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Assessment of movement coordination variability and neuromuscular characteristics during stair ambulation in those with and without patellofemoral pain syndrome

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A Dissertation

entitled

Assessment of Movement Coordination Variability and Neuromuscular Characteristics

During Stair Ambulation in those with and without Patellofemoral Pain Syndrome

by

Naoko Aminaka, MS, ATC

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

Doctor of Philosophy Degree in Exercise Science

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August 2010
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An Abstract of
Assessment of Movement Coordination Variability and Neuromuscular Characteristics
during Stair Ambulation in those with and without Patellofemoral Pain Syndrome

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Naoko Aminaka, MS, ATC

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Although patellofemoral pain syndrome (PFPS) is known as one of the most
common injuries in a physically active population, its influence on movement
coordination and neuromuscular functions has not been fully understood, and previous
studies have only reported discrete kinematics of a single joint. The aim of this study
was to perform simultaneous investigation of movement coordination between two joints
during stair ambulation combined with muscular activation patterns and kinetic
characteristics in those with and without PFPS. Our results revealed that movement
coordination patterns are different in the frontal and transverse planes in PFPS
individuals, with more restricted movement variability, indicating the reduced ability to
utilize multiple strategies for performing stair ambulation tasks. Furthermore, these
movement coordination alterations were present along with the increased knee abduction
moment and impulse, and altered muscle activation patterns of the lower extremity
muscles. Our results may provide additional support for implementing rehabilitative
exercise programs that promote a wider range of movement strategies while
reestablishing proper balance of the lower extremity muscles activation patterns.
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Chapter 1

1.1 Introduction

With the increased competition and physical activity levels in the United States, more physically active people are exposed to both acute and chronic injuries. Patellofemoral pain syndrome (PFPS) is considered to be one of the most common chronic conditions among the physically active. PFPS is a condition in which active people have diffuse pain in the anterior part of the knee caused by excessive irritation on the underside of the patella as it moves on the femur, and is one of the most common orthopedic injuries, affecting approximately 25% of the general population. PFPS causes pain with daily activities such as going up and down stairs, squatting, walking, and running, similar to the activities that may contribute to exacerbation of painful symptoms of knee OA.

The excessive loading placed repeatedly over time on the patellofemoral joint results in biomechanical and neuromuscular alterations, such as increased knee adduction moment, increased knee valgus, reduced knee flexion, and weakness and altered activation patterns in the lower extremity musculatures. Recent studies have reported weakness and imbalance in the activation timings of adductor longus, vastus medialis oblique and gluteus medius to be contributing factors for PFPS. Similarly, altered frontal plane knee biomechanics such as increased knee adduction moment have been associated with the development of PFPS. These changes may lead to diminished force...
distribution about the knee joint and may cause long-term damage to knee structures.

Dynamic systems theory of human movement suggests that variations in movement patterns are the results of the neuromuscular system’s response to various perturbations in and out of the body, not the results of pathologies as traditionally considered. Dynamic systems theory proposes that healthy individuals are able to demonstrate greater variance in the movement patterns to achieve a task, in order to adapt to perturbations. On the other hand, the theory explains that pathological individuals would demonstrate highly repeatable movement patterns.

Measurements of movement variability have been investigated on pathological populations such as PFPS, anterior cruciate ligament reconstruction, Parkinson’s disease, and cerebral palsy. However, to our knowledge, there is currently no cross-sectional study comparing the extent of alterations in dynamic movement strategies and neuromuscular control as presented in EMG measurements between PFPS and injury-free individuals. These comparisons will provide useful insight into the clinical assessment and development of effective treatment protocols for PFPS. If clinicians are able to identify a highly predictable movement pattern presented in patients with PFPS, then perhaps these problems may be addressed early on in the rehabilitation program, in order to reduce the risk of excess articular damage and development of more severe degenerative conditions.

