STRENGTH AND MUSCLE ACTIVITY COMPARISONS OF WOMEN WITH AND WITHOUT PATELLOFEMORAL PAIN

By

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A Dissertation Submitted in Partial Fulfillment of the Degree Requirements
for the Degree of Doctor of Philosophy in Health and Human Performance

Middle Tennessee State University
August 2021

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DEDICATION

In the interest of trying to exercise enough self-discipline to limit my words to one page, I will offer a heartfelt dedication to the following:

To my aunt, Jane Newman, the “later matriarch” of my family. She always encouraged me to be true to myself. If she were here today, she would insist on a bound copy of this dissertation for her bookshelf. Her children would know this to be true and would understand why. Family was truly everything to her.

To my mother, Sue Clark, a career educator in the state of Tennessee. She would have been so very proud of this accomplishment, and more so, she would have been proud of my decision to enter teaching as a “second act” so many years ago. More than 30 years after her passing, I return to the “teaching roots” that she put down in me.

To my father, Fred Clark, another career educator in the state of Tennessee. It was “just you and me” for so many years growing up. I am a reflection of your tireless work and your unwillingness to give up. Thank you for all you have done for me.

To my son Will and my daughter Hope. You are the reason I changed my career so many years ago, and I have not regretted it for one minute. I have loved being a part of your lives for the last ten years. I would not trade it for anything in the world.

Finally, to my wife, Stacy. You have been a stalwart companion. Throughout all the procrastination and indecision, you have never pressured me to “get going.” You have always encouraged and have listened so many times. I wish I could fully convey to you how thankful I am for your support. All I can say is “thank you” and “I love you.”

I love you all.

Dave

ACKNOWLEDGEMENTS

I have always taken pains to refer to my fellow professors at Middle Tennessee State University as co-faculty. I have always felt that for me to refer to them as colleagues is to imply that I am “on the same level” as them. Now that I am at the end of this journey, I am truly honored and humbled to be able to refer to them as my colleagues.

To my committee: Dr. Dana Fuller: of course, you have forgotten more about statistical analysis than I will ever know. Thank you for your innate ability to cheerfully explain so many things to me, so many times, while doing so in a way that produces the eventual “lightbulb moment.” Dr. Jenn Caputo: you have the patience of Job. Thank you for your direction and, more than anything, your willingness to put up with someone who can never, ever quite take life (or themselves) seriously. Dr. Sandy Stevens: you have been my sounding board so many times when I was doubting myself, either professionally or personally. You, more than anyone, simplified the idea of research to me in so many ways. Thank you so much for your steadfast, unwavering encouragement.

I would also like to sincerely thank Sarah Martinez. Sarah, you showed up at the perfect time to push me forward. You brought an invaluable amount of positivity, accountability, and companionship to this process. I am honored to call you my research partner and am thrilled that we will be graduating together.

Lastly, I would, of course, be remiss if I did not thank Dr. John Coons. You have been a mentor and have been patient beyond measure. More than anything, you have pushed me to be more than who I was without causing me to question who I am. I consider you a friend and a colleague, and I thank you for your guidance.

ABSTRACT

Patellofemoral pain (PFP) is a commonly occurring problem that is not well understood. However, it is thought to be related to decreased muscular control of the hip as it articulates with the pelvis, which can then be associated with faulty biomechanics at the knee. The purpose of the first study of this dissertation was to investigate and describe the hip strength and functional strength ratio profiles of women with PFP in comparison to women without PFP (*N = 19)*. The purpose of the second study was to identify muscle activity patterns in four hip muscles in women with PFP in comparison to women without PFP (*N = 21)*.

The primary finding in the first study was that women with PFP had a higher ratio of concentric hip abduction strength to eccentric hip adduction strength than women without PFP. This would suggest that there was a decreased level of muscular control and stability at the hip in women with PFP compared to women without. This may be associated with compromised biomechanics that could be related to increased dynamic valgus at the knee. This dynamic valgus has been attributed to PFP by previous research. Future studies should focus on continuing to identify both conventional as well as functional strength ratio patterns in persons with PFP, and how these ratios relate to the biomechanical attributes of the condition.

In the second study, the tensor fascia latae (TFL) was found to exhibit a higher level of muscle activity during several different functional movements in women with PFP when compared to women without PFP. It is thought that this higher level of activity may be related to a complex problem of decreased strength and activity in other muscle that stabilize the hip. It is possible that strengthening exercises that focus on increasing the strength of the external rotators of the hip as well as weight bearing stabilization exercises may improve symptoms in women with PFP. Future studies should focus on continued examination of muscle activity patterns in persons with PFP, including co-activation patterns and timing of activation.

TABLE OF CONTENTS

CHAPTER I

INTRODUCTION

Patellofemoral pain (PFP) is a commonly occurring although poorly understood problem, thought to affect up to 25% of individuals reporting lower extremity injuries (Clement et al., 1981). Individuals with PFP have been shown to have higher levels of disability, lower levels of quality of life (Rathleff et al., 2013), increased mental distress, and reduced self-perceived health (Jensen et al., 2005). It has also been suggested that individuals with higher levels of patellofemoral pain are more likely to avoid returning to work or physical activity due to increased fear-avoidance behavior (Piva et al., 2009). While research into the problem has progressed, there continues to be a need to further develop the body of knowledge regarding its overall profile.

Although the problem is a multifactorial one, it is thought that PFP is related to an altered biomechanical relationship between the femur, tibia, and patella (Bolgla & Boling, 2011; Powers, 2003). Numerous factors have been associated with PFP, including Q-angle, flexibility, and strength. With regard to strength, previous research has focused on the nature of the relationship between PFP and quadriceps strength. However, it has also been proposed that muscle strength imbalances could contribute to PFP (Baldon et al., 2011; Baldon et al., 2009). Previously, a specific imbalance between the VMO and VLL was thought to contribute to lateral deviation of the patella and increased compressive forces through the patella (Boling et al., 2006; Karst & Willett, 1995; Powers, 2000). More recently, it has been proposed that decreased stability of the femur in the frontal and transverse planes, specifically during weight bearing activities, is the primary culprit (Powers, 2003). An understanding of potential muscle strength imbalances at the hip could help to establish the relationship between muscle strength imbalances and PFP.

Traditional methods of measuring hip strength and establishing ratios for defining a muscle imbalance are limited in their scope. In the past, a commonly-used method to measure hip strength and establish strength ratios has been isometric dynamometry (Finnoff et al., 2011; Magalhaes et al., 2013). However, isometric dynamometry does not allow for dynamic assessment of maximal torque. In contrast, isokinetic dynamometry allows the researcher a more comprehensive profile of maximal torque through a plane of movement (Baltzopoulos & Brodie, 1989). Although this method of measure allows for more detail and better data analysis, research into isokinetically-measured dynamic hip strength ratios in a PFP population is limited (Baldon et al., 2009).

Measurement of strength may not provide a complete representation of the integration of strength into functional activities. It has been recently stated that more well-established aspects of physical fitness are established upon the foundation of basic functional movement, and the breakdown of proper joint motion during functional movement can lead to musculoskeletal injury (Teyhen et al., 2014). Various functional movements such as the single-leg squat, lateral step down, or forward lunge are typically used as a means of assessing quality of movement and can help form the basis for prescription of corrective exercise (Cook et al., 2006). However, muscular strength imbalances can cause a loss of joint stability during motion and thus permit improper joint motion during movement (Sahrmann, 2002). The interaction of agonists and antagonists during functional activities can have an effect on quality of movement

(Baratta et al., 1988), as well as joint stability and neuromuscular activity (Khanmohammadi et al., 2016).

The use of electromyography (EMG) during functional activities can provide a better understanding of muscle activity patterns throughout a functional movement (Ivanenko et al., 2004). Although the adductor longus and tensor fascia lata might contribute to the observed kinematic deviations in individuals with PFP (Aminaka et al., 2011; Sahrmann, 1987), there is a lack of research studying muscle activity patterns of the adductor longus and tensor fascia lata and the relationship between these patterns and those of the gluteus medius and gluteus maximus during the functional activities selected. In addition, the research that has been performed has not related peak EMG activity or mean EMG activity to electronically-measured ROM to establish the timing of activity within the range of motion of the joint.

Purpose

The research within this dissertation compared strength ratios and muscle activity patterns of individuals with PFP to those without PFP. The purpose of the first study was to compare various eccentric to concentric hip strength ratios and strength curves in individuals with PFP and those without PFP. The purpose of the second study was to compare muscle activity patterns during functional movements between individuals with PFP and those without PFP.

Significance of Studies

A more detailed description of strength ratios in individuals with PFP could provide rehabilitation professionals with a better understanding of how hip muscle imbalances relate to knee pain. However, objective strength measures don’t allow for an understanding of what is occurring during functional activities. A more in-depth understanding of peak muscle activity and peak timing patterns during functional activities movements such as a forward lunge, a lateral step-down, or a single-leg squat will help to better understand how the problem manifests during function. This information could then allow for further improvements of exercise programs or activity recommendations and modifications.

CHAPTER II

REVIEW OF THE LITERATURE

This review of the literature begins with a description of patellofemoral pain (PFP) and how it has been historically defined. This is followed by a summary of incidence and prevalence of the condition and a review of factors associated with it. A transition is then made into an overview of muscular strength imbalances and a review of previous research into the relationship between strength imbalances and PFP. This is followed by a review of the concept of functional movements and of the relationship between muscle activity as measured by electromyography (EMG) and functional movement assessments in individuals with PFP.

Patellofemoral Pain

PFP is commonly used to describe generalized knee pain not resulting from a specific trauma or injury (Fulkerson, 2002). Patellofemoral pain is commonly described as diffuse, generalized pain, often retropatellar or along the medial and lateral patellar borders (Brechter & Powers, 2002; Ireland et al., 2003; Malek & Mangine, 1981; Salsich et al., 2001). Confusion surrounds the use of the term, in part, due to variation in understanding of knee pathology (Callaghan et al., 2000; Wilk et al., 1998). Additional confusion is caused by phrases such as “anterior knee pain” and “chondromalacia patella” used to describe similar knee pain symptoms (Callaghan & Selfe, 2007; Devereaux & Lachmann, 1984). In theory, PFP could be inclusive of any anterior knee pathology of unknown origin which produces pain, including chondromalacia patella, patellar tendonitis, intra-articular lesions, and peri-patellar bursitis (Miller et al., 2005). However, it has been suggested that PFP is used in an excessively broad-based manner without adequate consideration given to the pathological cause of the syndrome (Grelsamer et al., 2009). Variation in the definition of PFP has produced a lack of consistency regarding estimates of the number of individuals affected by the disorder.

Epidemiology

The majority of epidemiological research on PFP has focused on establishing incidence rates rather than prevalence rates (Witvrouw et al., 2014b). In the literature, incidence rates of PFP among those reporting knee pain ranged from 5.4% to 25.8% (Clement et al., 1981; Dehaven & Lintner, 1986; Devereaux & Lachmann, 1984; Shwayhat et al., 1994). While the range is broad, it has been proposed that this is a reflection of differences in populations studied as well as variation in the diagnosis of PFP (Crossley et al., 2002). Heir and Glomsaker (1996) reported an incidence rate of 13.5%. However, the authors did not identify PFP as a distinct diagnostic category, and instead placed PFP into the general category of "overuse syndromes" of the knee. Similarly, Jones et al. (1993) determined an incidence rate of 5.9% for "overuse knee injuries." Kannus et al. (1987), while noting that injuries to the knee were the most commonly reported lower extremity injury, also did not offer a specific categorization of PFP. Instead, the category most representative of PFP is chondromalacia patella, which is often incorrectly used as a synonym for PFP (Devereaux & Lachmann, 1984).

The majority of individuals reporting PFP are in their mid-20's (Dehaven & Linter, 1986; Jones et al., 1993). However, there are data suggesting that PFP is common in adolescents, with a median reporting age of 17 years (Rathleff et al., 2013). With regard to association of PFP with sex, PFP has been found to be more prevalent in females than in males (Boling et al., 2010; Dehaven & Lintner, 1986; Taunton et al., 2002). Much of the data regarding incidence rates are obtained from sports clinics or clinics dealing with athletes, thus leading to potential sampling bias (Witvrouw et al., 2014a). Nearly all of the samples studied engaged in regular physical activity. Similar findings have been reported in athletic populations (Dehaven & Lintner, 1986) and military recruits (Jones et al., 1993). Heir and Glomsaker (1996) reported an incidence rate of 13.5% among military conscripts reporting injuries. The wide range of prevalence suggests a pathology with numerous factors contributing to its development.

Etiology of Patellofemoral Pain

Researchers have proposed that numerous factors alter the biomechanics among the femur, tibia, and patella (Bolgla & Boling, 2011). Excessive femoral and tibial motion in the transverse and frontal plane will cause a lateral displacement of the patella (Powers, 2003), resulting in patellofemoral pain. While earlier researchers suggested that PFP was due to overloading rather than a mechanical concern (Fairbank et al., 1984), more recent researchers have theorized that factors such as quadriceps angle (Bolgla & Boling, 2011; Messier et al., 1991), muscle weakness (Powers, 2003), and altered lower extremity flexibility (Piva et al., 2005; Smith et al., 1991; Witvrouw et al., 2000) contribute to an alteration in biomechanics among the femur, tibia, and patella.

Q-angle

The quadriceps angle (Q-angle) is frequently proposed as a factor in the development of PFP. The Q-angle is formed at the intersection of two lines that represent distinct force vectors in the leg. The upper line lies between the quadriceps origin at the anterior superior iliac spine (ASIS) of the pelvis and extends through the center of the patella. The lower line is drawn from the insertion of the patellar tendon through the same point at the center of the patella. Because the anatomical angle that is formed as the quadriceps crosses the patella is deflected laterally compared to the upper line, the effect is lateral displacement of the patella as the quadriceps contracts (Grelsamer & Klein, 1998).

There is an association between increased Q-angle and knee pain. Emami et al. (2007) compared standing Q-angle measures of symptomatic and pain free individuals and found larger standing Q-angle measures in the painful group. Similarly, Rauh et al. (2007) measured standing Q-angles in cross country runners and determined that the risk of lower extremity injury increased in those runners with large Q-angles or with asymmetry in Q-angle from left to right. Herrington (2013) found that individuals with knee pain adopted a larger Q-angle in unilateral stance than healthy individuals.

In contrast to these studies, other researchers have shown that static Q-angle measures are not related to knee pain. Fairbank et al. (1984) compared the static standing Q-angle measure of adolescents with knee pain to those without knee pain and found that Q-angle did not vary between the groups. In a study that would appear to refute the earlier works of Rauh et al. (2007), Park and Stefanyshin (2011) found that Q-angle was inversely associated with knee pain in runners, casting doubt as to whether Q-angle is predictive of knee injuries in runners. Similarly, in a prospective study of lower limb injury risk factors in runners, knee varus (instead of valgus) was found to be related to PFP (Lun et al., 2004).

Further research has been performed to determine the relationship between the dynamic assessment of Q-angle and knee pain. Herrington (2013) showed that individuals with PFP had greater Q-angle in single-leg stance than those without PFP and that Q-angle changed more during the transition from double leg to single-leg stance in symptomatic individuals when compared to healthy controls. Similarly, Silva et al. (2015) found that those with PFP had a greater amount of dynamic knee valgus during stair ascent than those without PFP. Stefanyshyn et al. (2006) quantified the amount of valgus force passing through the knee during running and found that painful participants sustained greater valgus force impulses through the knee than non-painful participants.

Overall, there is not conclusive evidence that static Q-angle is strongly related to PFP. Instead, the current research suggests that PFP is more strongly related to dynamic Q-angle than static Q-angle. However, factors which influence dynamic Q-angle must be more closely inspected. There are also additional factors that have been proposed as possible contributors to PFP, including strength and the balance of strength around the knee joint.

