decrease the neural drive to its antagonist (gluteus maximus) during hip extension (Clark et al., 2018; Buckthorpe et al., 2019), thus hindering optimal recruitment the gluteus maximus. It is suggested that increased reliance on the secondary hip extensors may result in overactive synergist muscles (hamstrings) to compensate for a weak or inhibited prime mover (GM)—a condition known a synergistic dominance (Clark et al., 2014; Aslan et al., 2018; Sahrmann, 2002; Wagner et al., 2010). It has been postulated that synergistic dominance of the hamstrings, leads to arthrokinetic dysfunction during sprinting and jumping movements may increase the risk of hamstring injury (Clark et al., 2014; Aslan et al., 2018; Sahrmann, 2002; Wagner et al., 2010). While the current study did not demonstrate significantly less GM activity between groups, the scores of the tight hip flexor group were consistently lower than the group without hip flexor tightness. The present study did find, however, that those with tight hip flexors display overactive peak BF and RF activity during both the ascending of the back squat. Individuals with tight hip flexors also produced significantly higher mean BF activity during the ascending phase of the front squat.

To our knowledge, this is the first study to investigate peak and mean muscle activity and co-activation in those with and without hip flexor tightness during the front squat. Muscle imbalances caused by an overactive agonist paired with an underactive functional antagonist, can potentially result in the change in neuromuscular control, structural alignment, and movement patterns (Clark et al., 2018). The results from the present study suggest that peak and mean BF and peak RF to be overactive in resistance trained females with hip flexor tightness during the front squat. Fitness professionals should consider providing a hip flexor stretching intervention to prevent over activation of the BF when selecting the front squat as a resistance training exercise. Providing a hip flexor stretching program to individuals who have tight hip flexors may decrease synergistic dominance of the hamstrings.

The main limitation of this study was its exploratory nature (low sample size) and unequal groups (control group n = 9, experimental group = 7). Thus, making the likelihood of a Type II error was high. Another limitation to this study was the calculation of the GM:H ratio only considered the BF (Mills et al., 2015), which may not fully represent the function of the hamstring muscle group during hip extension. Further investigations are required on the effect of hip flexor tightness on muscle activity. Futures research may want to consider examining muscle activity under different external loads and athletic movements. Future studies should also investigate the relationship between hip flexor tightness and hamstring injury, as well as the effect of hip flexor tightness stretching programs on muscle activity.

Chapter IV References

Aali, S., Letafatkar, A., Ebrahimi, I., Barati, A. H., & Hadadnejad, M. (2017). Does iliopsoas tightness affects synergistic muscle activity in hip extension during stance phase of gait?. *International Journal of Medical Research & Health Sciences*, *6*(6), 118-122.

Aslan, H., Buddhadev, H. H., Suprak, D. N., & San Juan, J. G. (2018). Acute effects of two hip flexor stretching techniques on knee joint position sense and balance. *International Journal of Sports Physical Therapy*, *13*(5), 846–859.

Buckthorpe, M., Stride, M., & Villa, F. D. (2019). Assessing and treating gluteus maximus weakness - a clinical commentary. *International Journal of Sports Physical Therapy*, *14*(4), 655–669.

Clapis, P. A., Davis, S. M., & Davis, R. O. (2008). Reliability of inclinometer and goniometric measurements of hip extension flexibility using the modified Thomas test. *Physiotherapy Theory and Practice*, *24*(2), 135-141.

Clark, M.A., Lucett, S.C., McGill, E., Montel, I., & Sutton, B. (2018). *National Academy of Sports Medicine Essentials of Personal Fitness Training.* Jones & Bartlett Learning.

Clark, M., Sutton, B. G., & Lucett, S. (2014). *NASM Essentials of Sports Performance Training.* Jones & Bartlett Learning.

Contreras, B. M., Cronin, J. B., Schoenfeld, B. J., Nates, R. J., & Sonmez, G. T. (2013). Are all hip extension exercises created equal?. *Strength & Conditioning Journal*, *35*(2), 17-22

Delgado, J., Drinkwater, E. J., Banyard, H. G., Haff, G. G., & Nosaka, K. (2019). Comparison between back squat, Romanian deadlift, and barbell hip thrust for leg and hip muscle activities during hip extension. *The Journal of Strength & Conditioning Research*, *33*(10), 2595-2601.

Deniz, E., & Ulas, Y. H. (2019). Evaluation of Muscle Activities During Different Squat Variations Using Electromyography Signals. *International Conference on Theory and Application of Soft Computing, Computing with Words and Perceptions* (pp. 859-865). Springer.