Therefore, the purpose of this study is to investigate the influence of PFPS on biomechanical and neuromuscular functions during stair ambulation, when compared with a cohort of healthy subjects.
1.2 Specific Aims and Hypotheses

Specific Aim 1: To determine if there are differences in movement patterns, using a dynamic systems theory, during stair ambulation, between individuals with PFPS and healthy individuals.

Hypothesis 1. 1. The subjects with PFPS will demonstrate more out-of-phase movement coordination relationships between 1) knee flexion/extension and hip abduction/adduction, 2) knee abduction/adduction and hip abduction/adduction, and 3) knee internal/external rotation and hip internal/external rotation during stair ascent and descent compared to the healthy subjects.

Hypothesis 1. 2. The subjects with PFPS will demonstrate altered or reduced variability in movement patterns between 1) knee flexion/extension and hip abduction/adduction, 2) knee abduction/adduction and hip abduction/adduction, and 3) knee internal/external rotation and hip internal/external rotation, during stair ascent and descent compared to the healthy subjects.

Hypothesis 1. 3. The symptomatic leg of the PFPS group will demonstrate a more out-of-phase relationship and reduced variability in movement coordination between 1) knee flexion/extension and hip abduction/adduction, 2) knee abduction/adduction and hip abduction/adduction, and 3) knee internal/external rotation and hip internal/external rotation during stair ascent and descent compared to the asymptomatic leg of the PFPS group.

Specific Aim 2: To determine if there are differences in frontal plane knee kinetics during stair ascent and descent compared to the healthy subjects.
Hypothesis 2. 1. The subjects with PFPS will demonstrate an increased knee adduction moment at the initial contact during stair ascent and descent, as compared with knee adduction moment of the healthy subjects.

Hypothesis 2. 2. The subjects with PFPS will demonstrate an increased knee adduction impulse during the stance phase of stair ascent and descent compared to the healthy subjects.

Hypothesis 2. 3. The symptomatic leg of the PFPS group will demonstrate an increased knee adduction moment and impulse during stair ascent and descent, when compared to the asymptomatic leg of the PFPS group.

Specific Aim 3: To determine if there are differences in neuromuscular control patterns during stair ambulation, quantified through a delay in muscle onset timing and activation onset, between individuals with PFPS and healthy individuals.

Hypothesis 3. 1. The subjects with PFPS will demonstrate a delayed muscle onset of gluteus medius, adductor longus, and vastus medialis oblique, as compared with healthy subjects during stair ascent and descent.

Hypothesis 3. 2. There will be differences in muscle activation duration for the gluteus medius, adductor longus, and vastus medialis oblique, between the subjects with PFPS and the healthy subjects during stair ascent and descent.

3. 2. 1. The subjects with PFPS will demonstrate a longer activation duration of adductor longus during stair ascent and descent compared with the healthy subjects.
3.2.2. The subjects with PFPS will demonstrate a shorter activation duration of gluteus medius, and vastus medialis oblique, as compared with the healthy subjects.

**Hypothesis 3.3.** The symptomatic leg of the PFPS subjects will demonstrate a later onset for all four muscles, longer activation duration for adductor longus, and shorter activation duration for gluteus medius, and vastus medialis oblique, when compared with the asymptomatic leg of the PFPS subjects.

**Specific Aim 4:** To determine if the subjects with PFPS experience increased pain during stair ascending and descending tasks, compared to the healthy subjects and compared to the PFPS subjects’ pain level at rest.

**Hypothesis 4.1.** The subjects with PFPS will demonstrate increased pain level compared to the healthy subjects across all time points (worst pain in the previous week, at rest before data collection trials, and worst pain during stair ascent and descent).

**Hypothesis 4.2.** The subjects with PFPS will demonstrate increased pain level during stair ambulation tasks compared to their pain level at rest.

**Hypothesis 4.3.** There will be no significant differences among the level of worst pain in the preceding week, pain level during stair ascent, and pain level during stair descent in the PFPS group.