Strength

Knee extenders. Individuals with PFP have exhibited quadriceps strength deficits. Dvir and Halperin (1992) reported that men and women with PFP exhibited a pattern of decreased quadriceps strength when compared to an age- and activity-matched control group. Similar findings were reported when comparing peak quadriceps torque values exclusively in women (Yosmaoglu et al., 2013), as well as when comparing symptomatic versus non-symptomatic extremities (Citaker et al., 2011). In addition, Anderson and Herrington (2003) used isokinetic dynamometry to test concentric and eccentric torque production in people with PFP. Symptomatic participants exhibited an inability to smoothly control eccentric quadriceps contraction when compared to healthy controls.

While many researchers have reported a relationship between decreased quadriceps strength and PFP, there have been contrasting findings. For example, increased isometric quadriceps strength has been reported to be a possible risk factor for PFP in military recruits (Milgrom et al., 1991). Esculier et al. (2015b) assessed isometric strength in runners and found no differences in quadriceps strength between a group with PFP and a group without PFP. Similar findings were obtained using externally stabilized hand held dynamometry (Toumi et al., 2013). Finally, in a two-year prospective study, Witvrouw et al. (2000) concluded that decreased quadriceps strength was not a risk factor for the development of PFP. Because there is not a current consensus regarding the relationship between quadriceps strength and PFP, further investigation into other strength related etiological factors is warranted.

Lateral tracking of the patella is frequently proposed as a possible cause of PFP (Souza & Gross, 1991). An imbalance between the activity of the vastus medialis obliquus (VMO) and vastus lateralis (VL) is thought to be a primary culprit. Sakai et al. (2000) studied cadaveric knees and found that when weakness of the VMO was simulated to varying degrees, lateral displacement of the patella occurred. In living participants, Sheehan et al. (2012) selectively blocked innervation of the VMO and noted a significant lateral shift of the patella during volitional movement.

Other works have refuted the association between the influence of the VMO on the patella and PFP. Citing the anatomical similarities in the knee joints of rabbits and humans, Sawatsky et al. (2012) ablated the vastus medialis muscle in rabbits and found no change in patellofemoral joint pressures during direct femoral nerve stimulation. These findings led the authors to question previous researchers who concluded that VMO weakness was a cause of PFP. The lack of a consensus regarding the relationship between PFP and strength factors surrounding the knee joint has led to further investigation into hip strength and its possible influence on PFP.

Hip abductors and external rotators. While earlier research focused on quadriceps strength and its influence on the patella, more recent research has investigated hip strength and its relationship to PFP. Ireland et al. (2003) used a stabilized handheld dynamometer (HHD) to assess hip abduction and hip external rotation strength in active women with PFP and found that the symptomatic group exhibited a strength deficit in both planes. The authors felt that hip weakness in symptomatic individuals represented an inability to resist knee valgus and hip internal rotation moments. This could lead to increased lateral patellar compressive forces at the patellofemoral joint. Bolgla et al. (2008) measured isometric hip abduction and hip external rotation strength in women with PFP. The authors found that participants with PFP presented with significantly decreased hip abduction and hip external rotation strength as compared to healthy controls. Similar findings of decreased isometric hip abduction and hip external rotation strength were found by Dierks et al. (2008), as well as by Willson and Davis (2009), Mousavi and Norasteh (2011), and Robinson and Nee (2007). Although these studies have all focused on establishing the relationship between hip external rotation and abduction strength and PFP, there is evidence to support the conclusion that PFP can be related to widespread weakness in the hip musculature.

Cichanowski et al. (2007) used HHD to study hip strength in female athletes. The authors found that, in symptomatic individuals, the hip abductors and hip external rotators were weaker in the symptomatic leg when compared to the uninjured leg, in agreement with previous research. In addition, the individuals with PFP exhibited global hip muscle weakness when compared to the uninjured individuals. Similarly, Magalhaes et al. (2010) used a HHD to test six planes of hip strength in sedentary females with PFP. When comparing hip strength to asymptomatic sedentary females, the authors found generalized hip weakness in most muscle groups in the painful group. Specifically, weakness was found in the hip abductors, external rotators, flexors, and extenders.

In contrast, some studies have shown a relationship between increased hip strength and PFP. Boling et al. (2009) used HHD to assess isometric hip strength in active men and women and found that increased hip external rotation strength was a risk factor for development of PFP. However, the authors felt that this increased strength may have been an acquired factor by the participants, in an effort to counteract an increased internal rotation moment at the knee during functional tasks. Finnoff et al. (2011) also measured isometric hip strength in male and female runners. Individuals who later developed PFP exhibited a higher abduction and external rotation strength value pre-injury as compared to post injury.

Some studies have found no relationship between hip strength and PFP. Piva et al. (2005) used HHD in both men and women to measure hip abduction and hip external rotation strength in a symptomatic group. These measures were compared to an asymptomatic group. No differences in hip abduction or external rotation strength were found between the groups. The authors suggested that a difference in testing position might have accounted for the difference in findings from previous works. Esculier et al. (2015a) measured isometric hip abduction, external rotations, and extension strength in runners, and found no difference between symptomatic and asymptomatic individuals.

Tyler et al. (2006) used a HHD to assess isometric hip strength in individuals with PFP. The authors found that improvements in hip flexor strength were associated with an improvement in PFP symptoms. However, in contrast to previous studies, improvements in PFP symptoms were not associated with an improvement in hip abduction or hip adduction strength. The authors felt that improved hip flexor strength might have provided additional rotation stability of the femur during functional activities, thus decreasing the potential of increased lateral patellar pressure during function. Long-Rossi and Salsich (2010) used manual HHD to assess isometric hip extension, abduction, and external rotation and found no correlation between strength and knee pain provocation during a single-leg squat in participants with PFP. Although isometric measures, especially those obtained via HHD, are more easily obtained in the clinic, such measures may not allow for an accurate representation of stability requirements during a closed chain functional activity.

Isokinetic measures have been obtained in an effort to better quantify muscle strength and its potential interaction with hip and knee motion during functional activities. Baldon et al. (2009) used isokinetic dynamometry (IKD) to measure eccentric hip strength. People with PFP were found to have decreased hip abduction and adduction strength when compared to healthy controls, although internal and external rotation strength did not differ. Boling et al. (2009) used IKD to measure both eccentric and concentric torque values in individuals with and without pain. Strength deficits were found in both concentric and eccentric hip external rotation. In addition, symptomatic individuals exhibited decreased eccentric hip abduction strength. However, neither concentric nor eccentric hip extension values were different in individuals with pain versus controls. The authors emphasized the clinical value of concentric and eccentric measures because such measures better reflect the functional contractions of muscle fibers. Nakagawa et al. (2008), in a randomized control study, used IKD to assess eccentric hip abduction and external rotation strength in symptomatic individuals. Participants were then assigned to either a quadriceps strengthening group or a combined quadriceps and hip strengthening group. After a 6-week intervention, the combined quadriceps and hip strengthening group had lower complaints of pain during some functional activities, although there was no improvement in hip strength values. The authors concluded that the decrease in pain may have been related to an improvement in motor control of the hip musculature, in the absence of detectable strength gains. Nakagawa et al. (2012) used IKD to compare eccentric hip abduction and external rotation torque between individuals with PFP and those without. Individuals with PFP exhibited significantly less eccentric torque in both planes of movement when compared to the healthy control participants. The authors stated that an emphasis on eccentric strengthening during rehabilitation could be of benefit to individuals with PFP, because the hip abductors and hip external rotators must act in an eccentric fashion to control femoral motion during functional activities.

Other authors have failed to find a relationship between isokinetically measured hip strength and PFP. Herbst et al. (2015) used isokinetic dynamometry to assess hip abduction strength in female athletes. The authors found that increased hip abduction strength was related to subsequent development of PFP. The authors concluded that faulty mechanics at the hip joint during functional activities may eccentrically load the hip abductors, causing hypertrophy. This same pattern of faulty mechanics later contributed to the development of PFP. McMoreland et al. (2011) used isokinetic dynamometry to test isometric hip strength in young active females and found that individuals with mild PFP showed no deficits in strength or endurance when compared to healthy controls. In summary, neither quadriceps strength nor gluteal strength has been conclusively shown to be the only determining factor in the development of PFP. Instead, it has been proposed that the development of PFP could be attributed to a muscle strength imbalance between agonists and antagonists.

Muscle Strength Imbalances

Hip muscle strength imbalances have been suggested as possible contributors to PFP (Baldon et al., 2011; Baldon et al., 2009). A muscle strength imbalance exists when there is an abnormal strength relationship between an agonist muscle and its antagonist (Kendall et al., 1993; Lucado, 2011). In addition, a muscle strength imbalance has also been defined as an alteration in the relationship between muscles within a synergistic muscle group (Janda, 1993; Sahrmann, 1987). Potential causes of muscle imbalance include paresis, disuse, and postural faults (Singer, 1986). Furthermore, in athletic populations, causes of muscle imbalances have been attributed to factors such as limb dominance in the upper or lower extremities, previous injuries, or sport-specific demands. Because such influences are not a factor in a sedentary population, it has been proposed that repetitive motions and/or poor posture can contribute to the development of muscle imbalances (Guyer & Ellers, 1990; Leahy, 1995 [as cited in Clark et al., 2014). Janda (1993) proposed that muscle imbalances develop when certain muscle groups develop tightness in response to dysfunction while other muscle groups respond with weakness. Among the muscle groups that were proposed by Janda to be predisposed to tightness are the hip adductors, hamstrings, and rectus femoris. Muscles that predispose to weakness include the vastus medius, lateralis, and gluteus medius, among others.

Muscle fibers have an optimal length at which maximal tension can develop. This is the length at which there is maximal overlap of thick and thin filaments within the muscle fiber (Brooks et al., 2005; McArdle et al., 2010). As the muscle fiber is either elongated or shortened past this optimal length, the fiber's ability to develop tension decreases (McArdle et al., 2010). Kendall et al. (1993) noted that muscles which are excessive in length are usually weak. This, in turn, can allow adaptive shortening of the opposing musculature. In the same manner, muscles that are too short are usually comparatively stronger, which leads to the lengthening of and weakening of opposing musculature.

Muscle groups act in a coordinated fashion to produce controlled joint movement. While agonists develop concentric tension to produce movement, antagonists simultaneously develop eccentric tension to refine and control that movement (Hall, 2007). A muscle that is allowed to consistently develop unopposed tension can adaptively shorten as a result. At the same time, the opposing muscle (antagonist) can adaptively lengthen. Eventually, this process can lead to reciprocal inhibition of the antagonist, which, in turn, can result in mild hypotonia and delayed activation of the antagonist during movement patterns (Janda, 1993). This would then lead to an imbalance of force production between an agonist and its antagonist.

In addition to the relationship between agonists and antagonists, a muscle imbalance within a synergistic muscle group can also develop. In a synergistic pair or group of muscles, it is not unusual for one muscle to dominate and become the prime mover across a joint. As a result of this synergistic dominance, the other muscles in the synergistic group may become less active (Sahrmann, 1987). The continued predominance of the primary mover in the synergistic group eventually causes the dominant synergist to adaptively shorten and become more readily activated (Janda, 1993). In addition to this, synergistic dominance can also cause excessive motion into a direction that is abnormal for the joint in question. Sahrmann (1987) noted an example of this in the synergistic dominance of the tensor fascia lata (TFL) over the gluteus medius. While both muscles are abductors of the hip, the TFL can also serve as a medial rotator of the hip. If the TFL becomes predominant, the action of the TFL during hip abduction can produce not only hip abduction, but also medial rotation. Janda (1993) proposed that this altered motion across a joint by a muscle can then lead to slight elongation of its antagonist. This elongation can lead to what has been called “stretch weakness,” a condition which can further contribute to a decrease in force generation by a muscle, as muscle fibers are elongated to a point which exceeds their optimum length.

As a result of muscle imbalances, faulty joint movement patterns can develop (Janda, 1993; Sahrmann, 1987). If a muscle is continually used or posturally placed in a shortened position, then this may allow the joint upon which it acts to assume an altered position during functional use. Excessive joint motion can result as the agonist member of the synergistic muscle pair essentially overpowers its antagonistic counterpart (Sahrmann, 1987).

Strength ratios. Limited research exists on the establishment of hip strength ratios and possible muscle imbalances. Although strength imbalances have been suggested as a possible contributor to PFP (Baldon et al., 2011; Baldon et al., 2009), the association between hip strength ratios and PFP has not been extensively studied.

Magahales et al. (2013) used HHD to determine isometric strength ratios of the hip agonist/antagonist groups. The authors concluded that in individuals with PFP, the ratio of adductor strength to abductor strength was greater than in those without PFP. However, no differences between groups was found in either the internal rotation/external rotation ratio or flexor/extensor ratio. The authors also grouped the strength measures into an anteromedial group (flexor/adductor/internal rotation) and a posterolateral group (extensor/abductor/external rotation) group. They found that the ratio of anteromedial to posterolateral strength was higher in the PFP group as compared to the control group. From these findings, the authors concluded that a specific hip muscle group weakness might not be sufficient to cause altered hip kinematics. Instead, an agonist to antagonist imbalance might be the primary cause. The authors also stated that a better understanding of the nature of strength deficits in this population was needed, and a better assessment of strength ratios should be pursued. In contrast to these findings, Finnoff et al. (2011) used manual HHD to assess isometric hip strength and strength ratios. It was determined that a greater isometric hip external rotation to internal rotation strength ratio reduced the risk of development of knee pain. However, the authors also found that greater hip abduction to adduction strength ratios were predictive of the development of knee pain.

In comparison to isometric dynamometry, isokinetic dynamometry allows for measurement of maximum torque during dynamic movement (Baltzopoulos & Brodie, 1989). Torque values of agonists and antagonists can be measured and, from these values, a ratio of agonist torque to antagonist torque can be derived. This “reciprocal muscle group ratio” can be used as an indicator of the state of muscle balance around a joint (Baltzopoulos & Brodie, 1989; Kannus, 1994). However, less research has been performed using isokinetic dynamometry to generate either concentric or eccentric hip strength ratios. Thorough review of the literature revealed only one study where eccentric hip strength ratio values in a female population with PFP were measured. Baldon et al. (2009) used isokinetic dynamometry to measure eccentric hip torque values and, in turn, establish eccentric hip agonist/antagonist strength ratio values. The authors were able to show that individuals with PFP have a greater eccentric hip adduction to abduction torque ratio than those without PFP. However, there was no difference between the groups with regard to the eccentric hip internal rotation to external rotation torque ratio. Given the fact that eccentric hip abductor and external rotation strength contribute to the stability of the femur during functional activities, using isokinetic dynamometry to establish a better understanding of the ratio of concentric agonist strength to eccentric antagonist strength is warranted.

In summary, although muscle strength imbalances have been suggested as a possible cause of PFP, little research has been performed to determine the extent to which this is the case. In addition, limited research has been performed using isokinetic dynamometry to measure either concentric or eccentric strength ratios. Further research into concentric and eccentric strength ratio values of individuals with PFP will produce a better understanding of the extent to which muscle strength imbalances contribute to this condition. However, information obtained during isokinetic strength testing does not fully represent how muscles function during movement. Electromyography can provide additional information regarding the activity levels and patterns of agonists and antagonists during functional movements.

Electromyography

Electromyography (EMG) is used to measure muscle activity. Using EMG during functional movements can provide the researcher with information that can possibly explain kinematic differences between symptomatic and asymptomatic individuals. Comparisons in peak muscle activity and activity timing patterns can help establish a more comprehensive understanding of PFP and its underlying cause.