Ferber, R., Kendall, K. D., & McElroy, L. (2010). Normative and critical criteria for iliotibial band and iliopsoas muscle flexibility. *Journal of Athletic Training*, *45*(4), 344-348.

Haff, G., & Triplett, N. T. (2016). *Essentials of Strength Training and Conditioning.* Fourth edition. Human Kinetics.

Janda, V., Frank, C., & Liebenson, C. (1996). Evaluation of muscular imbalance. *Rehabilitation of the Spine: A Practitioner's Manual*, *6*, 97-112. Lippincott Williams & Wilkins.

Kisner, C., Colby, L. A., & Borstad, J. (2017). *Therapeutic Exercise: Foundations and Techniques*. F.A. Davis Company

Korak, J. A., Paquette, M. R., Fuller, D. K., Caputo, J. L., & Coons, J. M. (2018). Muscle activation patterns of lower-body musculature among 3 traditional lower-body exercises in trained women. *The Journal of Strength & Conditioning Research*, *32*(10), 2770-2775.

McCurdy, K., Walker, J., & Yuen, D. (2018). Gluteus maximus and hamstring activation during selected weight-bearing resistance exercises. *The Journal of Strength & Conditioning Research*, *32*(3), 594-601.

Mehls, K., Grubbs, B., Stevens, S., Martinez, S., Jin, Y., & Coons, J. (2021) Correcting movement syndromes: the role of training load and its effects on muscle. *Sports Sciences for Health.* https://doi.org/10.1007/s11332-021-00764-5

Mills, M., Frank, B., Goto, S., Blackburn, T., Cates, S., Clark, M., Aguilar, A., Fava, N., & Padua, D. (2015). Effect of restricted hip flexor muscle length on hip extensor muscle activity and lower extremity biomechanics in college-aged female soccer players. *International Journal of Sports Physical Therapy*, *10*(7), 946–954.

Okkonen, O., & Häkkinen, K. (2013). Biomechanical comparison between sprint start, sled pulling, and selected squat-type exercises. *The Journal of Strength & Conditioning Research*, *27*(10), 2662-2673.

Peeler, J., & Anderson, J. E. (2007). Reliability of the Thomas test for assessing range of motion about the hip. *Physical Therapy in Sport*, *8*(1), 14-21.

Sahrmann, S. (2002). *Diagnosis and Treatment of Movement Impairment Syndromes.* Mosby.

SENIAM The SENIAM Project Retrieved January 2021, from http://wwwseniamorg/

Simenz, C. J., Garceau, L. R., Lutsch, B. N., Suchomel, T. J., & Ebben, W. P. (2012). Electromyographical analysis of lower extremity muscle activation during variations of the loaded step-up exercise. *Journal of Strength and Conditioning Research*, *26*(12), 3398–3405. https://doi.org/10.1519/JSC.0b013e3182472fad

Wagner, T., Behnia, N., Ancheta, W. K., Shen, R., Farrokhi, S., & Powers, C. M. (2010). Strengthening and neuromuscular reeducation of the gluteus maximus in a triathlete with exercise-associated cramping of the hamstrings. *The Journal of Orthopaedic and Sports Physical Therapy*, *40*(2), 112–119.

Yavuz, H. U., & Erdag, D. (2017). Kinematic and Electromyographic Activity Changes during Back Squat with Submaximal and Maximal Loading. *Applied Bionics and Biomechanics*. https://doi.org/10.1155/2017/9084725

CHAPTER V: OVERALL CONCLUSIONS

This dissertation concentrated on addressing muscular imbalances such as synergistic dominance by investigating the effect of hip flexor tightness on hip and leg muscle activity during functional movements and the front squat. Study one explored surface EMG of the RF, BF, ST, and GM, and GM:BF co-activation in females with and without hip flexor tightness during the overhead squat, in-line lunge, and forward step-up. Study two examined surface EMG of the RF, BF, ST, and GM, and GM:BF co-activation in resistance trained females with and without hip flexor tightness during 75% 1RM front squat.

Study one required females to perform 3 repetitions of the overhead squat, in-line lunge, and forward-step up. Surface EMG of the RF, BF, ST, and GM were recorded using a wireless EMG unit. Contrary to our hypothesis, no statistical differences were found in mean muscle activation of the RF, BF, ST, and GM and GM:BF co-activation ratio during the overhead squat, in-line lunge, or forward step-up between those with and without hip flexor tightness. However, the results of this study showed that individuals with hip flexor tightness generated greater mean BF compared to those without, although it was not statistically different. These results contradict Mills et al. (2015) who found higher GM:BF co-activation and peak GM activity during the bilateral air squat in those without hip flexor tightness compared to those without. However, Mills et al. (2015) used collegiate female soccer players as their sample. Between group statistical significance may not have been found between groups in the current study due to the participant sample in the current study being that of general population where activity level was not considered. Physically active individuals have greater motor unit activation and neuromuscular control compared to their untrained counterparts, thus not controlling for activity level may have influence EMG activity between groups more than hip flexor tightness. Further research is required to understand the effect of hip flexor tightness on EMG activity during functional movements.