The results of this study will benefit healthcare professionals who treat individuals with PFPS, by providing information that will help determine what type of
biomechanical and neuromuscular deficits they are experiencing, and to implement effective rehabilitation interventions to address these problems. These findings may potentially lead to the development of programs to deter or prevent progression into irreversible degenerative pathology such as knee (tibiofemoral or patellofemoral) OA.

1.3 Anticipated Outcomes

Dynamic systems theory states that our body segments must be coordinated to adapt to various internal and external perturbations. Therefore, we speculate that pathological individuals will demonstrate rather constrained, more predictable movement patterns as compared with healthy individuals who are able to move their body in various patterns. We expect to see that PFPS subjects will show reductions in variability of movement pattern compared to our control group of young healthy subjects. These results will help to emphasize the importance of identifying movement patterns in PFPS subjects in hopes of preventing the long-term joint degeneration that may lead to knee OA.

Differences in movement patterns may be dictated by, as well as influence, neuromuscular coordination. A recent notion is that people with PFPS are exhibiting increased internal knee adduction moment, which may indicate that the knee is moving in a valgus (abducted) and internally rotated direction, thereby migrating the moment arm medial to the knee joint center. Not only do we anticipate our pathological group to demonstrate an increased knee adduction moment, we speculate that the muscles will fire in a pattern that will make the lower extremity more susceptible to excessive adduction moment and restricted movement patterns. Therefore, we would expect to see an early
onset of adductor and gluteus medius relative to vastus medialis in PFPS subjects. We also anticipate that the adductor will have longer onset duration in the PFPS group compared to the control group, which may be resisting excess frontal and transverse plane movement.

These anticipated outcomes from this study will provide healthcare professionals insight into identification of the biomechanical and neuromuscular characteristics that may be present in individuals PFPS. We anticipate that information obtained from this study will ultimately aid the healthcare professionals in selecting the optimal therapeutic interventions for the individuals with PFPS to prevent advancement to degenerative joint pathology.

1.4 Known Limitations

It is possible that EMG leads and electrodes create noise during data collection. Friction from the subject’s clothing may also create noise to the EMG data. These low-frequency noises will be controlled using the filtering method as described in Methods section. It is also possible that impact from stair ascent and descent could create high-frequency noise; however, these will be controlled with the filtering method as well.

There is a possibility of cross-talk of surrounding muscles from the four electrode placements. Although the exact locations of the muscle belly vary from individual to individual, we have used multiple references and previous studies to identify the best possible electrode placement location, so that the surface EMG adequately records the electrical activity of the targeted muscle.
There is a possibility of excess skin or clothing movement due to the markers being attached to the skin or clothes. Placing the retroreflective markers directly on the skin or on tight-fitting clothing as close to the skin as possible will minimize the risk of excessive marker movement.
Chapter 2

Literature Review

2.1 Prevalence of PFPS

Almost one third of adults over 18 years and half of adults over 65 years seek medical help due to joint pain, aching or stiffness. In 2001, more than 13.5 million American adults reported having knee joint pain, swelling and stiffness.23

Patellofemoral pain syndrome (PFPS), the most common injury presented in runners and physically active population, affects approximately 11 percent of adults who complain of musculoskeletal disorders. PFPS is the most common diagnosis in outpatients presenting with knee pain. Studies have shown PFPS to be the most common single diagnosis among runners and in sports medicine centers. Eleven percent of musculoskeletal complaints in the office setting are caused by anterior knee pain (which most commonly results from PFPS), and PFPS constitutes 16 to 25 percent of all injuries in runners.3