Processing

As EMG equipment receives a raw EMG signal, the signal is filtered. Signal filtering allows passage of a specific range of frequencies while eliminating others. In doing so, the frequency spectrum of the signal is reduced (DeLuca, 2003). Most EMG equipment contains a filter that rejects electrical noise from the electrical environment. This “notch filter” is a band reject filter that operates in a narrow bandwidth, typically from 59 to 61 Hz (Cram, 2011). After filtering out electrical noise, the signal is processed through a band pass filter. This filter only allows passage of energy of a certain frequency range. For example, a typical band pass filter allows passage of energy that exceeds 20 Hz but is less than 300 Hz frequency. The lower cutoff point eliminates electrical noise and varied biological artifacts, while the upper cutoff point eliminates noise from tissue movement at the electrode site (Cram, 2011). However, it is important to consider the frequency content of the desired information when selecting what filtering parameters to use (Frigo & Crenna, 2009; Soderberg & Knutson, 2000).

Because EMG signal amplitudes are bipolar and vary in a positive and a negative fashion, averaging the signal will not yield useful information. For this reason, it is recommended that signal rectification be performed prior to further analysis (DeLuca, 2006; Konrad, 2006). During rectification, all signal values are translated to a single polarity (Gerleman & Cook, 1992). This is accomplished either by eliminating all negative signal values or by converting all signals to a positive value (Cram, 2011; Gerleman & Cook, 1992; Konrad, 2006). This process makes it easier to interpret the data as well as permitting application of standard parametric measures such as mean, peak value, and area to the curve (Konrad, 2006).

After EMG data are obtained, the data are often normalized. Normalization (dividing the obtained data by a reference value) allows comparisons to be made among people, and also muscles (Frigo & Crenna, 2009; Soderberg & Knutson, 2000). The resulting value is a ratio of the EMG output during the task being measured to the EMG output during the normalization procedure (Burden, 2010). In addition, normalization of data allows for comparison between studies (Knutson et al., 1994; Soderberg & Knutson, 2000). However, in a comparison between groups, normalization is not as important. While other procedures such as rectification and filtering are more widely agreed upon, there continues to be debate as to which normalization process is most appropriate (Frigo & Crenna, 2009; Soderberg & Knutson, 2000).

The most widely used means of normalization is the use of a maximal voluntary isometric contraction (MVIC) as the source of a reference EMG value (Frigo & Crenna, 2009). Although there is a lack of systematic research regarding the most effective MVIC position, general recommendations for the procedure include extensive stabilization of the participant and the provision of rigid resistance (Konrad, 2006). A contraction duration of 3-5 seconds is recommended (Soderberg & Knutson, 2000). This short contraction duration is thought to be adequate to avoid fatigue from one repetition to the next (Soderberg & Knutson, 2000). Up to 5 repetitions of each distinct contraction are recommended in order to obtain an adequate MVIC (Yang & Winter, 1983). In addition, a rest period of 1 minute between each repetition is recommended (Konrad, 2006).

The use of the MVIC is not without limitations, chief among them being a concern as to whether a participant is truly performing maximally during MVICs (Burden, 2010). Factors such as training level, motivation, and the specificity of the muscle activated can have an impact on a person's ability to generate a maximal contraction (Soderberg & Knutson, 2000). For this reason, other techniques have been proposed. However, the MVIC was shown to be the most reliable when compared to other normalization techniques in both the gastrocnemius (Knutson et al., 1994) and the hip (Bolgla & Uhl, 2007). Once EMG data are obtained and normalized, comparisons among populations during functional motions can be performed.

Functional Movements

Functional movement has been recently noted as the foundation upon which more well-known components of fitness are established (Teyhen et al., 2014), and a thorough understanding of human movement science is crucial in order to determine optimal functional movement (Clark et al., 2014). In addition, an assessment of functional movement patterns can provide a baseline of information from which corrective exercise can be prescribed (Cook et al., 2006). Observation of kinematic motion patterns during functional movements can indicate possible underlying strength, stability, range of motion, or flexibility deficits. Muscle imbalances can lead to a breakdown in the maintenance of proper joint motion during movement (Sahrmann, 2002) and can predispose to musculoskeletal injury (Teyhen et al., 2014). Excessive knee valgus during functional activities has been consistently noted in individuals with PFP. Commonly-used movement assessments for the lower extremities include the single-leg squat, the lateral step down, and the forward lunge (Clark et al., 2014).

Single-leg squat

The single-leg squat (SLS) can be used as a means to examine the alignment and kinematic function of the lower extremity during functional motion (Levinger et al., 2007). Because excessive kinematic motion in the transverse and frontal planes has been found to be related to PFP (Levinger et al., 2007; Nakagawa et al., 2012), these planes are of particular interest. Herrington (2013) studied dynamic knee valgus angles during a SLS in active women and reported that symptomatic women presented with greater valgus angles during SLS when compared to both healthy controls as well as when compared to their asymptomatic leg. Souza et al. (2010) used weight-bearing magnetic resonance imaging (MRI) to visualize displacement of the patella and rotation of the femur during a SLS. They determined that females with PFP exhibited a greater degree of medial femoral rotation and lateral patellar displacement during a SLS compared to healthy controls. The authors concluded that muscular control of femoral rotation during weight-bearing activities was a key factor in the management of PFP and restoration of normal patellofemoral joint kinematics. In another study comparing females with PFP to females without PFP, Levinger et al. (2007) found that symptomatic participants exhibited a greater femoral frontal angle (FFA) during a SLS than the asymptomatic participants. The authors stated that one possible cause of this deviation was decreased control of the muscles surrounding the thigh and the hip. Similar findings and conclusions were reached by Willson and Davis (2008). Individuals with PFP have consistently been shown to exhibit excessive motion during an SLS.

Numerous researchers have sought to determine the relationship between hip strength and kinematic motions observed during a SLS. Willson et al. (2006) used photo editing software to determine knee valgus during a SLS. These measures were correlated with isometric strength measures to assess the association between strength and frontal plane projection angles during the SLS. The authors reported that in a group of healthy females, hip external rotation strength negatively correlated with knee valgus during the SLS, although the correlation was weak. A statistically significant correlation was also reported between hip abduction strength and SLS-induced valgus, although the correlation was not considered to be clinically significant. Hip strength values have also been shown to be correlated with frontal plane projection angle (FPPA) of the knee during a SLS. Stickler et al. (2015) measured FPPA of healthy females performing a SLS using video analysis and visual review of marked angles during a SLS. The FPPA values were then correlated with isometric hip abduction, external rotation, and extension strength measures. There was a significant correlation between all hip strength measures with FPPA, with hip abduction strength being the best predictor of FPPA.

In a study comparing kinematic differences between people with and without PFP, Nakagawa et al. (2012) determined that women with PFP exhibited greater dynamic knee valgus during a SLS when compared to those without PFP. In addition, these same women presented with significantly decreased eccentric hip abduction and hip external rotation. The authors emphasized the importance of eccentric muscle function in maintaining stability of the hip during SLS. In contrast to this evidence regarding the role of hip lateral rotation strength in mediation of PFP, Baldon et al. (2015) reported that improvement in hip eccentric medial rotation strength was related to improvement in kinematics during a SLS in women with PFP. The authors concluded that because strength was tested in a seated position, test results were contradictory to previous studies. The gluteus maximus and medius medially rotate the hip while in a seated position, in contrast to externally rotating the hip in a standing position (Delp et al., 1999). In addition, Baldon et al. (2015) found that eccentric hip abduction torque had no mediating effect on kinematics during the SLS and concluded the gluteus maximus did not significantly contribute to eccentric hip abduction torque when tested in the chosen side lying position. DiMattia et al. (2005) related isometric hip abduction strength to visual observation of hip and knee kinematics during a SLS in a group of healthy females. The authors determined that there was no correlation between hip abductor strength and degree of visually observed medial knee displacement during a SLS. In addition, they concluded excessive motion during a SLS is not the product of isolated weakness in one muscle group, but instead represents a complex problem.

Willy and Davis (2011) studied the effect of a strengthening and movement training program on SLS and running kinematics in women. They found that the combination of strengthening and neuromuscular training led to improved knee kinematics during the SLS. However, they also concluded that the strength gains that were noted did not lead to improvement in kinematics during running. The authors concluded that increasing hip strength may not be sufficient to improve running kinematics. Dawson and Herrington (2015) studied the effect of either muscle strengthening or SLS technique correction training in recreationally active women.

Strength and skill proficiency increased after a 6 week training period. There was a concurrent decrease in dynamic valgus angles during a SLS in both groups. The authors noted that the technique correction training group sustained greater improvement in scored biomechanics than the strength training group. In addition, the improvement in biomechanics was sustained for 6 weeks post intervention in the technique correction group. This improvement in biomechanics was not sustained in the strength training group. The lack of a clearly defined relationship between strength and observed kinematic deviations during the SLS in individuals with PFP suggests that strength alone is not the sole factor in determining observed joint motion deviations during a SLS.

Forward Lunge

While the SLS allows for kinematic assessment of the hip and knee during functional movement, it does not produce a transitional movement in the sagittal plane. The forward lunge (FL) allows for assessment of hip and knee kinematics during forward functional movement. The FL has been examined in an effort to define the relationship between kinematics during a lunge and their potential impact on PFP. Escamilla et al. (2008) examined the relationship between patellofemoral joint stress and FL length in healthy men and women and found an indirect relationship between the length of a FL and patellofemoral joint stress. However, the study only included participants who did not deviate in the frontal or transverse planes during the motion. The authors concluded that further studies are needed which assess transverse and front plane motions and how they might affect joint stress. Thijs et al. (2007) examined the relationship between knee kinematics during a FL and muscle strength in healthy males. Using the FL as their functional motion of interest, the authors divided participants into groups by frontal plane deviation during the movement. Thijs et al. then measured hip strength differences between the two groups. The authors determined that strength was not related to FL frontal plane kinematics. However, they did find that a greater ratio of external rotation strength to internal rotation strength was positively related to the varus knee motion during the FL. The authors concluded that a relationship between strength and kinematics might be more evident in an injured population and that other factors such as proprioception or flexibility might be more of a determinant of frontal plane kinematics.

Dwyer et al. (2010) examined knee valgus and flexion angles as well as hip kinematic angles during a FL, comparing them between healthy men and women. No differences in knee valgus, hip external rotation, or adduction angles were found between sexes. However, differences between males and females were found in knee flexion and hip flexion and extension angles. Although strength was not measured, the authors theorized that the differences in angles that were shown might have been due to strength differences between males and females.

Few studies have included the FL as a functional motion of interest in participants with PFP. Loudon et al. (2002) looked at a variation of the FL and found that performance on the lunge correlated to pain in patients with PFP. The authors did not attempt to correlate strength with lunge performance or kinematics. Although knee valgus during functional motion has been related to PFP, and valgus has been observed during a FL, there is a lack of consensus regarding the potential cause of such kinematics. Further investigation into underlying factors during a FL in individuals with PFP is needed.

Lateral Step Down

The lateral step down (LSD) test was developed by Piva et al. (2006) as a means of assessing overall quality of movement during lower extremity function. The test requires the examiner to observe strategies of movement at various locations, including the arms, trunk, pelvis, and knee. Participants are assigned an overall grade of the quality of movement based on the degree of observed deviations from normal. In persons with PFP, the LSD tends to produce dynamic knee valgus, including hip adduction and internal rotation (Earl et al., 2005). However, similar to the findings of studies relating strength to functional motion during the SLS or the FL, there is a lack of consensus regarding strength and performance during the LSD. In separate studies investigating hip strength and its relationship to medial deviation during a LSD, Rabin and Kozol (2010) and Rabin et al. (2014) showed that isometric hip abduction and external rotation strength were not related to medial deviation in either healthy participants or participants with PFP.

There currently is a lack of clear, consistent findings which explain kinematic deviations in individuals with PFP during the highlighted functional movements. Further investigation into muscle activation patterns during functional motion would help to more clearly define what is occurring in the lower extremities during functional activities in individuals with PFP. A comparison of muscle activity levels and activation patterns between healthy individuals and individuals with PFP would add to the current body of knowledge of this population and would allow for a better understand of the relationship between muscle activity and functional performance.

Muscle Activity During Functional Movement

Electromyography (EMG) has been used during weight bearing functional movements in an effort to better understand the complex interaction among synergists, agonists, and antagonists. This co-contraction of multiple muscles helps to regulate and refine movement (Baratta et al., 1988) and can have an impact on joint stability, sensory input, and reciprocal inhibition (Khanmohammadi et al., 2016). For example, the adductor longus and tensor fascia lata have been shown to co-activate along with the gluteus medius during gait to produce both motion and stability (Gottschall et al., 2012). Functional activities such as walking have been shown to exhibit characteristic activation patterns that are common from person to person during the task (Ivanenko et al., 2004). In addition, previous research has demonstrated variabilities in both magnitude and timing of muscle activity in pathological populations, such as those with osteoarthritis (Childs et al., 2004).

With regard to PFP, much of the previous EMG research that has been performed has focused on the muscle activity of the VMO and VL during functional motion. Researchers have attempted to determine the extent to which activity and timing pattern differences exist between individuals with PFP and those without. During a step-up task, Karst and Willet (1995) observed no difference in onset timing of either the VL or the VMO when comparing a group of participants with knee pain to pain-free control participants. Participants with PFP demonstrated no difference in either onset or cessation of muscle activity when compared to a non-symptomatic group. Similar findings were reported by Cavazzuti et al. (2010). In contrast, Cowan et al. (2001) observed timing differences between the VMO and the VL in a symptomatic group. The control group showed no such differences. The authors cited differences in sample size and in EMG methodology as key factors that might account for the difference in outcomes. Timing and activity ratios between the VMO and VL have also been investigated. In separate EMG studies, McClinton et al. (2007) and Sheehy et al. (1998) compared timing and activity ratios of the VMO relative to the VL during stair climbing tasks. No differences between symptomatic groups and healthy controls were found in either study. However, Souza and Gross (1991) reported lower ratios of VMO to VL activation in participants with unilateral PFP than healthy controls. In summary, the body of research that has been performed with regard to the activity patterns of the VMO and VL and their relationship to PFP is inconclusive. More recently, researchers have sought to describe hip muscle activity during functional movements and how such activity might be related to PFP.

Muscle Activity During Single-Leg Squat

Hip muscle activity during the SLS has been researched. In a study comparing muscle activity across four different muscle groups during various unilateral weight-bearing exercises, Ayotte et al. (2007) found that a unilateral wall squat produced the greatest amount of both gluteus maximus and gluteus medius activity in a healthy sample. A unilateral “mini-squat,” unsupported by the wall, produced the least amount of activity in the gluteus maximus and gluteus minimus compared to the other unilateral exercises tested. The authors concluded that because the “mini-squat” produced the least amount of recruitment, this functional activity might be more appropriate for earlier stages of exercise and rehabilitation. McCurdy et al. (2010) compared a unilateral squat to a traditional 2-legged squat and found that the unilateral squat produced greater gluteus medius activity when performed by female athletes. The authors concluded that the increased gluteus medius activity was related to the need to biomechanically stabilize the pelvis and to control resulting knee valgus.

Hip muscle activity during the SLS has also been examined in symptomatic groups, with conflicting findings. When comparing a group of individuals with PFP to a control group, gluteus medius activity did not differ during the SLS when compared to other functional activities (O'Sullivan et al., 2012). Different subdivisions of the gluteus medius responded differently during functional activities, but injury was not a determining factor. These findings are in contrast to the work of Nakagawa et al. (2012), who found that women with PFP exhibited less gluteus medius activity than women without PFP during a SLS. There was no difference in gluteus maximus activity between groups. The authors also concluded that future studies should examine gluteus medius and/or maximus onset timing, in an effort to understand the relationship between muscle activity patterns and kinematics of the hip and knee.