Study two required resistance trained females to perform 3 repetitions during 75% 1RM front squat. Surface EMG of the RF, BF, ST, and GM were recorded using a wireless EMG unit. To our knowledge, this is the first study to investigate peak and mean muscle activity and co-activation in those with and without hip flexor tightness during the front squat. The results of this study showed that peak and mean BF and peak RF to be significantly higher in resistance trained females with hip flexor tightness during the front squat. The GM:BF co-activation ratio was also found to be significantly lower in those with hip flexor tightness compared to those without during both the ascending and descending phase of the front squat, indicating that those with hip flexor tightness generate less muscle activity in the GM relative to the BF during the front squat. Muscle imbalances caused by overactive hip flexors paired with underactive GM can potentially result synergistic dominance of the hamstrings, ultimately changing the neuromuscular control, structural alignment, and movement patterns during a front squat. Synergistic dominance of the hamstrings may lead to arthrokinetic dysfunction during sprinting and jumping movements may increase the risk of hamstring injury. Fitness professionals should consider providing a hip flexor stretching intervention to prevent over activation of the BF when selecting the front squat as a resistance training exercise. Providing a hip flexor stretching program to individuals who have tight hip flexors may decrease synergistic dominance of the hamstrings, thus possibly decreasing risk of injury during dynamic movements.

Poor flexibility has been noted to alter muscle recruitment patterns and cause muscle imbalances that distort normal human movement patterns. Restricted hip extension caused by tight hip flexors can inhibit neural drive to the gluteus maximus. Tight and over active hip flexors can cause altered reciprocal inhibition, where the gluteus maximus is lengthened and underactive during hip extension. This may lead to synergistic dominance where there is a greater reliance on the synergist, hamstrings, to move the body through hip extension. The results of the current studies and Mills et al. (2015) suggest that an active population may experience changes in muscle activity during functional and resistance training movements due to differences in neuromuscular control compared to the general population. Therefore, coaches and fitness professionals may consider a hip flexor tightness stretching intervention to promote greater GM activation compared to the BF to possibly prevent lower extremity injury.

REFERENCES

Aali, S., Letafatkar, A., Ebrahimi, I., Barati, A. H., & Hadadnejad, M. (2017). Does iliopsoas tightness affects synergistic muscle activity in hip extension during stance phase of gait?. *International Journal of Medical Research & Health Sciences*, *6*(6), 118-122.

Alessandro, C., Delis, I., Nori, F., Panzeri, S., & Berret, B. (2013). Muscle synergies in neuroscience and robotics: from input-space to task-space perspectives. *Frontiers in Computational Neuroscience*, *7*, 43.

Alessandro, C., & Nori, F. (2012). Identification of synergies by optimization of trajectory tracking tasks. *International Conference on Biomedical Robotics and Biomechatronics (BioRob)* (pp. 924-930). IEEE.

Arboleda, B. M. W., & Frederick, A. L. (2008). Considerations for maintenance of postural alignment for voice production. *Journal of Voice*, *22*(1), 90-99.

Aslan, H., Buddhadev, H. H., Suprak, D. N., & San Juan, J. G. (2018). Acute effects of two hip flexor stretching techniques on knee joint position sense and balance. *International Journal of Sports Physical Therapy*, *13*(5), 846–859.

Ayotte, N. W., Stetts, D. M., Keenan, G., & Greenway, E. H. (2007). Electromyographical analysis of selected lower extremity muscles during 5 unilateral weight-bearing exercises. *Journal of Orthopaedic & Sports Physical Therapy*, *37*(2), 48-55.

Berger, D. J., & D'Avella, A. (2014). Effective force control by muscle synergies. *Frontiers in Computational Neuroscience*, *8*, 46. https://doi.org/10.3389/fncom.2014.00046

Blazevich, A. J., Kay, A. D., Waugh, C., Fath, F., Miller, S., & Cannavan, D. (2012). Plantarflexor stretch training increases reciprocal inhibition measured during voluntary dorsiflexion. *Journal of Neurophysiology*, *107*(1), 250–256.