PFPS involves irritation on the undersurface of the patella as it tracks improperly on the femur. Untreated PFPS symptoms may not only alter muscle function and movement strategies, but may also cause irreparable chondral damage to the patella and the femur, leading to patellofemoral osteoarthritis (OA). Osteoarthritis is a condition that causes degenerative changes in cartilage and bone. While it can occur in any joint, it is
more common in the knee joint. This condition causes a great deal of pain and a significant decrease in function, and many times results in total knee replacements. In 2002, approximately 43 million adults in the United States (21%) were diagnosed with arthritis, and the total cost of arthritis and other rheumatic conditions (AORC) in 1997 was $86.2 billion. Osteoarthritis is the most common type of arthritis, estimated to affect approximately 21 million adults. The number of people affected by OA is on the rise, mainly because more people are being physically active throughout their life. There are a number of risk factors for OA, such as age, sex, family history, obesity, reduction in bone mass, repetitive stressful activities such as heavy lifting, kneeling, squatting, walking, and history of previous knee injuries. Specifically, patellofemoral pain syndrome (PFPS), or anterior knee pain, is considered to be one of the predisposing factors for development of knee OA, more specifically patellofemoral OA, later in life. PFPS is a condition in which active people have pain in the anterior part of the knee caused by excessive irritation on the underside of the patella as it moves on the femur, and is one of the most common orthopedic injuries in the physically active population, affecting approximately 25% of the general population. PFPS causes pain with daily activities such as going up and down stairs, squatting, walking, and running, similar to the activities that may contribute to exacerbation of painful symptoms of knee OA. Although the majority of people affected by knee OA are the elderly population greater than the age of 65 years, the study by Utting et al suggests that many of these patients have suffered with PFPS before developing knee OA. Patellofemoral OA may be predisposed by PFPS, as the condition progresses to cause degenerative changes on the articular cartilages of the patellofemoral joint.
The excessive patellofemoral joint loading placed repeatedly over a long period of time has been considered to result in biomechanical and neuromuscular alterations, such as increased knee adduction moment, increased knee valgus, reduced knee flexion, and weakness in the lower extremity musculatures. It may eventually increase the risk for developing or exacerbating the symptoms of PFPS and patellofemoral OA. There is limited research on the effect of changes in muscle activity and movement patterns during activities among individuals with PFPS and patellofemoral OA. Therefore, the exact cause for developing this degenerative condition is unknown. However, there are striking similarities in altered movement patterns during locomotion between PFPS and patellofemoral OA individuals. Recent studies have found the imbalance in the activation timings of knee adductors, vastus medialis oblique and gluteus medius compared to the healthy population as contributing factor for PFPS and knee OA.\(^\text{34}\) Similarly, frontal plane knee biomechanics such as increased knee adduction moment has been associated with the development of PFPS and knee OA.\(^\text{34, 35}\) More specifically, studies suggest that knee valgus alignment, sagittal plane knee movement, and excessive lateral tracking of the patella may contribute to progression of patellofemoral OA.\(^\text{36, 37}\) These findings lead us to speculate that PFPS and patellofemoral OA are strongly related with each other, and the individuals with PFPS are more likely to develop patellofemoral OA due to changes in muscle activity around the knee joint and changes in movement pattern during functional activities. These changes may lead to changes in force distribution over the knee joint and may cause long-term damage to knee structures. If specific muscle and movement pattern alterations can be identified, rehabilitation may be
able to improve muscle function and movement patterns to prevent these individuals with PFPS from developing patellofemoral OA.

2.2 Functional Anatomy of the Patellofemoral Joint

The patellofemoral joint is comprised of the patella and the distal portion of the femur, especially the femoral trochlear groove, the sulcus between the lateral and medial femoral condyles. The patella, the largest sesamoid bone in the body, sits within the quadriceps tendon, increases the mechanical efficiency of the quadriceps muscles by increasing their lever arm, and protects the anterior portion of the knee joint. The patella also absorbs and functions to redirect the patellofemoral joint reaction force exerted by the quadriceps. The articular surfaces of the patellofemoral joint have a unique profile and are comprised of the thickest articular cartilage in the body, which assists in distributing the biomechanical demands placed on the joint. Bellemans discusses that articular cartilage of the patella is distributed as such that the patellar surface area with the thickest articular cartilage occurs where the maximal patellofemoral contact occurs and hence where the highest compression load is applied at the patellofemoral joint. The normal anatomical characteristics of the patellofemoral joint, including the concavity of the trochlea, convexity of the articular surface of the patella (retropatellar surface), and the surrounding soft connective tissues and muscles, provide the joint with stability. The patella is structurally stabilized by the shape of the patella, trochlea of the femur, and the peripatellar retinaculum. The anterior projection of the lateral wall serves as a static restraint on the tendency for lateral patellar tracking, which is generated by the extensor mechanism. The lateral femoral condyle is larger and
projects more anteriorly than the medial femoral condyle; therefore the trochlear groove may provide stability resisting laterally directed forces on the patella.⁴² As the patella articulates with the trochlea of the femur, many forces act on the patella to provide stability and guide its tracking movement during knee flexion and extension.²⁸