Although the gluteals are the primary stabilizers of the hip and pelvis during unilateral activities such as the SLS, their actions are not in isolation, but are instead in co-contraction with other muscles, such as the adductor longus. There has been limited research into the activity of the adductor longus during the SLS. Boudreau et al. (2009) measured muscle activity patterns in various muscles acting on the hip during a SLS and concluded that adductor longus activity levels were no greater during the SLS than in a lunge or a step-over exercise. However, the authors only examined the activity of the adductor longus in an asymptomatic group, so their findings cannot be generalized to a group of participants with PFP. Dwyer et al. (2010) compared average muscle activity of the gluteus maximus, gluteus medius, and adductor longus during a SLS between women and men, and found that only gluteus maximus activity was different between sexes during the SLS. Gluteus medius and adductor longus activity for women was no different during the SLS than for other exercises. However, this research involved a non-painful group of participants. In their discussion, the authors suggested further study be performed with regard to pathological populations. In summary, there has been limited research on hip muscle activity patterns during a SLS, especially in a symptomatic population. The findings of previous research are inconclusive. In addition, muscle activity in antagonist or synergist muscles such as the TFL or adductor longus has not been examined in a symptomatic population. Further research which examines such patterns in a symptomatic population is needed in order to better clarify the underlying cause of the problem.

While the SLS represents a motion that requires eccentric control of the hip, it does not allow the examiner to assess the quality of control that an individual has during forward motion. A forward lunge (FL) has been recommended as a functional motion that would permit such an assessment.

Muscle Activity During the Forward Lunge

Hip muscle activity occurring during a FL has not been as extensively studied as activity during other functional activities such as the SLS. In addition, the studies that have been performed have not included populations with PFP. Instead, researchers have sought to quantify the amount of muscle activity that occurs in a healthy population. Dwyer et al. (2010) compared hip muscle activity patterns between healthy men and women during a lunge, including the adductor magnus, gluteus medius, rectus femoris, and gluteus maximus. With the exception of gluteus maximus and rectus femoris activity levels, no between-sex differences were found. The authors concluded that the differences in activity levels may have been due to inherent strength differences that were noted between male and female participants. In addition, they recommended that further study on activity levels and patterns in an injured population be performed.

In a comparison of muscle activity patterns across different exercises, Ekstrom et al. (2007) concluded that, with respect to the gluteus medius and gluteus maximus, the FL did not produce an adequate stimulus to be considered appropriate for strength or endurance training. Regardless, this was in a non-PFP population. These findings are in general agreement with the work of Distefano et al. (2009), who used EMG to measure gluteus medius and gluteus maximus activity in healthy participants during functional activities, including a FL. The authors found that gluteus medius activity during the FL was in the “lower tier” of activity levels across the exercises examined. Gluteus maximus activation levels for the FL did not fare much better. The authors theorized that the decreased muscle activity was due in part to the closed-chain nature of the functional motion. In keeping with the recommendations of previous authors, the authors continued to recommend work with pathological populations. In summary, research regarding hip muscle activity during the FL is limited, and is not generalizable to a population with PFP. Further research into hip muscle activity during a lunge in individuals with PFP would help to clarify the nature of the disorder. In addition to the previously mentioned functional motions, the lateral step-down can also be used as a functional movement assessment in individuals with PFP.

Muscle Activity During Lateral Step Down

In general, there seems to be a lack of research dedicated to quantifying and describing muscle activity during the lateral step down (LSD). In addition, there is little research on muscle activity in the LSD compared to other functional movements, such as the single-leg squat or the forward lunge.

Much of the focus regarding muscle activity has been on determination of the level of activity in the VMO and VL. Less emphasis has been placed on trying to determine activity in the hip musculature. Saad et al. (2011) studied the total muscle activity in the VMO, vastus lateralis obliquus (VLO), and vastus lateralis longus (VLL) as well as in the gluteus medius, although this was during both a forward step up and step down versus a LSD. The authors found that the symptomatic group presented with generalized reductions in average muscle activity in all the muscles studied during both the step up and step down. They determined that a muscle imbalance did not exist in the vastii. Instead, widespread reduction in peak muscle activity as a whole was noted, especially in the step-down, for individuals with PFP. There have also been findings of delayed muscle activity onset and shortened activity durations during both stair ascent and descent in people with anterior knee pain (Brindle et al., 2003). However, again, these data were not obtained during a LSD, but instead during a forward stair ascent and descent. In addition, the authors did not assess the relationship between hip muscle activity and hip motion during the stepping activities, and the only hip muscle studied was the gluteus medius. In a review of the literature, only one author studied the LSD. Earl et al. (2005) studied muscle activity patterns during a LSD in both male and female participants with patellofemoral pain and compared them to a healthy control group. The authors investigated whether muscle activity patterns accurately predicted the presence of PFP. Although the authors did examine the timing aspect of muscle activity, this was done with regard to foot contact with the floor during the LSD, not with regard to the nature of muscle activity patterns throughout the range of motion at the hip. They concluded that muscle activity onset times in both the hip and quadriceps musculature were poor indicators of PFP. In addition, the authors stated in their conclusion that a better understanding of the relationship between motion and neuromuscular function is needed. In summary, although the LSD has been used as a functional motion that helps to identify the kinematics that are consistent with PFP, there is little research into EMG patterns of agonists or antagonists during the LSD.

In conclusion, with regard to muscle activity patterns during functional activities, it is possible that the femoral deviations that are characteristic of PFP – femoral adduction and internal rotation – are not only the result of decreased activity of those muscles that act eccentrically to stabilize the femur (gluteus medius and maximus), but also a result of altered activity patterns of the muscles that would cause increased adduction and internal rotation – specifically the tensor fascia lata and adductors of the hip. However, little to no research has been performed in an effort to determine this. In order to improve understanding of the strength, functional, and muscle activity profile of people with PFP, further investigation into muscle activity patterns during functional activities is warranted.

Conclusion

Although PFP is a common problem, there continues to be a lack of understanding regarding how factors such as muscular strength and activity contribute to the condition. Previous research has focused on factors in close proximity to the patella, such as Q-angle and quadriceps strength. However, more recent thought regarding causative factors has emphasized proximal control of the hip and the subsequent effect on the patella. Although muscle imbalances have been proposed as a possible factor in the development of PFP, there is a lack of research on hip muscle strength ratios in women with PFP, and no researcher has sought to define a functional strength ratio of agonists and antagonists that act on the hip. In addition to objective measurements of muscle strength and establishment of strength ratios, functional movements such as a forward lunge, a lateral step-down, or a single-leg squat can allow the researcher to look for possible differences in muscle activity patterns between a PFP group and a non-PFP group. An understanding of muscle activity characteristics during functional activities in women with PFP might allow for a more thorough understanding of the nature of the problem and the development of more effective rehabilitation programs in this population. Further research is justified in order to better define and describe hip muscle strength ratios as well as muscle activity patterns in women with PFP.

CHAPTER III

DIFFERENCES IN HIP STRENGTH FUNCTIONAL RATIOS IN WOMEN WITH PATELLOFEMORAL PAIN VERSUS WOMEN WITHOUT PATELLOFEMORAL PAIN

Introduction

Patellofemoral pain (PFP) is described as generalized knee pain, located behind the patella or along the medial and/or lateral borders of the patella (Brechter & Powers, 2002; Ireland et al., 2003; Malek & Mangine, 1981). It is more common in women (Boling et al., 2010; Dehaven & Lintner, 1986; Taunton et al., 2002), with incidence rates as high as 25% (Clement et al., 1981) in some populations. Patellofemoral pain has been shown to negatively impact quality of life (Rathleff et al., 2013), participation in work, and leisure physical activity (Piva et al., 2009).

While the etiology of PFP is not fully understood (Grelsamer et al., 2009), Q-angle (Messier et al., 1991; Silva et al., 2015), muscle weakness (Anderson & Herrington, 2003; Yosmaoglu et al., 2013), and altered muscle activity (Sakai et al., 2000; Sheehan et al., 2012; Voight & Wieder, 1991) are factors associated with the disorder. Additionally, studies have focused on hip muscle weakness and how subsequent excessive femoral internal rotation during weight bearing movements may be associated with PFP (Souza & Powers, 2009). This rotation can increase the dynamic Q-angle and thus increase contact pressure along the lateral patellar borders (Powers, 2003). Although the relationship between hip strength and PFP is well established, a more thorough understanding of the relationship between hip muscle agonists and antagonists and the impact on PFP would provide further insight into the nature of the problem.

A muscle strength imbalance, in which an agonist is stronger than an antagonist (Sahrmann, 1987), can impact joint movement patterns and contribute to PFP (Baldon et al., 2009). However, the limited research into hip muscle strength ratios in people with PFP has produced contrasting findings (Finnoff et al., 2011; Magalhaes et al., 2013). In most studies where agonist and antagonist relationships are evaluated, a concentric-to-concentric strength ratio is used. However, a concentric-to-eccentric (functional) ratio (Aagaard et al., 1998) has been proposed as an additional measure that offers a more thorough description of muscular strength properties at a joint (Aagaard et al., 1995).

To the authors' knowledge, no previous research has identified differences in functional ratios of hip strength in females with PFP. Therefore, the purpose of this research study was to measure mean and peak concentric and eccentric hip strength values in women with PFP and determine whether females with PFP exhibited differences in functional hip strength ratios compared to those without PFP. Because PFP typically presents with excessive femoral adduction and internal rotation, it was hypothesized that the functional ratios of concentric abduction to eccentric adduction strength and concentric internal rotation strength to eccentric external rotation strength would be lower in those with PFP.

Methods

Participants

Adult females ($N = 19$, age 20.07 – 45.43 years) were recruited from the local community. Participants were excluded from the study if they had a history of patellar dislocation or patellofemoral joint surgery. In addition, if the individual exhibited signs or symptoms of meniscal or articular pathology, collateral or cruciate ligament involvement, patellar tendonitis, iliotibial band or pes anserine tendon tenderness, patellar apprehension sign, hip pain, back pain, sacroiliac joint pain, or knee joint effusion, she was excluded from the study (Cichanowski et al., 2007; Crossley et al., 2002).

For inclusion in the experimental group, participants had to have self-reported anterior or retropatellar pain during at least two of the following activities: Squatting, prolonged sitting, kneeling, ascending stairs, descending stairs, hopping, running, or jumping. The onset of symptoms had to be unrelated to an injury or trauma and present for at least 4 weeks. Additional criteria to be included in the experimental group included pain provoked during a 20.3-cm step descent, during a double-legged squat, or with palpation of the patellar facets (Baldon et al., 2009; Cowan et al., 2002; Crossley et al., 2002). For inclusion in the control group, participants had to have no self-reported anterior or retro-patellar pain. In addition, each experimental group participant had to be matched with a control group participant with respect to age (+/- 2.5 years). This study was approved by the University Institutional Review Board (see Appendix A) and all participants signed an informed consent document prior to screening.

Instrumentation

Isokinetic Dynamometer. Concentric and eccentric hip abduction, adduction, external rotation, internal rotation, flexion, and extension were measured using an isokinetic dynamometer (Biodex System 3, Biodex Medical Systems, Shirley, NY).

Procedures

Participants signed the informed consent form and were screened for exclusion criteria. Following this, participants were screened for inclusion criteria and age was recorded. Inclusion criteria were assessed using a self-report of pain symptoms with functional activities. All testing procedures were performed by a physical therapist with more than 20 years' experience in evaluating musculoskeletal problems. If self-reported criteria were met, the participant then performed a counterbalanced screening, during which the researcher assessed pain in the symptomatic knee with a step-down task, during a squat, and with palpation of the medial and lateral patellar facets. For the step down test, the participant stood on a 20.3-cm wooden step with feet shoulder width apart. She was then asked to step forward to the floor, stepping onto her unaffected side. For the double leg squat assessment, the participant was asked to stand with feet shoulder width apart, slowly squat to a 45.7-cm high plastic chair, and then return to standing. Palpation of the medial and lateral patellar facets was performed by the researcher with the participant in a supine position. Following completion of all inclusion criteria screening and testing, participant height was assessed to the nearest 0.1 cm using a stadiometer (SECA Corporation, Model 222, Hamburg, Germany) and body mass was measured to the nearest 0.1 kg using a digital scale (Tanita Corporation, Model BF-522, Arlington Heights, IL).

Participants then proceeded with isokinetic testing on a Biodex System 3 isokinetic dynamometer, which was calibrated on each day of use in accordance with the manufacturer's recommendations. Prior to testing, each participant completed a 5-minute submaximal warm up (1/2 kp, 50 rpm) on a cycle ergometer (Monark Ergomedic 828e, Monark Exercise AB, Vansbro, Sweden). Tests were performed in groups according to testing positions, such as seated or standing. However, the order of groups was randomized. Prior to each testing series, neutral joint angle was confirmed using a goniometer. The limb was then weighed using the Biodex System 3 in accordance with the manufacturer instructions.

Participants performed a series of ten reciprocal concentric and eccentric voluntary contractions to become familiar with assessment procedures. Following familiarization, a 3-minute rest period was provided. Participants performed two sets of five repetitions of reciprocal maximal concentric and eccentric voluntary contractions, with a 3-minute rest period between sets. Torque was measured, filtered, and windowed at 30°/s in a reciprocal manner for each plane of movement (Boling et al., 2009; Claiborne et al., 2006; Donatelli et al., 1991; Lindsay et al., 1992). It has been noted that peak torque values are generally unchanged between angular velocities of 0°/s and 60°/s, after which time a linear decline in torque is seen with increasing angular velocity (Kannus, 1994; Perrin, 1993). The testing protocol was the same for all testing positions.

External/Internal Rotation Testing Position. Unilateral testing of eccentric and concentric hip external rotation and internal rotation were performed in the seated position (Boling et al., 2009; Kollock et al, 2013). The participant's thigh and pelvis were stabilized with straps to prevent muscular compensation during testing. The participant's knee was flexed to 90 degrees, after which the dynamometer's axis of rotation was positioned in front of the knee, centered through the long axis of the participant's femur. The lever arm of the dynamometer was then secured to the participant's lower leg, 5 cm proximal to the lateral malleolus.

Abduction/Adduction Testing Position. Unilateral testing of eccentric and concentric hip abduction and adduction was performed in the standing position, with the participant standing on the non-tested leg. This position has been used in previous research (Kollock et al, 2013). To determine the participant's axis of hip rotation, a line was projected from the greater trochanter towards the midline of the body, and another line was projected from the posterior superior iliac spine towards the popliteal fossa of the knee. The dynamometer's axis of rotation was then aligned at this point. The dynamometer's lever arm was then secured to the leg being tested, 5 cm proximal to the superior pole of the patella.

Flexion/Extension Testing Position. Unilateral testing of eccentric and concentric hip flexion and extension were performed in the standing position. The tested hip was closest to the dynamometer. The dynamometer's axis of rotation was aligned with the participant's greater trochanter. The dynamometer's lever arm was secured to the thigh, 5 cm proximal to the lateral joint line between the tibia and the femur.

Data Reduction

After data collection, all data values were compiled in a Microsoft Excel spreadsheet for data reduction. Mean and peak values for concentric and eccentric torque were determined for each plane of movement. Following determination of mean and peak torque values, functional torque ratios for agonist/antagonist groups were calculated.

Statistical Analysis

Independent samples *t* tests were used to compare mean and peak torque values for all measured planes of movement. Additionally, three independent samples *t* tests were used to compare functional ratio values of hip abduction/hip adduction, hip external rotation/internal rotation, and hip extension/flexion between groups. An alpha level of .05 was used for all statistical procedures. Effect sizes for all analyses were calculated using Hedges *g*.

Results

Descriptive statistics for participant characteristics of body mass, height, and age appear in Table 1. For measures of isokinetic strength, there were no statistically significant findings. Significant findings were found when examining functional strength ratios (see Tables 2 – 5). Women with PFP were found to have a significantly greater ratio of peak concentric abduction to eccentric adduction strength ($p = .04$, $g = -0.99$).

Discussion

In this study, concentric and eccentric hip strength in women with PFP was compared to women without PFP. Secondly, the functional hip strength ratios for agonist/antagonist muscle groups were calculated. Women with PFP were found to have a greater ratio of peak concentric abduction to eccentric adduction strength ($p = .04$, $g = -0.99$). These findings refute the researchers' hypothesis regarding functional strength ratios.