Boudreau, S. N., Dwyer, M. K., Mattacola, C. G., Lattermann, C., Uhl, T. L., & McKeon, J. M. (2009). Hip-muscle activation during the lunge, single-leg squat, and step-up-and-over exercises. *Journal of Sport Rehabilitation*, *18*(1), 91-103.

Bouillon, Lucinda E et al. Electromyographic assessment of muscle activity between genders during unilateral weight-bearing tasks using adjusted distances. *International Journal of Sports Physical Therapy* vol. 7,6 (2012): 595-605.

Bradley, P. S., & Portas, M. D. (2007). The relationship between preseason range of motion and muscle strain injury in elite soccer players. *Journal of Strength and Conditioning Research*, *21*(4), 1155–1159. https://doi.org/10.1519/R-20416.1

Buckthorpe, M., Stride, M., & Villa, F. D. (2019). Assessing and treating gluteus maximus weakness - a clinical commentary. *International Journal of Sports Physical Therapy*, *14*(4), 655–669.

Bushell, J. E., Dawson, S. M., & Webster, M. M. (2015). Clinical relevance of foam rolling on hip extension angle in a functional lunge position. *The Journal of Strength & Conditioning Research*, *29*(9), 2397-2403.

Caterisano, A., Moss, R. F., Pellinger, T. K., Woodruff, K., Lewis, V. C., Booth, W., & Khadra, T. (2002). The effect of back squat depth on the EMG activity of 4 superficial hip and thigh muscles. *Journal of Strength and Conditioning Research*, *16*(3), 428–432.

Chiaia, T. A., Maschi, R. A., Stuhr, R. M., Rogers, J. R., Sheridan, M. A., Callahan, L. R., & Hannafin, J. A. (2009). A musculoskeletal profile of elite female soccer players. *HSS Journal : The Musculoskeletal Journal of Hospital for Special Surgery*, *5*(2), 186–195.

Clark, M.A., Lucett, S.C., McGill, E., Montel, I., & Sutton, B. (2018). *National Academy of Sports Medicine Essentials of Personal Fitness Training.* Jones & Bartlett Learning.

Clark, M., Sutton, B. G., & Lucett, S. (2014). *NASM Essentials of Sports Performance Training.* Jones & Bartlett Learning.

Contreras, B. M., Cronin, J. B., Schoenfeld, B. J., Nates, R. J., & Sonmez, G. T. (2013). Are all hip extension exercises created equal?. *Strength & Conditioning Journal*, *35*(2), 17-22

Contreras, B., Vigotsky, A. D., Schoenfeld, B. J., Beardsley, C., & Cronin, J. (2016). A Comparison of Gluteus Maximus, Biceps Femoris, and Vastus Lateralis Electromyography Amplitude in the Parallel, Full, and Front Squat Variations in Resistance-Trained Females. *Journal of Applied Biomechanics*, *32*(1), 16–22. https://doi.org/10.1123/jab.2015-0113

Cook, G., Burton, L., & Hoogenboom, B. (2006). Pre-participation screening: the use of fundamental movements as an assessment of function-part 1. *North American journal of sports physical therapy: NAJSPT*, *1*(2), 62-72.

Cook, G., Burton, L., Hoogenboom, B. J., & Voight, M. (2014). Functional movement screening: the use of fundamental movements as an assessment of function-part 2. *International Journal of Sports Physical Therapy*, *9*(4), 549–563.

Cowan, S. M., Crossley, K. M., & Bennell, K. L. (2009). Altered hip and trunk muscle function in individuals with patellofemoral pain. *British Journal of Sports Medicine*, *43*(8), 584-588.

D'Avella, A., Portone, A., Fernandez, L., & Lacquaniti, F. (2006). Control of fast-reaching movements by muscle synergy combinations. *Journal of Neuroscience*, *26*(30), 7791-7810.

Delgado, J., Drinkwater, E. J., Banyard, H. G., Haff, G. G., & Nosaka, K. (2019). Comparison between back squat, Romanian deadlift, and barbell hip thrust for leg and hip muscle activities during hip extension. *The Journal of Strength & Conditioning Research*, *33*(10), 2595-2601.

Delis, I., Hilt, P. M., Pozzo, T., Panzeri, S., & Berret, B. (2018). Deciphering the functional role of spatial and temporal muscle synergies in whole-body movements. *Scientific Reports*, *8*(1), 1-17.

Delp, S. L., Hess, W. E., Hungerford, D. S., & Jones, L. C. (1999). Variation of rotation moment arms with hip flexion. *Journal of Biomechanics*, *32*(5), 493-501.