In full extension, the patella rests completely above the trochlear groove. This is often clinically observed by relatively free movement of the patella produced by a clinician, while the subject is relaxed in a long-sitting position. During the first 20 degrees of knee flexion, the first contact between the patella and the trochlear groove occurs at the inferior pole of the patella. At 20 to 30 degrees of knee flexion, the lateral border of the trochlear groove becomes more prominent, creating a barrier to keep the patella from displacing laterally. As the knee moves into more flexion, the contact surface of the patella moves more superiorly, or towards the center of the patella. The compression forces of the patellofemoral joint between the distal portion of the patella and the lateral femoral condyle increase as the knee flexion angle increases up to 90 degrees.¹,³⁸,⁴⁰,⁴³ The compressive force in the patellofemoral joint is the greatest around 60-90 degrees of flexion. At this range, the patella comes into the most contact with the femur, which is thought to provide protection of the joint against degeneration.³⁸,⁴⁴ Grelsamer and Klein³⁹ also discuss that the contact area of the patellofemoral joint increases from 0° to 60° of knee flexion, and tends to stay the same or increases between 60° and 90° of knee flexion. At 135 degrees of flexion, the superior pole of the patella contacts the distal femur below the trochlear groove. When moving from knee flexion to extension, the patella tracks medially within the trochlear groove from 45 degrees to 18 degrees. During the final 18 degrees of knee extension, the patella tracks laterally again.
This pattern of tracking is thought to follow the “screw-home” mechanism of femoral rotation during the final 20 degrees of knee extension.

The efficacy of the patellofemoral joint’s protective mechanisms against the excess joint stress is imperative, as even at the highest contact point, only 30% of the total surface area of the patella contacts the femur, therefore still putting a relatively high pressure on the patellofemoral joint.\textsuperscript{44} Stress is defined as the force over the area, and therefore it is critical for a clinician to consider both patellar and femoral aspects of the patellofemoral joint that contribute to excess joint stress,\textsuperscript{39} which may cause the pain either at the subchondral bone or peripatellar soft tissues. During an open-chain task, the patellofemoral joint reaction force is lowest at 90° of knee flexion.\textsuperscript{39, 44} As the knee moves into extension, the quadriceps muscle force increases and the joint reaction force increases, while the contact area of the patellofemoral joint decreases, as described above. As a result the patellofemoral joint stress increases with knee extension during an open-chain activity.\textsuperscript{39} On the other hand, during a closed-chain activity such as squat or gait, the patellofemoral joint stress increases from 0° to 90° knee flexion.\textsuperscript{39, 44} Beyond 90° of knee flexion, the quadriceps muscle comes into contact with the trochlear groove as the patella surface shares less contact with the trochlear groove; therefore the patellofemoral joint stress starts to plateau or decrease.\textsuperscript{39}

2.3 Propagation of Pain at the Patellofemoral Joint

It is critical that proper tracking of the patella on femur is achieved during movement; however, there are a number of factors that affect patellofemoral stability.\textsuperscript{28} Intricate interactions of anatomical and functional characteristics at the patellofemoral
joint are critical in maintaining pain-free function. Although patellofemoral articular cartilage is not innervated, any subtle change in the patellofemoral mechanisms may increase stress at the patellofemoral joint that may eventually cause pain arising from the subchondral bones, synovial inflammation, or any other surrounding soft tissue inflammation.\textsuperscript{1, 45}