Previous authors (Boling et al., 2009; Boling & Padua, 2013, Nakagawa et al., 2011) have documented an association between hip abduction and external rotation strength deficits and the presence of symptoms or kinematics related to the problem. Isokinetic dynamometry has been used to measure concentric and eccentric hip strength, and in numerous previous studies, concentric and/or eccentric strength deficits of the abductors and external rotators have been found in persons with PFP. These deficits were associated with faulty kinematics and pain symptoms associated with PFP. However, abduction and external rotation deficits are not unique to PFP. They are also associated with other pathologies at the knee, such as tibio-femoral or patellofemoral osteoarthritis (OA). For example, Costa et al. (2010) used isokinetic dynamometry to investigate

Table 1

Descriptive Statistics for Study Groups

	Experimental		Control	
	M	*SD*	*M*	*SD*
Age (years)	23.02	± 4.46	24.81	± 7.62
Height (cm)	163.91	± 6.92	163.67	± 5.76
Weight (kg)	66.06	± 8.50	65.07	± 10.58

Table 2

Comparisons of Concentric and Eccentric Mean Torque

	Experimental		Control				
Movement	*M*	*SD*	*M*	*SD*	*t*	*p*	*g*
Concentric							
CONAB	45.92	± 13.17	37.73	± 9.93	-1.54	.14	-0.68
CONAD	52.96	± 16.92	56.78	± 21.12	0.43	.67	0.19
CONEX	92.63	± 28.18	81.89	± 18.29	-1.00	.33	-0.44
CONFL	47.17	± 15.24	47.64	± 15.59	0.95	.07	0.03
CONER	27.28	± 6.62	33.11	± 5.58	2.08	.05	0.91
CONIR	48.57	± 16.47	51.99	± 11.91	0.52	.61	0.23
Eccentric							
ECCAB	32.56	± 17.36	41.17	± 13.16	1.23	.24	0.54
ECCAD	32.65	± 15.90	44.20	± 19.98	1.38	.19	0.61
ECCEX	35.47	± 17.33	31.24	± 14.91	-0.57	.58	0.48
ECCFL	34.89	± 18.55	47.95	± 13.93	1.75	.10	-0.25
ECCER	23.92	± 4.74	27.36	± 8.25	1.09	.29	0.77
ECCIR	42.39	± 14.48	44.15	± 16.67	0.25	.81	0.11

Note. CONAB = concentric abduction, CONAD = concentric adduction, CONIR = concentric internal rotation, CONER = concentric external rotation, CONFL = concentric flexion, CONEX= concentric extension, ECCAB = eccentric abduction, ECCAD = eccentric adduction, ECCIR = eccentric internal rotation, ECCER = eccentric external rotation, ECCFL = eccentric flexion, ECCEX = eccentric extension; *df = 17.*

Table 3

Comparisons of Concentric and Eccentric Peak Torque

	Experimental		Control				
Movement	*M*	*SD*	*M*	*SD*	*t*	*p*	*g*
Concentric							
CONAB	61.85	± 15.26	53.56	±14.70	-1.21	.24	-0.53
CONAD	71.26	± 21.63	75.16	±24.49	0.37	.72	0.16
CONEX	117.90	± 30.89	103.23	±21.68	-1.22	.24	-0.53
CONFL	68.02	± 15.45	67.43	±19.73	-0.07	.94	-0.03
CONER	38.39	± 8.99	47.61	±10.55	2.04	.06	0.90
CONIR	69.30	± 21.55	70.29	±17.82	0.11	.91	0.05
Eccentric							
ECCAB	49.87	± 18.57	56.31	±15.56	0.82	.42	0.36
ECCAD	52.65	± 20.09	64.67	±22.66	1.22	.24	0.53
ECCEX	62.27	± 22.99	55.45	±17.22	-0.74	.47	-0.32
ECCFL	56.88	± 26.30	70.14	±21.14	1.22	.24	0.53
ECCER	33.17	± 5.61	41.51	±11.44	2.05	.06	0.87
ECCIR	60.34	± 19.90	63.74	±21.11	0.36	.72	0.16

Note. CONAB = concentric abduction, CONAD = concentric adduction, CONIR = concentric internal rotation, CONER = concentric external rotation, CONFL = concentric flexion, CONEX = concentric extension, ECCAB = eccentric abduction, ECCAD = eccentric adduction, ECCIR = eccentric internal rotation, ECCER = eccentric external rotation, ECCFL = eccentric flexion, ECCEX = eccentric extension; *df = 17.*

Table 4

Comparisons of Mean Functional Ratios

	Experimental		Control				
Movement Tested	*M*	*SD*	*M*	*SD*	*t*	*p*	*g*
CONAB/ECCAD	1.79	± 1.24	0.96	± 0.33	-2.03	.06	-0.89
CONAD/ECCAB	3.00	± 4.15	1.70	± 1.54	-0.93	.37	-0.41
CONIR/ECCER	2.02	± 0.49	2.00	± 0.54	-0.11	.92	-0.05
CONER/ECCIR	0.69	± 0.23	0.85	± 0.34	1.13	.28	0.49
CONFL/ECCEX	4.50	± 7.59	1.02	± 0.33	-1.37	.21	-0.64
CONEX/ECCFL	6.34	± 8.83	1.80	± 0.53	-1.54	.16	-0.71

Note. CONAB/ECCAD = ratio of average concentric abduction to average eccentric adduction, CONAD/ECCAB = ratio of average concentric adduction to average eccentric abduction, CONIR/ECCER = ratio of average concentric internal rotation to average eccentric external rotation, CONER/ECCIR = ratio of average concentric external rotation to average eccentric internal rotation, CONFL/ECCEX = ratio of average concentric flexion to average eccentric extension, CONEX/ECCFL = ratio of average concentric extension to average eccentric flexion; *df = 17.*

Table 5

Comparisons of Peak Functional Ratios

	Experimental		Control				
Movement Tested	*M*	*SD*	*M*	*SD*	*t*	*p*	*g*
CONAB/ECCAD	1.32	± 0.57	0.87	± 0.25	-2.25	.04*	-0.99
CONAD/ECCAB	1.70	± 1.19	1.46	± 0.84	-0.50	.62	-0.22
CONIR/ECCER	2.07	± 0.45	1.74	± 0.39	-1.69	.11	-0.74
CONER/ECCIR	0.67	± 0.18	0.79	± 0.19	1.37	.19	0.60
CONFL/ECCEX	1.21	± 0.44	1.24	± 0.24	0.18	.86	0.08
CONEX/ECCFL	2.69	± 1.69	1.56	± 0.49	-1.92	.09	-0.93

Note. CONAB/ECCAD = ratio of average concentric abduction to average eccentric adduction, CONAD/ECCAB = ratio of average concentric adduction to average eccentric abduction, CONIR/ECCER = ratio of average concentric internal rotation to average eccentric external rotation, CONER/ECCIR = ratio of average concentric external rotation to average eccentric internal rotation, CONFL/ECCEX = ratio of average concentric flexion to average eccentric extension, CONEX/ECCFL = ratio of average concentric extension to average eccentric flexion; *df = 17, * = p < .05* concentric hip strength in persons with knee OA and found a correlation between decreased hip strength and the presence of the pathology. Additional research has been carried out in individuals with patellofemoral OA. In a study where isokinetic dynamometry was used to assess eccentric hip strength, Carvalho et al. (2021) found people with patellofemoral OA exhibited deficiencies in peak torque in multiple planes of motion at the hip, including hip eccentric hip abduction. While the current study did not find any statistical difference between the groups in concentric and eccentric strength measures, there were notable differences in mean and peak torque as indicated by the medium and large effect size estimates (Cohen, 1992), particularly in the external rotation measures. The low sample size of the current exploratory study may have contributed to the findings.

Previous researchers have used muscle strength ratios to quantify agonist/antagonist muscle imbalances to determine the extent to which muscle strength imbalances exist in persons with PFP. Assessments have been conducted with hand-held dynamometry (HHD) and isokinetic dynamometers. Magalhaes et al. (2013) used HHD to establish isometric hip strength ratios in women with PFP. The women with PFP showed a higher adduction to abduction ratio than healthy controls. The authors concluded frontal plane muscle imbalances are a common kinematic tendency in the pathology. Finnoff et al. (2011) also used HHD to establish isometric strength ratios. Like the work of Magalhaes et al. (2013), they found a lower external rotation to internal rotation ratio in persons who tended to develop PFP. However, they also found persons with a higher abduction to adduction ratio tended to develop PFP. They theorized that anthropometric factors as well as weakness of prime movers of the hip could have been related to abduction to adduction findings. Only Baldon et al. (2009) have used eccentric strength values to establish strength ratios in women with PFP. In their research, women with PFP had a higher eccentric hip adduction to hip abduction ratio than those without PFP and they theorized this could help control hip rotation in women with PFP. In the current study, women with PFP had a higher ratio of concentric abduction strength to eccentric adduction strength than those without PFP.

This primary outcome of a higher functional strength ratio of concentric abduction to eccentric adduction in women with PFP conflicts with some previous findings (Baldon et al., 2009; Magalhaes et al, 2013) but is like others (Finnoff et al., 2011). In the work by Finnoff et al., it was suggested that people with PFP may have increased recruitment of the gluteus medius over time in response to weakening of the deep external rotators of the hip. This long-term recruitment of the gluteus medius could be a possible explanation for increased strength values during testing. Additionally, Finnoff et al. (2011) noted the PFP group had a higher weight, which could have, in turn, increased the hip adduction moment during stance and gait. As a result, the participants with PFP developed stronger hip abductors to compensate. If this is considered, this could explain the results of the current investigation where external rotation strength was decreased in the PFP group, although not reaching the threshold of significance. This trend towards decreased strength is consistent with the rationale presented by Finnoff et al. (2011). However, in the current study, strength measures were not normalized for body mass, and so no conclusions can be made regarding mass-normalized torque values.

The functional strength ratio was originally proposed to evaluate the eccentric function of the hamstrings and their ability to provide dynamic stability during fast, forceful extension of the knee (Aagard et al, 1998). However, significant differences exist between the functional characteristics of the knee and the femur. In turn, there are significant differences in how dynamic stability would manifest at the knee when compared to the hip. The biomechanical model that is used to explain what is occurring at the knee with PFP is one that proposes the “dynamic valgus” that occurs during stance (Powers, 2003; Souza et al., 2010). This dynamic valgus is a result of a combination of adduction and internal rotation of the femur during stance. It is important to understand the biomechanical nature of both eccentric and concentric contractions and how they stabilize the pelvis and femur during movement (Boling et al., 2009). However, the use of a “single plane” functional ratio to define muscle imbalances and their effect on PFP might not be the most appropriate application. Previous researchers have investigated a conventional strength ratio in a PFP population between the anteromedial complex and the posterolateral complex (Magalhaes et al., 2013). Research into a functional ratio between these two complexes might provide a better understanding of the nature of the combined effect of multiple planes of eccentric and concentric contractions

One limitation of the current study is that obtained torque values were not normalized for participant body mass. Although the groups were not significantly different regarding body mass, it is possible that normalizing average and peak torque for body mass may provide an improved measure of force generation. This is important to note because several of the torque values were approaching significance but did not rise to the threshold of statistical significance. In addition, in the current study, kinematics were not examined, and so no determination can be made regarding possible correlations between strength measures and biomechanical differences between the groups. Finally, although inclusion criteria for this study were similar to criteria used in previous research (Baldon et al., 2009; Crossley et al., 2002), PFP remains a problem that is not easily quantifiable, such as osteoarthritis, chondromalacia, or meniscal tears. Instead, the classification and diagnosis of the problem relies on the history of the individual.

The agonist/antagonist ratio has been proposed to quantify dynamic stability (Aagaard et al., 1995), and previous works have emphasized the importance of maintaining a 1:1 ratio between agonists and antagonists (Magalhaes et al., 2013). If the 1:1 ratio is considered indicative of more dynamic stability, then current results indicate the PFP group has an imbalance between the two directions, regardless of which direction of movement is stronger. The assumption may be that the PFP group is better able to keep the knee from going into valgus. However, if external rotation strength is considered, the control group was stronger in both concentric and eccentric peak external rotation, in results that were close to reaching the threshold of significance. The results of the current study may instead indicate persons with PFP tend to recruit that muscle, habitually, as a strategy to counteract either adduction or internal rotation during function (Finnoff et al., 2011). If this is a possibility, then strengthening exercises integrated with functional training that emphasize dynamic stability and improved co-contraction during weight acceptance and load transfer during gait may be of benefit.

Conclusions

This exploratory investigation of the functional ratio indicates that women with PFP exhibit a possible imbalance between concentric abduction strength and eccentric abduction strength. The presence of an abnormally high or low strength ratio may be indicative of a strategy to compensate for biomechanical anomalies during function.

Further investigation into this functional ratio and its association with kinematic or biomechanical properties in people women PFP would help to improve the understanding of this condition and how it manifests in women.

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APPENDICES FOR CHAPTER III

IRB
INSTITUTIONAL REVIEW BOARD
Office of Research Compliance,

010A Sam Ingram Building, 2269 Middle Tennessee Blvd

Murfreesboro, TN 37129

FWA: 00005331/IRB Regn. 0003571

IRBN001 - EXPEDITED PROTOCOL APPROVAL NOTICE

Wednesday, October 14, 2020

Protocol Title	***Strength and Muscle Activation Profiles of Women inPatellofemoral Pain***
Protocol ID	**21-2043 4i (19-2114)**
Principal Investigator	**David Clark** (Student)
Faculty Advisor	John Coons
Co-Investigators	Sarah Martinez
Investigator Email(s)	*david.clark@mtsu.edu; john.coons@mtsu.edu*
Department	Health and Human Performance (Exercise Science)
Funding	**NONE**

Dear Investigator(s),

The above identified research proposal has been reviewed by the MTSU IRB through the **EXPEDITED** mechanism under 45 CFR 46.110 and 21 CFR 56.110 within the category *(4) Collection of data through noninvasive procedures*. A summary of the IRB action is tabulated below:

IRB Action	**APPROVED for ONE YEAR**		
Date of Expiration	**10/31/2021**	*Date of Approval*: 10/14/20	*Recent Amendment*: NONE
Sample Size	ONE HUNDRED (100)		
Participant Pool ☐	*Target Population:* Primary Classification: **General Adults (18 or older)** Specific Classification: **Female adults**		
Type of Interaction	Virtual/Remote/Online interaction ☒ **In person or physical interaction – Mandatory COVID-19 Management**		
Exceptions	In person interactions without social distancing is permitted for data collection (actualdescription on file and provided in the informed consent tempalte)		
Restrictions	**1. Mandatory SIGNED Informed Consent.** **2. Other than the exceptions above, identifiable data/artifacts, such as, audio/video data, photographs, handwriting samples, personal address, drivingrecords, social security number, and etc., MUST NOT be collected.** **3. Mandatory Final report (refer last page).** **4. CDC guidelines and MTSU safe practice must be followed**		
Approved Templates	*IRB Templates:* Informed Consent, Recruitment Email and IRB Flyer *Non-MTSU Templates:* Verbal recruitment script		
Research Inducement	NONE		
Comments	NONE		

Post-approval Requirements

The PI and FA must read and abide by the post-approval conditions (Refer "*Quick Links*" in the bottom):

- ***Reporting Adverse Events:*** The PI must report research-related adversities suffered by the participants, deviations from the protocol, misconduct, and etc., within 48 hours from when they were discovered.
- ***Final Report:*** The FA is responsible for submitting a final report to close-out this protocol before **10/31/2021** **(Refer to the Continuing Review section below)**; REMINDERS WILLNOT BE SENT. **Failure to close-outor request for a continuing review may result in penalties** including cancellation of the data collected using this protocol and/or withholding student diploma.
- ***Protocol Amendments***: An IRB approval must be obtained for all types of amendments, such as: addition/removal of subject population or investigating team; sample size increases; changes to the research sites (appropriate permission letter(s) may be needed); alternation to funding; and etc. The proposed amendments must be requested by the FA in an addendum request form. The proposed changes must be consistent with the approval category and they must comply with expedited review requirements
- ***Research Participant Compensation:*** Compensation for research participation must be awarded as proposed in Chapter 6 of the Expedited protocol. The documentation of the monetary compensation must Appendix J and MUST NOT include protocol details when reporting to the MTSU Business Office.
- ***COVID-19:*** Regardless whether this study poses a threat to the participants or not, refer to the COVID-19 Management section for important information for the FA.