De Luca, C. J. (1997). The use of surface electromyography in biomechanics. *Journal of Applied Biomechanics*, *13*(2), 135-163.

De Luca, C. J. (2008). A Practicum on the use of surface EMG signals in movement sciences. *Delsys Inc*.

De Luca, C. J., Kuznetsov, M., Gilmore, L. D., & Roy, S. H. (2012). Inter-electrode spacing of surface EMG sensors: reduction of crosstalk contamination during voluntary contractions. *Journal of biomechanics*, *45*(3), 555–561.

Delsys (2020). Delsys Trigno Wireless Biofeedback System User's Guide. Delsys Incorporated. Retrieved from https://delsys.com/downloads/USERSGUIDE/trigno/wireless-biofeedback-system.pdf

Distefano, L. J., Blackburn, J. T., Marshall, S. W., & Padua, D. A. (2009). Gluteal muscle activation during common therapeutic exercises. *Journal of Orthopaedic & Sports Physical Therapy*, *39*(7), 532-540.

Deniz, E., & Ulas, Y. H. (2019). Evaluation of Muscle Activities During Different Squat Variations Using Electromyography Signals. In *International Conference on Theory and Application of Soft Computing, Computing with Words and Perceptions* (pp. 859-865). Springer.

Dostal, W. F., Soderberg, G. L., & Andrews, J. G. (1986). Actions of hip muscles. *Physical Therapy*, *66*(3), 351–361.

Duehring, M. D., Feldmann, C. R., & Ebben, W. P. (2009). Strength and conditioning practices of United States high school strength and conditioning coaches. *The Journal of Strength & Conditioning Research*, *23*(8), 2188-2203.

Ebben, W. P. (2009). Hamstring activation during lower body resistance training exercises. *International Journal of Sports Physiology and Performance*, *4*(1), 84-96.

Ebben, W. P., & Blackard, D. O. (2001). Strength and conditioning practices of National Football League strength and conditioning coaches. *Journal of Strength and Conditioning Research*, *15*(1), 48-58.

Ebben, W. P., Carroll, R. M., & Simenz, C. J. (2004). Strength and conditioning practices of National Hockey League strength and conditioning coaches. *The Journal of Strength & Conditioning Research*, *18*(4), 889-897.

Edgerton, V. R., Wolf, S. L., Levendowski, D. J., & Roy, R. R. (1996). Theoretical basis for patterning EMG amplitudes to assess muscle dysfunction. *Medicine and Science in Sports and Exercise*, *28*(6), 744–751.

Eliassen, W., Saeterbakken, A. H., & Tillaar, R. (2018). Comparison of bilateral and unilateral squat exercises on barbell kinematics and muscle activation. *International Journal of Sports Physical Therapy*, *13*(5), 871–881.

Ekstrom, R. A., Donatelli, R. A., & Carp, K. C. (2007). Electromyographic analysis of core trunk, hip, and thigh muscles during 9 rehabilitation exercises. *The Journal of Orthopaedic and Sports Physical Therapy*, *37*(12), 754–762. https://doi.org/10.2519/jospt.2007.2471

Farrokhi, S., Pollard, C. D., Souza, R. B., Chen, Y. J., Reischl, S., & Powers, C. M. (2008). Trunk position influences the kinematics, kinetics, and muscle activity of the lead lower extremity during the forward lunge exercise. *The Journal of Orthopaedic and Sports Physical Therapy*, *38*(7), 403–409.

Flash, T., & Hochner, B. (2005). Motor primitives in vertebrates and invertebrates. *Current Opinion in Neurobiology*, *15*(6), 660-666.

Floyd, R. T., & Thompson, C. W. (1998). *Manual of Structural Kinesiology*. WCB.

Gabbe, B. J., Bennell, K. L., & Finch, C. F. (2006). Why are older Australian football players at greater risk of hamstring injury?. *Journal of Science and Medicine in Sport*, *9*(4), 327-333

Gorkovenko, A. V., Sawczyn, S., Bulgakova, N. V., Jasczur-Nowicki, J., Mishchenko, V. S., & Kostyukov, A. I. (2012). Muscle agonist–antagonist interactions in an experimental joint model. *Experimental Brain Research*, *222*(4), 399-414.

Gullett, J. C., Tillman, M. D., Gutierrez, G. M., & Chow, J. W. (2009). A biomechanical comparison of back and front squats in healthy trained individuals. *The Journal of Strength & Conditioning Research*, *23*(1), 284-292.

Haff, G., & Triplett, N. T. (2016). *Essentials of Strength Training and Conditioning.* Fourth edition. Human Kinetics.