There are numerous factors that contribute to increased patellofemoral joint stress and propagation of pain, such as structural abnormalities and muscular weakness/imbalances. Structural abnormalities include tightness or laxity of lateral and medial patellar retinaculi and medial and lateral patellofemoral ligaments, and inflammation or abnormalities of fat pads, bursae, and synovial plica.\textsuperscript{1} Structural or mechanical abnormalities arising from the femur or the tibia may contribute to excessive overloading and patellofemoral instability that causes PFPS.\textsuperscript{38} Position of the tibial tuberosity has been discussed as one factor that affects the resultant force vector of the patella via the patellar tendon. Common abnormality is the laterally positioned tibial tuberosity, which results in the increased quadriceps angle (Q-angle) and increased force on the patella to shift laterally.\textsuperscript{46, 47} The length of the patellar tendon also affects the contact area and hence the contact pressure of the patella, as well as the overall stability of the patella within the trochlear groove. Patella alta is a common abnormality that affects the patellar tracking since the patellofemoral congruency is affected due to the long patellar tendon.\textsuperscript{48, 49} Since the patella stays superiorly or proximally to the trochlear groove, protective mechanism of the trochlear groove against patellar displacement seems to become less effective. The depth of the trochlear groove also affects the patellofemoral congruency. A shallow groove may be a more common problem, which
allows the patella to subluxate either medially and laterally from the trochlear groove during repetitive flexion/extension movement.\textsuperscript{42} This repetitive subluxation over time causes the undersurface of the patella to create friction against the medial or lateral femoral condyle, develop pain due to excessive pressure on the subchondral bone of the patellofemoral joint, and eventually cause the articular cartilage of the patella or the femur to degenerate. Femoral anteversion is a condition where the distal end of the femoral shaft is spiraled downward, causing apparent internal rotation of the thigh.\textsuperscript{50} Internal rotation of the femur caused by femoral anteversion causes the patella to sit relatively laterally in the trochlear groove, thereby increasing lateral pulling force on the patella and increasing the contact pressure on the lateral aspect of the patellofemoral joint.\textsuperscript{40} Distal structures such as ankle and foot also contribute to abnormal patellofemoral articulation, since the patella is connected to the tibial tuberosity via the patellar tendon. Excessive pronation of the foot has been considered as one of the major contributing factors of PFPS.\textsuperscript{28, 51} Although there are surgical interventions to correct these structural abnormalities and tissue tightness, the invasive procedures often results in secondary problems or recurrent pain. This may suggest that the majority of PFPS sufferers develop their pain from insufficiencies of the dynamic stabilizers, rather than from anatomical abnormalities alone.

In addition to the structural configuration of the patella and the femur and the static stabilizers, various dynamic stabilizers act upon the patellofemoral joint to maintain proper tracking of the patella synchronous to the movement of the femur, so that forces on the patellofemoral articular surface are kept as little as possible. Muscle tightness, weakness or imbalance of vasti muscles, rectus femoris, hamstring muscles, iliotibial
band, and gluteal muscles dynamically affect the patellofemoral mechanics, and contribute to development of pain. Earl et al\textsuperscript{12} found that the combination of IT Band flexibility, navicular drop, pronation, knee flexion, hip adduction, gluteus medius onset time, vastus medialis oblique (VMO) onset time predicted those with PFPS (92.3%). Their findings may further support the importance of analyzing multiple factors including various static and dynamic malalignment as well as abnormal neuromuscular function of the entire lower extremity in order to identify individuals with PFPS.