Continuing Review (The PI has requested early termination)

Although this protocol can be continued for up to THREE years, The PI has opted to end the study by **10/31/2021**

The PI must close-out this protocol by submitting a final report before 10/31/2021 Failure to close-out may result in penalties that include cancellation of the data collected using this protocol and delays in graduationof the student PI.

Post-approval Protocol Amendments:

The current MTSU IRB policies allow the investigators to implement minor and significant amendments that would fitwithin this approval category. ***Only TWO procedural amendments will be entertained per year*** *(changes like addition/removal of research personnel are not restricted by this rule).*

Date	**Amendment(s)**	**IRB Comments**
NONE	NONE.	NONE

Other Post-approval Actions:

The following actions are done subsequent to the approval of this protocol on request by the PI/FA or onrecommendation by the IRB or by both.

Date	**IRB Action(s)**	**IRB Comments**
NONE	NONE	NONE

COVID-19 Management:

The PI must follow social distancing guidelines and other practices to avoid viral exposure to the participants andother workers when physical contact with the subjects is made during the study.

- The study must be stopped if a participant or an investigator should test positive for COVID-19 within 14 daysof the research interaction. This must be reported to the IRB as an “adverse event.”
- The MTSU’s “Return-to-work” questionnaire found in Pipeline must be filled by the investigators on the dayof the research interaction prior to physical contact.
- PPE must be worn if the participant would be within 6 feet from the each other or with an investigator.
- Physical surfaces that will come in contact with the participants must be sanitized between use
- **FA’s Responsibility:** The FA is given the administrative authority to make emergency changes to protect the wellbeing of the participants and student researchers during the COVID-19 pandemic. However, the FAmust notify the IRB after such changes have been made. The IRB will audit the changes at a later date andthe FA will be instructed to carryout remedial measures if needed.

Data Management & Storage:

All research-related records (signed consent forms, investigator training and etc.) must be retained by thePI or the faculty advisor (if the PI is a student) at the secure location mentioned in the protocol application.

The data must be stored for at least three (3) years after the study is closed. Additional Tennessee Statedata retention requirement may apply (*refer "Quick Links" for MTSU policy 129 below*). The data may be destroyed in a manner that maintains confidentiality and anonymity of the research subjects.

The MTSU IRB reserves the right to modify/update the approval criteria or change/cancel the termslisted in this letter without prior notice. Be advised that IRB also reserves the right to inspect or audit your records if needed.

Sincerely,

Institutional Review Board

Middle Tennessee State University

IRB
INSTITUTIONAL REVIEW BOARD
Office of Research
Compliance,010A
Sam Ingram Building,
2269 Middle
Tennessee Blvd
Murfreesboro, TN
37129

IRBN001 - EXPEDITED PROTOCOL APPROVAL NOTICE

Wednesday, January 30, 2019

Principal Investigator	**David Clark** (Student)
Faculty Advisor	John Coons
Co-Investigators	Sarah Martinez
Investigator Email(s)	*david.clark@mtsu.edu;* *john.coons@mtsu.edu;* *sm9x@mtmail.mtsu.edu*
Department	Exercise Science, Health and Human Performance
Protocol Title	***Strength and muscle activation profiles of women inpatellofemoral pain***
Protocol ID	**19-2114**

Dear Investigator(s),

The above identified research proposal has been reviewed by the MTSU Institutional Review Board (IRB) through the **EXPEDITED** mechanism under 45 CFR 46.110 and 21 CFR 56.110 within the category *(4) Collection of data through noninvasive procedures*. A summary of the IRBaction and other particulars in regard to this protocol application is tabulated below:

IRB Action	**APPROVED for ONE YEAR**		
Date of Expiration	**1/31/2020**	Date of Approval	1/30/19
Sample Size	100 (ONE HUNDRED)		
Participant Pool	Primary Classification: **General Adults (18 years to 55 years old)** Specific Classification: **Female adults who self-report anterior or retropatelar pain of at least 3 on a 10cm visual analog scale (VAS)**		
Exceptions	Older version of informed consent template is permitted with restriction		
Restrictions	**1. Mandatory signed informed consent; the participants must have accessto an official copy of the informed consent document signed by the PI.** **2. Collection of identifiable information not permitted.** **3. Mandatory implementation of inclusion/exclusion criteria to screenpotentially risky participants**		
Comments	NONE		

This protocol can be continued for up to THREE years (**1/31/2022**) by obtaining a continuation approval prior to **1/31/2020**. Refer to the following schedule to plan your annual project reports and be aware that you may not receive a separate reminder to complete your continuing reviews.Failure in obtaining an approval for continuation will automatically result in cancellation of this protocol. Moreover, the completion of this study MUST be notified to the Office of Compliance byfiling a final report in order to close-out the protocol.

Post-approval Actions

The investigator(s) indicated in this notification should read and abide by all of the post-approvalconditions imposed with this approval. Refer to the post-approval guidelines posted in the MTSUIRB's website. Any unanticipated harms to participants or adverse events must be reported to the Office of Compliance at (615) 494-8918 within 48 hours of the incident. Amendments to this protocol must be approved by the IRB. Inclusion of new researchers must also be approved by the Office of Compliance before they begin to work on the project.

Continuing Review **(Follow the Schedule Below:)**

Submit an annual report to request continuing review by the deadline indicated below and please be aware that **REMINDERS WILL NOT BE SENT.**

Reporting Period	Requisition Deadline	IRB Comments
First year report	12/31/2019	This protocol is set to expire on 11/15/2019 as requested by the PI (Revised Expedited Application dated 01.22.2019) unless a continuing review isrequested by the PI before the date of expiration.
Second year report	12/31/2020	NOT COMPLETED
Final report	12/31/2021	NOT COMPLETED

Post-approval Protocol Amendments:

Only two procedural amendment requests will be entertained per year. *In addition, the researchers can request amendments during continuing review. This amendment restriction does not apply to minor changes such as language usage and addition/removal of research personnel. .*

Date	**Amendment(s)**	**IRB Comments**
NONE	NONE.	NONE

Other Post-approval Actions:

Date	**IRB Action(s)**	**IRB Comments**
NONE	NONE.	NONE

Mandatory Data Storage Requirement: All of the research-related records, which include signedconsent forms, investigator information and other documents related to the study, must be retained by the PI or the faculty advisor (if the PI is a student) at the secure location mentioned in the protocol application. The data storage must be maintained for at least three (3) years after study has been closed. Subsequent to closing the protocol, the researcher may destroy the data in a manner that maintains confidentiality and anonymity.

IRB reserves the right to modify, change or cancel the terms of this letter without prior notice. Be advised that IRB also reserves the right to inspect or audit your records if needed.

Sincerely,

Institutional Review Board
Middle Tennessee State University

CHAPTER IV

MUSCLE ACTIVITY COMPARISONS DURING FUNCTIONAL MOVEMENTS IN WOMEN WITH AND WITHOUT PATELLOFEMORAL PAIN

Introduction

Patellofemoral pain (PFP) is described as generalized knee pain located behind the patella or along its medial and/or lateral borders (Brechter & Powers, 2002; Ireland et al., 2003; Malek & Mangine, 1981). It is more common in women (Boling et al., 2010; Dehaven & Lintner, 1986; Taunton et al., 2002), with incidence rates as high as 25% (Clement et al., 1981) in some populations. The condition has been shown to negatively impact quality of life (Rathleff et al., 2013) and participation in work and physical activity. The etiology of PFP is not fully understood (Grelsamer et al., 2009), but impaired motor control (Anderson & Herrington, 2003; Yosmaoglu et al., 2013) is thought to be related to the disorder. Previous researchers have suggested that quadriceps weakness and decreased motor control contributes to PFP (Sakai et al., 2000; Sheehan et al., 2012; Voight & Wieder, 1991). More recent studies have focused on the hip musculature, specifically motor control issues and the resulting alterations in hip motion during functional movement (Nakagawa et al., 2012; Nakagawa et al., 2008).

Functional movement observations may be used to assess movement quality and identify deviations from desired kinematics (Clark et al., 2014). Such deviations are thought to be related to an unbalanced relationship among muscle groups (Clark et al., 2014), with some muscles being prone to inhibition and others susceptible to overuse and excessive activity (Janda, 1993; Sahrmann, 1987). Alterations in movements have been observed in persons with painful disorders (Childs et al., 2004; Messier et al., 1992;

Powers, 2003). Specifically, excessive adduction and internal rotation of the femur during weight bearing activities have been noted in persons with PFP. It has been suggested that these deviations increase the compressive forces along the lateral aspect of the patella (Powers, 2003), an etiological factor in PFP (Lee et al., 2003).

It is plausible that altered hip muscle activation patterns during functional movement may be associated with knee pain. Childs et al. (2004) showed individuals with arthritic knee pain had greater hamstring, gastrocnemius, tibialis anterior, and vastus lateralis co-activation values and greater duration of co-activation during functional movements compared to an asymptomatic group. In people with PFP, muscles that produce internal rotation and adduction, such as the adductor longus (AL) and tensor fascia lata (TFL), might be more active, while those that oppose these motions, such as the gluteus medius (GMED) and gluteus maximus (GMAX), might be less active.

To our knowledge, there has been little research on differences in muscle activity profiles during functional movements of agonist/antagonist groups or synergistic groups in women with PFP. As such, the purpose of this study was to determine whether women with PFP would exhibit a difference in muscle activity patterns during functional movements when compared to a control group. It was hypothesized that both average and peak muscle activity in the PFP group would differ from the control group.

Methods

Participants

Adult females (*N* = 21, age 19.63 – 44.16 years) were recruited from the local community. Participants were excluded from the study if they had a history of patellofemoral joint surgery or patellar dislocation. In addition, if the individual exhibited signs or symptoms of collateral or cruciate ligament involvement, meniscal or articular pathology, iliotibial band or pes anserine tendon tenderness, patellar tendonitis, patellar apprehension sign, back pain, hip pain, sacroiliac joint pain, or knee joint effusion, she was excluded from the study (Cichanowski et al., 2007; Crossley et al., 2002).

For inclusion in the experimental group, participants had to have self-reported anterior or retro-patellar pain during at least two of the following activities: kneeling, prolonged sitting, squatting, ascending stairs, descending stairs, jumping, hopping, or running. The onset of symptoms had to be unrelated to an injury or trauma and present for at least 4 weeks. Additional criteria to be included in the experimental group included pain provoked during a 20.3-cm step descent, during a double-legged squat, or with palpation of the patellar facets (Baldon et al., 2009; Crossley et al., 2002). For inclusion in the control group, participants had to have no self-reported anterior or retro-patellar pain. In addition, each experimental group participant had to be matched with a control group participant with respect to age (+/- 2.5 years). This study was approved by the university Institutional Review Board (see Appendix A) and all participants signed an informed consent document prior to beginning the screening.

Instrumentation

Electromyography. Muscle activity was measured using the Trigno electromyographic (EMG) wireless system (Delsys, Natick, MA). The system consists of wireless Trigno Flex electromyographic sensors, which were placed directly on the skin surface over the mid-muscle belly of the muscles that were assessed. Biplanar joint angle was measured using wireless goniometers (Biometrics, Newport, UK), which were also affixed to the skin with double-sided adhesive tape. Surface EMG (sEMG) data were managed using EMGworks software. These data were then integrated directly into the EMGworks software via wireless adapters provided by the manufacturer. An external trigger device (Delsys, Natick, MA) was used to initiate and terminate data collection.

Procedures

Participants signed the informed consent form and were screened for exclusion criteria. Following this, participants were screened for inclusion criteria and age was recorded. Inclusion criteria were assessed using a self-report of pain symptoms with functional activities. All testing procedures were performed by a licensed physical therapist with more than 20 years' experience in evaluating musculoskeletal problems. If self-reported criteria were met, the participant then performed a counterbalanced screening, during which the researcher assessed pain in the symptomatic knee with a step-down task, during a squat, and with palpation of the medial and lateral patellar facets. For the step-down test, the participant stood on a 20.3-cm wooden step with feet shoulder width apart. She was then asked to step forward to the floor, stepping onto her unaffected side. For the double leg squat assessment, the participant was asked to stand with feet shoulder width apart, slowly squat to a 45.7-cm high plastic office chair, and then return to standing. Palpation of the medial and lateral patellar facets was performed by the researcher with the participant in a supine position. Following completion of all inclusion criteria screening and testing, participant height was assessed to the nearest 0.1 cm using a stadiometer (SECA Corporation, Model 222, Hamburg, Germany) and body mass was measured to the nearest 0.1 kg using a digital scale (Tanita Corporation, Model BF-522, Arlington Heights, IL).

Participants were instructed to avoid application of topical skin lotion prior to testing. Prior to Trigno sensor and electronic goniometer sensor placement, if necessary, hair was shaved from all areas underlying sensor placement with a safety razor and then exfoliated with Redux paste. Sensors were affixed with double-sided adhesive tape to the skin over the mid-muscle belly of the GMED, GMAX, AL, and TFL (Hermens et al., 1999). Electronic goniometers were affixed to the lateral side of the body for measurement of hip and knee joint angles. Alignment landmarks were consistent with landmarks used for manual goniometry (Clarkson, 2000). For hip joint angle measurement, the proximal goniometer sensor was affixed over the lateral midline of the trunk. The distal measurement sensor was affixed over the lateral midline of the thigh, determined by a line drawn from the greater trochanter to the lateral femoral condyle. For knee joint angle measurement, the proximal goniometer sensor was affixed over the lateral midline of the thigh, and the distal goniometer sensor was affixed over the lateral tibia, determined by a line drawn from the fibular head to the lateral malleolus (Piriyaprasarth et al., 2008). The sensors were reinforced with stretch adhesive covering.

Maximal Voluntary Isometric Contraction. Functional movement EMG data were normalized to EMG generated during a maximal voluntary isometric contraction (MVIC) of respective muscles/muscle groups (Bolgla & Uhl, 2007). For each MVIC movement, participants were positioned to allow for maximal generation of force (Kendall et al., 1993). External resisting force was provided by the researcher. Participants performed one practice trial, followed by three MVIC trials for each movement. Instruction was given to the participant to build to a maximal level of force over a period of 2 to 3 seconds, after which time she was told to hold this maximal force against external pressure for 5 seconds. A 30-second rest was given between trials.

Adductor Longus. Establishment of the MVIC for the adductor longus was performed in the side lying position, with the participant lying on the side to be tested. The non-tested leg was most superior, and was positioned in flexion, abduction, and external rotation. The participant was instructed to flex, abduct, and externally rotate the opposite hip to allow space through which to adduct the tested leg (Magalhaes et al., 2010). The foot was placed on the surface of the testing table. The participant was instructed to then adduct the tested leg upward from the table. Pressure was given at the distal medial femur of the tested leg, downward towards the table, in the direction of abduction.

Gluteus Medius. Establishment of the MVIC for the gluteus medius was performed in the side lying position, with the participant lying on the non-tested side. The tested leg was most superior. The bottom leg was flexed at the hip to approximately 45 degrees. The participant was instructed to then abduct the tested leg upward from the table, positioning the leg in abduction, with slight extension and external rotation. Pressure was given at the lateral surface of the knee, in the direction of adduction and slight flexion.