Halaki, M., & Ginn, K. (2012). Normalization of EMG signals: to normalize or not to normalize and what to normalize to. *Computational Intelligence in Electromyography Analysis- A Perspective on Current Applications and Future Challenges*, 175-194.

Hamill, J., & Knutzen, K. M. (2006). *Biomechanical Basis of Human Movement*. Lippincott Williams & Wilkins.

Hamlyn, N., Behm, D. G., & Young, W. B. (2007). Trunk muscle activation during dynamic weight-training exercises and isometric instability activities. *The Journal of Strength & Conditioning Research*, *21*(4), 1108-1112.

Henderson, G., Barnes, C. A., & Portas, M. D. (2010). Factors associated with increased propensity for hamstring injury in English Premier League soccer players. *Journal of Science and Medicine in Sport*, *13*(4), 397-402.

Hirabayashi, R., Edama, M., Kojima, S., Miyaguchi, S., & Onishi, H. (2020). Enhancement of spinal reciprocal inhibition depends on the movement speed and range of repetitive passive movement. *European Journal of Neuroscience*.

Hirabayashi, R., Edama, M., Kojima, S., Ito, W., Nakamura, E., Kikumoto, T., & Onishi, H. (2019). Spinal reciprocal inhibition in the co-contraction of the lower leg depends on muscle activity ratio. *Experimental Brain Research*, *237*(6), 1469-1478.

Hug, F., Turpin, N. A., Guével, A., & Dorel, S. (2010). Is interindividual variability of EMG patterns in trained cyclists related to different muscle synergies?. *Journal of Applied Physiology*, *108*(6), 1727-1736.

Iles, J. F. (1986). Reciprocal inhibition during agonist and antagonist contraction. *Experimental Brain Research, 62*(1), 212–214.

Jacobs, R., & Macpherson, J. M. (1996). Two functional muscle groupings during postural equilibrium tasks in standing cats. *Journal of Neurophysiology*, *76*(4), 2402–2411. https://doi.org/10.1152/jn.1996.76.4.2402

Janda, V., Frank, C., & Liebenson, C. (1996). Evaluation of muscular imbalance. *Rehabilitation of the Spine: A Practitioner's Manual*, *6*, 97-112. Lippincott Williams & Wilkins.

Jones, P. A., & Bampouras, T. M. (2010). A comparison of isokinetic and functional methods of assessing bilateral strength imbalance. *The Journal of Strength & Conditioning Research*, *24*(6), 1553-1558.

Kankaanpää, M., Taimela, S., Laaksonen, D., Hänninen, O., & Airaksinen, O. (1998). Back and hip extensor fatigability in chronic low back pain patients and controls. *Archives of Physical Medicine and Rehabilitation*, *79*(4), 412–417.

Kendall, F.P., McCreary, E.K., Provance, G.P., & Rodgers, M.M., Romani, W.A. (2005). *Muscles: Testing and Function, with Posture and Pain.* Lippincott Williams & Wilkins.

Kim, D. H., & Lee, J. J. (2018). Effects of instrument-assisted soft tissue mobilization technique on strength, knee joint passive stiffness, and pain threshold in hamstring shortness. *Journal of Back and Musculoskeletal Rehabilitation*, *31*(6), 1169-1176.

Kisner, C., Colby, L. A., & Borstad, J. (2017). *Therapeutic Exercise: Foundations and Techniques*. F.A. Davis Company

Korak, J. A., Bruininks, B. D., & Paquette, M. R. (2020). The influence of normalization technique on between-muscle activation during a back-squat. *International Journal of Exercise Science*, *13*(1), 1098.

Korak, J. A., Paquette, M. R., Fuller, D. K., Caputo, J. L., & Coons, J. M. (2018). Muscle activation patterns of lower-body musculature among 3 traditional lower-body exercises in trained women. *The Journal of Strength & Conditioning Research*, *32*(10), 2770-2775.

Krivickas, L. S., & Feinberg, J. H. (1996). Lower extremity injuries in college athletes: relation between ligamentous laxity and lower extremity muscle tightness. *Archives of Physical Medicine and Rehabilitation*, *77*(11), 1139–1143.

Lavoie, B. A., Devanne, H., & Capaday, C. (1997). Differential control of reciprocal inhibition during walking versus postural and voluntary motor tasks in humans. *Journal of Neurophysiology*, *78*(1), 429-438.

Lunnen, J. D., Yack, J., & LeVeau, B. F. (1981). Relationship between muscle length, muscle activity, and torque of the hamstring muscles. *Physical Therapy*, *61*(2), 190-195.