Pain may cause people to use different movement strategies. Overtime, they will adopt the altered movement strategies to avoid exacerbation of pain. Pain may also change neural input that are relayed to the central nervous system and change the output signal to the muscles, causing people to become more selective in their movement pattern, limiting the degrees of freedom to which they achieve the task. Therefore, regardless of whether PFPS is caused by static structural abnormalities, prolonged pain experienced by the individuals with PFPS may result in alterations of kinematic and neuromuscular control. There are a number of previous studies that have investigated the effect of PFPS on neuromuscular and biomechanical characteristics.

2.4 Effect of PFPS on neuromuscular function

2.4.1 Local Factor – Vastus Medialis Oblique (VMO)

Quadriiceps muscles (rectus femoris, vastus medialis, vastus lateralis, and vastus intermedius), also commonly referred to as the extensor mechanism, provide resultant force that pulls the patella superiorly and laterally. Vastus medialis obliquus (VMO), the distal portion of vastus medialis which has fiber orientation of 55 degrees from the
quadriceps tendon, works to pull the patella medially against lateral force from all other parts of the quadriceps. In fact, the VMO is considered to be the only dynamic medial stabilizer of the patella and is the only dynamic restraint to the patella’s tendency to track laterally. An in vitro study by Sakai et al revealed that the weakness of the VMO contributes to increased lateral shift of the patella. For this reason, VMO has been discussed as one of the major contributors to lateral patellar maltracking, and also development of PFPS.

Several authors discuss that the delayed onset of the VMO compared to the vastus lateralis (VL) is observed in the subjects with PFPS. Cowan et al found that during a postural task, subjects with PFPS displayed later onset of the VMO compared to the VL, whereas the healthy subjects demonstrated simultaneous activation of these muscles. In another study, the same group demonstrated the similar onset latency of the VMO compared to the VL in PFPS subjects during step-up and step-down activities. The authors discuss that pain may contribute to the alteration in neuromuscular control of the vasti muscles in those with PFPS. Cesarelli et al investigated the control strategy of the quadriceps muscles in those with and without anterior knee pain during concentric knee extension. They found that VM activation is significantly later than the rectus femoris or VL muscles in the individuals with anterior knee pain, when compared with the healthy subjects. The authors discuss that the responsive inhibition due to pain may alter the muscle activation control of the quadriceps muscles in the individuals with PFPS. Lam and Ng investigated the activities of the VMO and VL in a semi-squat position at different knee flexion angles (20° and 40°) and with different hip orientation (medial rotation, neutral, and lateral rotation) in individuals with PFPS. The results yielded a
statistically significantly higher VMO/VL activity ratio at 40° knee flexion with medial hip rotation compared to the same the knee flexion position with lateral hip rotation, suggesting that the VMO activity is higher with the combination of larger knee flexion angle and medial hip rotation. However, it could be also possible that the VL activity was relatively lower with medial hip rotation, thereby resulting in a higher VMO/VL ratio. Since the authors did not compare the amplitudes of the VMO and VL individually, it is difficult to conclude which factor contributed more to the higher VMO/VL ratio with medial hip rotation. There are several studies that did not find statistically significant differences in the VMO activity amplitude or activation onset.\textsuperscript{57}

The adverse effect of painful symptoms may not be limited to the strength deficits or activation latency of a single muscle, but rather influence coordination of multiple muscles. The study by Mellor and Hodges found that motor units synchronization between the VMO and VL is reduced in subjects with anterior knee pain compared to the asymptomatic subjects.\textsuperscript{58} The authors suggest that reduced central drive to coordinate the medial and lateral muscles may occur as a result of pain. The reduced motor unit synchronization may therefore have further effect in movement coordination in the individuals with PFPS.