Tensor Fascia Latae. Establishment of the MVIC for the TFL was performed in the supine position. The participant was instructed to hold on to the table for stabilization during testing. They were then told to flex, abduct, and internally rotate the tested leg. Pressure was given by the researcher toward the surface of the table, in the direction of extension and adduction malleolus.

Gluteus Maximus. Establishment of the MVIC for the gluteus maximus was performed in the prone position. The participant was instructed to bend the knee of the tested leg to approximately 90 degrees, and then lift the thigh upward, positioning the thigh in slight extension. Pressure was given by the researcher at the distal posterior thigh, toward the surface of the table, in the direction of flexion.

Functional Movements

Prior to each test, participants were permitted to practice each functional movement until the movement was performed in a stable, controlled fashion. For each test, participants were instructed to perform at least 5 repetitions, with a 1 min rest period between repetitions to prevent fatigue. A digital metronome with a beat frequency of 60 beats per minute was used for each functional movement to establish a consistent speed.

Single-leg Squat. Participants were instructed to stand with their feet shoulder width apart and with their hands on their hips. They were then told to assume a single-leg stance, flexing the non-tested knee to 90 degrees. Participants were instructed to perform a single-leg squat as far as comfortably possible while keeping their stance foot completely on the floor. Participants were instructed to slowly squat as far as possible over a two second period, then to return from the squat to the original stance position over a two second period, using the digital metronome to establish consistency in movement.

Lateral Step-Down. The lateral step-down was performed in a manner originally described by Piva et al. (2006). Participants were asked to stand on a 20 cm high step in a single-leg stance on the leg being tested, with hands on the waist and the knee straight. The non-symptomatic leg was positioned over the floor adjacent to the step, with the knee in extension. The participant was asked to bend the tested knee until the non-symptomatic foot gently contacted the floor and then re-extend the knee to the starting position.

Forward Lunge. The forward lunge was performed with the tested leg forward. Participants were instructed to first stand with feet placed adjacent to each other and hands on their hips. Participants then stepped forward with the tested leg to a point that equaled the distance from the anterior superior iliac spine to medial malleolus of the ankle. Maintaining hands on their hips, the participant was then instructed to lunge downward as far as possible, pause, and then return to full knee extension of the forward leg, concluding by returning to the starting position (Distefano et al., 2009; Dwyer et al., 2010).

Data Processing

Surface EMG data were initially processed using a 2nd order Butterworth band-pass filter at frequencies of 20Hz and 450Hz. These data were then smoothed using a root-mean-square (RMS) filter with a 125 ms window. Both average and peak muscle activity were obtained during five repetitions of each functional movement and then averaged to obtain a mean average and mean peak surface EMG signal for each movement. These were then normalized to the previously obtained MVIC values.

Statistical Analysis

Independent samples *t* tests were used to compare normalized mean average and peak muscle activity of the GMAX, GMED, TFL, and AL between the groups. Because the nature of this study was exploratory, the alpha level was not adjusted downwards to control for a potential Type-I error. An alpha level of .05 was used for all statistical procedures. Effect sizes for all analyses were calculated using Hedge's *g*.

Results

Descriptive statistics for participant characteristics of body mass, height, and age are contained in Table 1. Average muscle activity of the GMED, GMAX, and AL were not statistically different between females with and without PFP during performance of the forward lunge. However, average activity of the TFL was higher in females with PFP when compared to females without PFP during the descent phase (*p* = .010, *g* = -1.20*)*. Similar results were seen during the ascent phase of the forward lunge. Women with PFP demonstrated a higher average level of TFL activity when compared to women without PFP (*p* = .030, *g* = -0.99*)*. Peak activity of the TFL was higher in females with PFP when compared to females without PFP during the descent phase (*p* = .015, *g* = -1.13*)*. A similar pattern was seen during the ascent phase; peak TFL activity was higher in females with PFP when compared to women without PFP (*p* = .010, *g* = -1.22*)*. See Table 2.

During the lateral step down, average muscle activity of the TFL was higher in women with PFP than in women without PFP during the descent phase (*p* = .021, *g* = -1.94*)*. Average TFL activity was also higher in women with PFP compared to women without during the ascent phase of the motion (*p* = .022, *g* = -1.94). Finally, peak muscle activity of the TFL was higher in women with PFP when compared to women without PFP during the descent phase of the motion (*p* = .042, *g* = -1.80*)*. See Table 3.

During the single leg squat, similarly to the forward lunge and the lateral step down, there was no significant difference in muscle activity of the GMED, GMAX, or AL during either the descent phase or ascent phase. However, peak muscle activity of the

Table 1

Descriptive Statistics for Study Groups

	Experimental		Control	
	M	*SD*	*M*	*SD*
Age (years)	25.99	± 8.46	23.59	± 6.57
Height (cm)	167.43	± 5.29	161.46	± 11.39
Weight (kg)	71.08	± 12.22	67.70	± 10.29

Table 2

Average and Peak Muscle Activity During the Forward Lunge

	Experimental		Control				
Muscle Tested	*M*	*SD*	*M*	*SD*	*t*	*p*	*g*
Average Activity							
AL (D)	0.45	± 0.18	0.64	± 0.59	0.91	.37	0.39
AL (A)	0.49	± 0.22	0.70	± 0.58	1.01	.33	0.43
TFL (D)	0.29	± 0.10	0.18	± 0.08	-2.84	.01*	-1.20
TFL (A)	0.29	± 0.09	0.20	± 0.09	-2.35	.03*	-0.99
GMED (D)	0.24	± 0.25	0.19	± 0.14	-0.53	.60	-0.22
GMED (A)	0.39	± 0.40	0.24	± 0.15	-1.23	.24	-0.52
GMAX (D)	0.13	± 0.08	0.14	± 0.09	0.49	.63	0.21
GMAX (A)	0.23	± 0.13	0.22	± 0.12	-0.22	.83	-0.09
Peak Activity							
AL (D)	1.01	± 0.43	1.15	± 0.75	0.50	.62	0.21
AL (A)	0.95	± 0.43	1.21	± 0.71	0.99	.33	0.42
TFL (D)	0.67	± 0.25	0.40	± 0.22	-2.66	.02*	-1.13
TFL (A)	0.65	± 0.20	0.41	± 0.19	-2.88	.01*	-1.22
GMED (D)	0.48	± 0.55	0.29	± 0.17	-1.14	.27	-0.48
GMED (A)	0.71	± 0.89	0.35	± 0.20	-1.36	.19	-0.58
GMAX (D)	0.27	± 0.19	0.24	± 0.13	-0.32	.75	-0.14
GMAX (A)	0.39	± 0.20	0.33	± 0.17	-0.73	.47	-0.31

Note. AL = adductor longus, TFL = tensor fasciae latae, GMED = gluteus medius, GMAX = gluteus maximus, D = descent phase, A = ascent phase; *df* = 19; * = $p < .05$.

Table 3

Average and Peak Muscle Activity During the Lateral Step Down

Muscle Tested	Experimental *M* *SD*	Control *M* *SD*	*t*	*p*	*g*
Average Activity					
AL (D)	0.49 ± 0.18	0.09 ± 0.77	1.70	.11	0.63
AL (A)	0.53 ± 0.20	0.84 ± 0.62	1.44	.17	0.61
TFL (D)	0.29 ± 0.09	0.19 ± 0.09	-2.51	.02*	-1.06
TFL (A)	0.30 ± 0.11	0.20 ± 0.07	-2.50	.02*	-1.06
GMED (D)	0.24 ± 0.19	0.19 ± 0.14	-0.65	.52	-0.28
GMED (A)	0.59 ± 0.74	0.27 ± 0.16	-1.47	.16	-0.62
GMAX (D)	0.12 ± 0.09	0.13 ± 0.09	0.31	.76	0.13
GMAX (A)	0.24 ± 0.17	0.19 ± 0.13	-0.65	.53	-0.27
Peak Activity					
AL (D)	1.05 ± 0.38	1.64 ± 0.18	1.61	.13	0.60
AL (A)	1.19 ± 0.44	1.79 ± 0.13	1.51	.15	0.64
TFL (D)	0.61 ± 0.18	0.42 ± 0.21	-2.19	.04*	-0.93
TFL (A)	0.65 ± 0.23	0.49 ± 0.20	-1.71	.10	-0.72
GMED (D)	0.48 ± 0.50	0.29 ± 0.17	-1.20	.25	-0.51
GMED (A)	1.15 ± 0.54	0.43 ± 0.24	-1.38	.20	-0.68
GMAX (D)	0.22 ± 0.18	0.21 ± 0.13	-0.27	.79	-0.12
GMAX (A)	0.38 ± 0.25	0.31 ± 0.19	-0.75	.46	-0.32

Note. AL = adductor longus, TFL = tensor fasciae latae, GMED = gluteus medius, GMAX = gluteus maximus, D = descent phase, A = ascent phase; $df = 19$; * = $p < .05$.

TFL was higher in women with PFP when compared to women without PFP during the ascent phase (*p* = .046, *g* = -0.90*)*. See Table 4.

Discussion

The purpose of this study was to determine whether hip muscle activity patterns in women with PFP differ from women without PFP, when measured during common functional movements. To our knowledge, there are few studies that have investigated the TFL and AL, in addition to the GMED and GMAX, in this population during functional movements. Muscle activity for the AL, GMED, and GMAX were not different between women with and without PFP in the ascending and descending phases of the forward lunge, lateral step down, and single leg squat. Women with PFP did exhibit a higher level of average and peak TFL activity during both the descent and ascent phase of the forward lunge (*p* < .05). Similar findings of increased average TFL activity were seen in both the descent and ascent phase of the lateral step down (*p* < 05). In addition, peak TFL activity was higher during the descent phase of the lateral step down and in the ascent phase of the single leg squat (*p* < .05; see Tables 2 – 4).

Few researchers have examined the relationship between TFL muscle activity and knee pain (Besomi et al., 2020). Baker et al. (2018) investigated biomechanics and muscle activity during treadmill running in persons with iliotibial band syndrome and found increased average TFL activity and increased knee valgus during running. Average TFL muscle activity increased initially during the run and then plateaued after three minutes. The authors could not fully explain the phenomenon and proposed that a comprehensive assessment of the EMG activity would yield a clearer understanding. The

Table 4

Average and Peak Muscle Activity During the Single Leg Squat

	Experimental	Control			
Muscle Tested	*M* *SD*	*M* *SD*	*t*	*p*	*g*
Average Activity					
AL (D)	0.51 ± 0.26	0.86 ± 0.70	1.43	.17	0.61
AL (A)	0.48 ± 0.20	0.78 ± 0.60	1.45	.16	0.61
TFL (D)	0.33 ± 0.16	0.23 ± 0.10	-1.81	.09	-0.77
TFL (A)	0.31 ± 0.18	0.21 ± 0.08	-1.75	.10	-0.74
GMED (D)	0.35 ± 0.44	0.22 ± 0.14	-0.93	.37	-0.39
GMED (A)	0.61 ± 0.98	0.29 ± 0.16	-1.12	.28	-0.48
GMAX (D)	0.11 ± 0.07	0.13 ± 0.09	0.56	.59	0.24
GMAX (A)	0.17 ± 0.09	0.18 ± 0.12	0.17	.86	0.07
Peak Activity					
AL (D)	1.13 ± 0.62	1.60 ± 1.02	1.22	.24	0.52
AL (A)	1.17 ± 0.58	1.43 ± 0.86	0.77	.45	0.33
TFL (D)	0.71 ± 0.35	0.48 ± 0.27	-1.74	.10	-0.74
TFL (A)	0.68 ± 0.35	0.42 ± 0.21	-2.14	.05*	-0.90
GMED (D)	0.64 ± 0.85	0.34 ± 0.17	-1.23	.23	-0.52
GMED (A)	1.04 ± 1.71	0.44 ± 0.26	-1.21	.24	-0.51
GMAX (D)	0.21 ± 0.14	0.21 ± 0.13	0.04	.97	0.02
GMAX (A)	0.29 ± 0.16	0.26 ± 0.18	-0.39	.70	-0.17

Note. AL = adductor longus, TFL = tensor fasciae latae, GMED = gluteus medius, GMAX = gluteus maximus, D = descent phase, A = ascent phase; *df* = 19; * = $p < .05$.

author’s observed results of increased TFL activity in the painful group are similar to the findings of the current study.

To our knowledge, few studies have investigated AL activity during functional movements in women with PFP. Goto et al. (2018) examined activity levels of the AL in women with PFP during a performance of the Star Excursion Balance Test (SEBT). Although there was no difference in AL activity between groups, the PFP group did demonstrate a significantly decreased ratio of GMED activation to AL activation compared to the control group. This was not coupled with an increase in instability during the SEBT. The findings of the current study reflect the results of Goto et al. (2018) in that there were no differences in AL activity between the 2 groups in the movements studied. However, coactivation ratios were not calculated and no analogies between the coactivation findings of Goto et al. (2018) and the current study can be made. Future studies should include coactivation outcome measures to allow for a more comprehensive analysis.

Further comparisons can be drawn between the current research study and earlier works on activity patterns of the GMED and the GMAX. However, these previous works have been inconclusive (Barton et al., 2013). For example, Nakagawa et al. (2011) found no difference in GMED activation patterns during functional tasks, including stair descent. Similarly, Souza and Powers (2009) investigated muscle activity patterns of the GMED and the GMAX in women with PFP during different functional tasks. The authors also found no differences in GMED activity. However, they did find increased GMAX activation in the PFP group during both running and a step-down task. In contrast, Bolgla et al. (2011) found increased GMED activity during loading and single leg stance of a stair descent task. It was suggested that the increased gluteal muscle activity may be an attempt by symptomatic participants to increase recruitment of a weakened muscle. In the current study, the GMED was not different between control and experimental groups during the movements. However, higher GMED activity is apparent in the experimental group. The low sample size of the current exploratory study may have contributed to the lack of statistical significance.

In the current study, the primary outcome was increased activation of the TFL during functional movements. The role of the TFL is two-fold. In the open kinetic chain, the TFL functions as a hip flexor and abductor. During the closed kinetic chain, the primary function of the TFL is to stabilize the pelvic girdle and to rotate the pelvis towards the weight bearing lower extremity during the swing phase of gait, when the contralateral lower extremity is unsupported (Gottschalk et al., 1989; Neumann, 2010). In addition, the TFL stabilizes the femur by resisting external rotation during the stance phase of gait. Furthermore, research studies have shown that persons with PFP demonstrate an alteration in muscle activity patterns in the GMED and the GMAX (Aminaka et al., 2011; Brindle et al., 2003; Souza & Powers, 2009). It is possible that some of the muscles that stabilize the pelvis during weight bearing tasks, such as the GMED or GMAX, have progressively become underactive. As a result, the TFL adopts an increased role in stabilization of the hip during closed-chain functional tasks. However, because the action of the TFL is complex, an increase in activity may have secondary deleterious effects. Although the TFL might be acting as a stabilizer in the frontal plane to help control adduction, increased TFL activity might also produce an effect in the transverse plane. This could produce internal rotation, or at the least, a “resistance effect” that might stabilize the knee into some degree of internal rotation, especially upon weight acceptance.

Increased activity of the TFL during closed kinetic chain activities could lead to potential reciprocal inhibition of the external rotators of the hip, including the GMAX and short external rotators. Any excessive internal rotation of the femur that is observed during gait may not solely be a result of active internal rotation by the TFL or the internal rotators of the hip, but also from a decrease in muscle activation of these external rotators. This could be associated with a strength loss of these same muscles and a functional internal rotation moment of the femur during gait. If increased gluteal muscle activity is indicative of increased recruitment of a weakened muscle, then the findings of the current study could possibly be related to this previously proposed explanation (Bolga et al., 2011)

Recent researchers have proposed that PFP is associated with decreased stability and control of the femur joint with the pelvis (Souza et al., 2010). If this theoretical explanation is followed, the gluteals would first show a pattern of increased activity because they are weak and unable to stabilize the hip and pelvis. This would be followed by increased activation in the TFL as it adopts an increased role in this task. Finally, what could follow would be lower extremity problems such as PFP. The emphasis in addressing the problem might be to focus on strengthening the gluteals to decrease the stabilization required by the TFL. A secondary result of this would be a potential reversal of reciprocal inhibition that is occurring between the TFL and the external rotators. Finally, if it is assumed that the problem is one of stabilization and not mobility, then a greater emphasis must be placed on closed chain stabilization exercise versus open chain strengthening exercises.