Neumann, D. A. (2010). *Kinesiology of the Musculoskeletal System: Foundations for Rehabilitation*. St. Louis, Mo: Mosby/Elsevier.

Neumann, D. A. (2010). Kinesiology of the hip: a focus on muscular actions. *Journal of Orthopaedic & Sports Physical Therapy*, *40*(2), 82-94.

Norkin, C. C., & Levangie, P. K. (2005). Joint Structure and Function, Comprehensive Analysis. 4th ed. F.A. Davis Company

Norris, C. M. (1995). Spinal stabilization: 4. Muscle imbalance and the low back. *Physiotherapy*, *81*(3), 127-138.

Macadam, P., & Feser, E. H. (2019). Examination of gluteus maximus electromyographic excitation associated with dynamic hip extension during body weight exercise: a systematic review. *International Journal of Sports Physical Therapy*, *14*(1), 14.

MacAskill, M. J., Durant, T. J., & Wallace, D. A. (2014). Gluteal muscle activity during weight bearing and non- weight bearing exercise. *International Journal of Sports Physical Therapy*, *9*(7), 907.

Marques, V. B., Medeiros, T. M., de Souza Stigger, F., Nakamura, F. Y., & Baroni, B. M. (2017). The functional movement screen (FMS™) in elite young soccer players between 14 and 20 years: composite score, individual-test scores and asymmetries. *International Journal of Sports Physical Therapy*, *12*(6), 977–985.

McGill, S. M., & Marshall, L. W. (2012). Kettlebell swing, snatch, and bottoms-up carry: back and hip muscle activation, motion, and low back loads. *The Journal of Strength & Conditioning Research*, *26*(1), 16-27.

Mehls K., Grubbs, B., Stevens S., Martinez, S. Jin, Y., Coons, J. (2019). Dissertation: Correcting movement syndromes: the role of training load and its effects on muscle activity.

Mercer, V. S., Gross, M. T., Sharma, S., & Weeks, E. (2009). Comparison of gluteus medius muscle electromyographic activity during forward and lateral step-up exercises in older adults. *Physical Therapy*, *89*(11), 1205-1214.

Michaud, F., Shourijeh, M. S., Fregly, B. J., & Cuadrado, J. (2020). Do muscle synergies improve optimization prediction of muscle activations during gait?. *Frontiers in Computational Neuroscience*, *14*, 54.

Mills, M., Frank, B., Goto, S., Blackburn, T., Cates, S., Clark, M., Aguilar, A., Fava, N., & Padua, D. (2015). Effect of restricted hip flexor muscle length on hip extensor muscle actvity and lower extremity biomechanics in college-aged female soccer players. *International Journal of Sports Physical Therapy*, *10*(7), 946–954.

Mohr, A. R., Long, B. C., & Goad, C. L. (2014). Effect of foam rolling and static stretching on passive hip-flexion range of motion. *Journal of Sport Rehabilitation*, *23*(4), 296-299.

Muyor, J. M., Martín-Fuentes, I., Rodríguez-Ridao, D., & Antequera-Vique, J. A. (2020). Electromyographic activity in the gluteus medius, gluteus maximus, biceps femoris, vastus lateralis, vastus medialis and rectus femoris during the monopodal squat, forward lunge and lateral step-up exercises. *PloS One*, *15*(4).

Myer, G. D., Kushner, A. M., Brent, J. L., Schoenfeld, B. J., Hugentobler, J., Lloyd, R. S., Vermeil, A., Chu, D. A., Harbin, J., & McGill, S. M. (2014). The back squat: A proposed assessment of functional deficits and technical factors that limit performance. *Strength and Conditioning Journal*, *36*(6), 4–27.

Pan, B., Sun, Y., Sun, L., Huang, Z., & Wu, J. (2019). Control of upper limb motions by combinations of basic muscle synergies. In *Proceedings of the 2019 4th International Conference on Biomedical Signal and Image Processing (ICBIP 2019)* (pp. 36-40).

Patel, K. (2014). *Corrective Exercise: A Practical Approach: A Practical Approach*. Routledge.

Petersen, N., Morita, H., & Nielsen, J. (1999). Modulation of reciprocal inhibition between ankle extensors and flexors during walking in man. *The Journal of Physiology*, *520*(2), 605-619.

Reiman, M. P., Bolgla, L. A., & Loudon, J. K. (2012). A literature review of studies evaluating gluteus maximus and gluteus medius activation during rehabilitation exercises. *Physiotherapy Theory and Practice*, *28*(4), 257-268.

Rodgers, C. D., & Raja, A. (2019). *Anatomy, Bony Pelvis and Lower Limb, Hamstring Muscle*. StatPeals.

Robertson, D. G. E., Wilson, J.-M. J., & St Pierre, T. A. (2008). Lower extremity muscle functions during full squats. *Journal of Applied Biomechanics, 24*(4), 333–339.

Sahrmann, S. (2002). *Diagnosis and Treatment of Movement Impairment Syndromes.* Mosby.

Scano, A., Dardari, L., Molteni, F., Giberti, H., Molinari Tosatti, L., & d'Avella, A. (2019). A comprehensive spatial mapping of muscle synergies in highly variable upper-limb movements of healthy subjects. *Frontiers in Physiology*, *10*, 1231.

Selkowitz, D. M., Beneck, G. J., & Powers, C. M. (2016). 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*, *46*(9), 794-799.

Smith, J. L., Betts, B., Edgerton, V. R., & Zernicke, R. F. (1980). Rapid ankle extension during paw shakes: selective recruitment of fast ankle extensors. *Journal of Neurophysiology*, *43*(3), 612-620.

Sole, G., Milosavljevic, S., Nicholson, H., & Sullivan, S. J. (2012). Altered muscle activation following hamstring injuries. *British Journal of Sports Medicine*, *46*(2), 118-123.

Tamaki, H., Kitada, K., Akamine, T., Murata, F., Sakou, T., & Kurata, H. (1998). Alternate activity in the synergistic muscles during prolonged low-level contractions. *Journal of Applied Physiology, 84*(6), 1943–1951.

Teyhen, D. S., Shaffer, S. W., Lorenson, C. L., Halfpap, J. P., Donofry, D. F., Walker, M. J., ... & Childs, J. D. (2012). The functional movement screen: a reliability study. *Journal of Orthopaedic & Sports Physical Therapy*, *42*(6), 530-540.

Thelen, D. G., Chumanov, E. S., Sherry, M. A., & Heiderscheit, B. C. (2006). Neuromusculoskeletal models provide insights into the mechanisms and rehabilitation of hamstring strains. *Exercise and Sport Sciences Reviews*, *34*(3), 135-141.

Tresch, M. C., & Jarc, A. (2009). The case for and against muscle synergies. *Current Opinion in Neurobiology*, *19*(6), 601–607.

Van Gelder, L. H., Hoogenboom, B. J., Alonzo, B., Briggs, D., & Hatzel, B. (2015). EMG Analysis and Sagittal Plane Kinematics of the Two-Handed and Single-Handed Kettlebell Swing: A Descriptive Study. International journal of sports physical therapy, 10(6), 811–826.

Van Zuylen, E. J., Gielen, C. C., & Denier Van Der Gon, J. J. (1988). Coordination and inhomogeneous activation of human arm muscles during isometric torques. *Journal of Neurophysiology*, *60*(5), 1523-1548.

Vigotsky, A. D., Lehman, G. J., Beardsley, C., Contreras, B., Chung, B., & Feser, E. H. (2016). The modified Thomas test is not a valid measure of hip extension unless pelvic tilt is controlled. *PeerJ*, *4*.

Wagner, T., Behnia, N., Ancheta, W. K., Shen, R., Farrokhi, S., & Powers, C. M. (2010). Strengthening and neuromuscular reeducation of the gluteus maximus in a triathlete with exercise-associated cramping of the hamstrings. *The Journal of Orthopaedic and Sports Physical Therapy*, *40*(2), 112–119.

Watt, J. R., Jackson, K., Franz, J. R., Dicharry, J., Evans, J., & Kerrigan, D. C. (2011). Effect of a supervised hip flexor stretching program on gait in frail elderly patients. *PM&R*, *3*(4), 330-335.

Winters, M. V., Blake, C. G., Trost, J. S., Marcello-Brinker, T. B., Lowe, L., Garber, M. B., & Wainner, R. S. (2004). Passive versus active stretching of hip flexor muscles in subjects with limited hip extension: a randomized clinical trial. *Physical Therapy*, *84*(9), 800-807.

Witvrouw, E., Danneels, L., Asselman, P., D'Have, T., & Cambier, D. (2003). Muscle flexibility as a risk factor for developing muscle injuries in male professional soccer players. A prospective study. *The American Journal of Sports Medicine*, *31*(1), 41–46. https://doi.org/10.1177/03635465030310011801

Zaheer, F., Roy, S. H., & De Luca, C. J. (2012). Preferred sensor sites for surface EMG signal decomposition. *Physiological Measurement*, *33*(2), 195–206. https://doi.org/10.1088/0967-3334/33/2/19