Previous researchers have investigated muscle activity in the gluteals, however, their results have been inconclusive (Barton et al, 2013). While investigations into the muscle activity of the secondary external rotators and potential stabilizers of the femur are warranted, they are complicated by the need to use fine wire or needle EMG because of the location of these muscles. In addition, previous studies have shown evidence that strengthening the external rotators have improved symptoms of PFP (Khayambashi et al., 2014). It is possible that the improvement in symptomology is not only due to an improvement in the ability of the external rotators to eccentrically resist and control internal rotation of the femur during gait, but also to normalize reciprocal inhibition of the TFL. Future researchers should investigate these topics as the findings could have implications for treatment of PFP. Additionally, if it is assumed that a pattern of increased gluteal activity is first seen, followed by an increase in TFL activity and then eventually a development of PFP symptoms, epidemiological research into when people start having increased recruitment of the gluteals might be warranted. Perhaps most importantly, it is important to remember that the actions of the TFL, especially in closed chain function, are complex and poorly understood. The action of the TFL may produce biomechanical effects that are beneficial in one plane but problematic in another, specifically in the initial weight acceptance and deceleration phase of function (Baker et al., 2018). Further expansion of the information gathered (such as onset times, duration of activity, and area of EMG activity under the curve) would add to the current level of understanding of the actions of the TFL.

A limitation of the current study is in the criteria for determining PFP. Unlike pathologies such as osteoarthritis, chondromalacia, or meniscal tears, PFP is a condition that is not quantifiable. Instead, the classification and diagnosis of the problem is reliant on the history of the individual and is often made once other potential problems are excluded. While the inclusion criteria for this study was similar to criteria used in previous studies (Baldon et al., 2009; Crossley et al., 2002), the lack of criteria that definitively assesses and/or stratifies the severity of the condition creates potentially large variability within persons with PFP. Finally, the amount of femoral internal rotation or valgus that was occurring during the motions that were performed were not objectively measured, and so it is difficult to make conclusions as to whether the presence of PFP symptoms can be correlated with femoral dynamic valgus.

Conclusion

Women with PFP showed a higher level of both average and peak TFL activity during functional movements that are commonly used in the assessment of PFP and lower extremity function. This could be indicative of increased use of the TFL to provide stability to the lower extremity during function, perhaps concurrent with decreased recruitment by other muscles that are also responsible for providing lower extremity stability. Further research is needed to determine the extent to which reciprocal inhibition is taking place, as well as the possible impact of exercise on the level of muscle activity in the TFL.

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APPENDICES FOR CHAPTER IV

IRB
INSTITUTIONAL REVIEW BOARD
Office of Research Compliance,

010A Sam Ingram Building, 2269 Middle Tennessee Blvd

Murfreesboro, TN 37129

FWA: 00005331/IRB Regn. 0003571

IRBN001 - EXPEDITED PROTOCOL APPROVAL NOTICE

Wednesday, October 14, 2020

Protocol Title	***Strength and Muscle Activation Profiles of Women inPatellofemoral Pain***
Protocol ID	**21-2043 4i (19-2114)**
Principal Investigator	**David Clark** (Student)
Faculty Advisor	John Coons
Co-Investigators	Sarah Martinez
Investigator Email(s)	*david.clark@mtsu.edu; john.coons@mtsu.edu*
Department	Health and Human Performance (Exercise Science)
Funding	**NONE**

Dear Investigator(s),

The above identified research proposal has been reviewed by the MTSU IRB through the **EXPEDITED** mechanism under 45 CFR 46.110 and 21 CFR 56.110 within the category *(4) Collection of data through noninvasive procedures*. A summary of the IRB action is tabulated below:

IRB Action	**APPROVED for ONE YEAR**
Date of Expiration	**10/31/2021** *Date of Approval*: 10/14/20 *Recent Amendment*: NONE
Sample Size	ONE HUNDRED (100)
Participant Pool ☐	*Target Population:* Primary Classification: **General Adults (18 or older)** Specific Classification: **Female adults**
Type of Interaction	Virtual/Remote/Online interaction ☒ **In person or physical interaction – Mandatory COVID-19 Management**
Exceptions	In person interactions without social distancing is permitted for data collection (actualdescription on file and provided in the informed consent tempalte)
Restrictions	**5. Mandatory SIGNED Informed Consent.** **6. Other than the exceptions above, identifiable data/artifacts, such as, audio/video data, photographs, handwriting samples, personal address, drivingrecords, social security number, and etc., MUST NOT be collected.** **7. Mandatory Final report (refer last page).** **8. CDC guidelines and MTSU safe practice must be followed**
Approved Templates	*IRB Templates:* Informed Consent, Recruitment Email and IRB Flyer *Non-MTSU Templates:* Verbal recruitment script
Research Inducement	NONE
Comments	NONE

Post-approval Requirements

The PI and FA must read and abide by the post-approval conditions (Refer "*Quick Links*" in the bottom):

- ***Reporting Adverse Events:*** The PI must report research-related adversities suffered by the participants, deviations from the protocol, misconduct, and etc., within 48 hours from when they were discovered.

- ***Final Report:*** **The** FA is responsible for submitting a final report to close-out this protocol before **10/31/2021** **(Refer to the Continuing Review section below)**; REMINDERS WILLNOT BE SENT. **Failure to close-outor request for a continuing review may result in penalties** including cancellation of the data collected using this protocol and/or withholding student diploma.

- ***Protocol Amendments***: An IRB approval must be obtained for all types of amendments, such as: addition/removal of subject population or investigating team; sample size increases; changes to the research sites (appropriate permission letter(s) may be needed); alternation to funding; and etc. The proposed amendments must be requested by the FA in an addendum request form. The proposed changes must be consistent with approval category and must comply with expedited review requirements
- ***Research Participant Compensation:*** Compensation for research participation must be awarded as proposed in Chapter 6 of the Expedited protocol. The documentation of the monetary compensation must Appendix J and MUST NOT include protocol details when reporting to the MTSU Business Office.
- ***COVID-19:*** Regardless whether this study poses a threat to the participants or not, refer to the COVID-19 Management section for important information for the FA.

Continuing Review (The PI has requested early termination)

Although this protocol can be continued for up to THREE years, The PI has opted to end the study by **10/31/2021**

The PI must close-out this protocol by submitting a final report before 10/31/2021 Failure to close-out may result in penalties that include cancellation of the data collected using this protocol and delays in graduationof the student PI.

Post-approval Protocol Amendments:

The current MTSU IRB policies allow the investigators to implement minor and significant amendments that would fitwithin this approval category. ***Only TWO procedural amendments will be entertained per year*** *(changes like addition/removal of research personnel are not restricted by this rule).*

Date	Amendment(s)	IRB Comments
NONE	NONE.	NONE

Other Post-approval Actions:

The following actions are done subsequent to the approval of this protocol on request by the PI/FA or onrecommendation by the IRB or by both.

Date	IRB Action(s)	IRB Comments
NONE	NONE	NONE

COVID-19 Management:

The PI must follow social distancing guidelines and other practices to avoid viral exposure to the participants andother workers when physical contact with the subjects is made during the study.

- The study must be stopped if a participant or an investigator should test positive for COVID-19 within 14 days of the research interaction. This must be reported to the IRB as an “adverse event.”
- MTSU’s “Return-to-work” questionnaire found in Pipeline must be filled by the investigators on the day of the research interaction prior to physical contact.
- PPE must be worn if participant would be within 6 feet from each other or with an investigator.
- Physical surfaces that will come in contact with the participants must be sanitized between use
- **FA’s Responsibility:** The FA is given the administrative authority to make emergency changes to protect the wellbeing of the participants and student researchers during the COVID-19 pandemic. However, the FAmust notify the IRB after such changes have been made. The IRB will audit the changes at a later date andthe FA will be instructed to carryout remedial measures if needed.

Data Management & Storage:

All research-related records (signed consent forms, investigator training and etc.) must be retained by thePI or the faculty advisor (if the PI is a student) at the secure location mentioned in the protocol application.

The data must be stored for at least three (3) years after the study is closed. Additional Tennessee Statedata retention requirement may apply (*refer "Quick Links" for MTSU policy 129 below*). The data may be destroyed in a manner that maintains confidentiality and anonymity of the research subjects.

The MTSU IRB reserves the right to modify/update the approval criteria or change/cancel the termslisted in this letter without prior notice. Be advised that IRB also reserves the right to inspect or audit your records if needed.

Sincerely,

Institutional Review Board

Middle Tennessee State University

Quick Links:

- Post-approval Responsibilities: http://www.mtsu.edu/irb/FAQ/PostApprovalResponsibilities.php
- Expedited Procedures: https://mtsu.edu/irb/ExpeditedProcedures.php
- MTSU Policy 129: Records retention & Disposal: https://www.mtsu.edu/policies/general/129.php

IRB

INSTITUTIONAL REVIEW BOARD
Office of Research
Compliance,010A
Sam Ingram Building,
2269 Middle
Tennessee Blvd
Murfreesboro, TN
37129

IRBN001 - EXPEDITED PROTOCOL APPROVAL NOTICE

Wednesday, January 30, 2019

Principal Investigator	**David Clark** (Student)
Faculty Advisor	John Coons
Co-Investigators	Sarah Martinez
Investigator Email(s)	*david.clark@mtsu.edu;* *john.coons@mtsu.edu;* *sm9x@mtmail.mtsu.edu*
Department	Exercise Science, Health and Human Performance
Protocol Title	***Strength and muscle activation profiles of women inpatellofemoral pain***
Protocol ID	**19-2114**

Dear Investigator(s),

The above identified research proposal has been reviewed by the MTSU Institutional Review Board (IRB) through the **EXPEDITED** mechanism under 45 CFR 46.110 and 21 CFR 56.110 within the category *(4) Collection of data through noninvasive procedures*. A summary of the IRBaction and other particulars in regard to this protocol application is tabulated below:

IRB Action	**APPROVED for ONE YEAR**		
Date of Expiration	**1/31/2020**	Date of	1/30/19

		Approval	
Sample Size	100 (ONE HUNDRED)		
Participant Pool	Primary Classification: **General Adults (18 years to 55 years old)** Specific Classification: **Female adults who self-report anterior or retropatelar pain of at least 3 on a 10cm visual analog scale (VAS)**		
Exceptions	Older version of informed consent template is permitted with restriction		
Restrictions	**4. Mandatory signed informed consent; the participants must have accessto an official copy of the informed consent document signed by the PI.** **5. Collection of identifiable information not permitted.** **6. Mandatory implementation of inclusion/exclusion criteria to screenpotentially risky participants**		
Comments	NONE		

This protocol can be continued for up to THREE years (**1/31/2022**) by obtaining a continuation approval prior to **1/31/2020**. Refer to the following schedule to plan your annual project reports and be aware that you may not receive a separate reminder to complete your continuing reviews.Failure in obtaining an approval for continuation will automatically result in cancellation of this protocol. Moreover, the completion of this study MUST be notified to the Office of Compliance byfiling a final report in order to close-out the protocol.

Post-approval Actions

The investigator(s) indicated in this notification should read and abide by all of the post-approval conditions imposed with this approval. Refer to the post-approval guidelines posted in the MTSUIRB's website. Any unanticipated harms to participants or adverse events must be reported to the Office of Compliance at (615) 494-8918 within 48 hours of the incident. Amendments to this protocol must be approved by the IRB. Inclusion of new researchers must also be approved by the Office of Compliance before they begin to work on the project.

Continuing Review (**Follow the Schedule Below:)**

Submit an annual report to request continuing review by the deadline indicated below and please be aware that **REMINDERS WILL NOT BE SENT.**

Reporting Period	Requisition Deadline	IRB Comments
First year report	12/31/2019	This protocol is set to expire on 11/15/2019 as requested by the PI (Revised Expedited Application dated 01.22.2019) unless a continuing review isrequested by the PI before the date of expiration.
Second year report	12/31/2020	NOT COMPLETED
Final report	12/31/2021	NOT COMPLETED

Post-approval Protocol Amendments:

Only two procedural amendment requests will be entertained per year. *In addition, the researchers can request amendments during continuing review. This amendment restriction does not apply to minor changes such as language usage and addition/removal of research personnel. .*

Date	Amendment(s)	IRB Comments
NONE	NONE.	NONE

Other Post-approval Actions:

Date	IRB Action(s)	IRB Comments
NONE	NONE.	NONE

Mandatory Data Storage Requirement: All of the research-related records, which include signedconsent forms, investigator information and other documents related to the study, must be retained by the PI or the faculty advisor (if the PI is a student) at the secure location mentioned in the protocol application. The data storage must be maintained for at least three (3) years after study has been closed. Subsequent to closing the protocol, the researcher may destroy the data in a manner that maintains confidentiality and anonymity.

IRB reserves the right to modify, change or cancel the terms of this letter without prior notice. Beadvised that IRB also reserves the right to inspect or audit your records if needed.

Sincerely,

Institutional Review Board
Middle Tennessee State University

CHAPTER V

OVERALL CONCLUSIONS

The purpose of this dissertation was to investigate and describe hip strength and muscle activity characteristics of women with PFP. In the first study hip strength functional ratios for agonist/antagonist muscle groups were established. In the second study, the average and peak muscle activity of four hip muscles during the performance of three functional movements were examined.

In study one, average and peak torque was measured for hip abduction, adduction, external rotation, internal rotation, flexion, and extension. This was measured both concentrically and eccentrically. These torque values were then used to calculate functional strength ratios. Women with PFP had a higher functional ratio of concentric hip abduction to eccentric hip adduction. This higher functional ratio indicates a discrepancy of contraction, specifically in the frontal plane, with a greater difference between concentric abduction force and eccentric adduction force being exhibited by women with PFP than women without PFP. This suggests there is decreased level of dynamic hip stability in women with PFP than women without PFP. It can be speculated that women with PFP have adopted a strategy of concentric hip abduction to compensate for the tendency to move into dynamic valgus during function. Stabilization training and strengthening of the external rotators of the hip may be of benefit to improving functional stability at the hip and the knee.

In study two, muscle activity in the AL, TFL, GMED, and GMAX during three functional movements was measured. Women with PFP showed a pattern of increased average and peak TFL muscle activity in both the descent phase and ascent phase of the forward lunge. Average muscle activity of the TFL was also higher in women with PFP in both the descent and ascent phases of the lateral step down. Peak activity of the TFL was also increased during the descent phase of the lateral step down and the ascent phase of the single leg squat. It is possible the increased activity is due, in part, to the TFL acting as a stabilizer of the lower extremity during weight bearing, functional activities. This could be occurring as a compensatory action in response to weakened hip external rotators and abductors. Although this action may assist with stabilization of the femur and/or pelvis during function, it could also be associated with internal rotation of the femur during gait, which may be related to functional dynamic valgus that is often seen in PFP. Implications for treatment include strengthening the external rotators, with the intended outcome of improved stabilization of the femur, thus decreasing the compensatory action of the TFL.

Together, the studies in this dissertation contribute to the growing body of knowledge about the association between hip strength and hip muscle activity and PFP in women. An improved understanding of the condition would be of benefit, due to its high occurrence rate in women and its potential impact on daily function. Strengthening and training exercises that focus on stabilization may improve functional biomechanics that could lead to a reduction in pain. The complex nature of the interaction between the function of the hip and possible biomechanical implications at the knee leave many opportunities for further research. Further study is needed to address the dearth of evidence on factors contributing to PFP in women.

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