The study by Ownings and Grabiner\textsuperscript{54} assessed the VMO and VL muscle activation timing and onset during a seated, open-chain isokinetic knee flexion and extension in subjects with and without PFPS. In contrast to the other studies, their results revealed no statistically significant difference in activation timing of the VMO and VL between PFPS and asymptomatic subjects. The authors also found that activation amplitudes of the VMO and VL between groups were significantly different when
comparing the direction of contraction (contraction starting with the knee extended or flexed). The authors discuss that the higher VL activity amplitude compared to the VMO during eccentric contraction of these muscles may allude to tendency of lateral patellar tracking in those with PFPS. However, it must be noted that the performance was open-chain and therefore the results may be different during a closed-chain task that is more functional. McClinton et al\(^5\) utilized a step-up to different heights to investigate the onset timings of the VMO and VL between those with and without PFPS. The results revealed no statistically significant differences between groups or between step heights for the activation onset or magnitude ratio of the VMO and VL. However, the authors found that the duration of VL activation was much shorter in the PFPS group compared to the healthy group, whereas the duration of VMO activation was not different between groups, regardless of the step height. Although the significance of shorter activation duration of the VL is not discussed extensively, the authors suggest that this observation could be related to kinematic differences other than knee flexion; however, these other frontal and transverse plane kinematics were not measured in this study. Powers\(^6\) found that the higher activation of vastus medialis longus compared to the VL in the PFPS subjects was a predictor of increased lateral patellar tilt, while there was no significant difference of the VL:VMO ratio between PFPS and healthy groups.

The common idea from previous research is that pain arising from the patellofemoral joint is associated with altered neuromuscular control of the vastii muscles. Whether this alteration occurs as a result of pain or causes pain remains a topic of debate. Regardless, clinicians should be cautious when making clinical decisions about
rehabilitation programs and be mindful that movement coordination is achieved by neuromuscular contribution from various muscles of the lower extremity.

2.4.2 Proximal factor

In the light of global adaptation to local patellofemoral pain, more recent researchers have started to investigate the influence of PFPS on proximal muscular and kinematic deficits during functional activities. Gluteus maximus and gluteus medius are considered to contribute to frontal and transverse movement of the femur. Primary function of gluteus maximus is hip extension. However, orientation of the proximal fibers also produces hip external rotation and abduction. Gluteus medius primarily produces hip abduction; however, the anterior and posterior fibers are thought to assist in internal and external rotation, respectively. Altered kinematics associated with weakness or imbalance in activation of these hip muscles, therefore, may pose threat to maintenance of proper patellofemoral tracking and contact pressure. Brindle et al investigated the firing patterns of the VMO, VL and gluteus medius and the lower extremity kinematics during stair ambulation. While the onset timing of the VMO relative to VL did not reveal any statistical significance, the subjects with PFPS demonstrated shorter duration of VMO (PFPS= 777.1±143.5 ms; Control= 913.6±154.2 ms; p≤0.05) and VL (PFPS= 792.7±168.5 ms; Control= 913.2±121.0 ms; p≤0.05) activities during stair descent as compared to the healthy subjects. Furthermore, the delayed onset (PFPS= -88.1±110.3 ms; Control= -182.1±110.5 ms; p≤0.05) and shorter duration (PFPS= 608.1±206.4 ms; Control= 758.8±115.7 ms; p≤0.05) of the gluteus medius activity during stair ascent and shorter duration of gluteus medius activity
(PFPS= 494.2±246.5 ms; Control= 712.5±314.4 ms; p≤0.05) during stair descent were observed in the PFPS subjects when compared to the healthy subjects.

Cowan et al measured differences in neuromuscular control, hip and trunk muscle strength, and range of motion of hip muscles between those with and without PFPS. They reported that the PFPS subjects demonstrated the delayed activation onset of the anterior and posterior gluteus medius (p=0.01 and p=0.012, respectively) during the stair-stepping task compared to the healthy subjects, with activation of both portions occurring approximately 20ms after the heel strike. Also, the PFPS group during the stair-stepping task had a delayed onset of the VMO compared to the healthy group, and also compared to the vastus lateralis (p=0.001). The authors suggest the presence of altered in neuromuscular control of both local and proximal musculature in PFPS individuals arising from pain at the knee.

Ireland et al investigated differences in isometric hip muscle strength among young females with PFPS and healthy females. They reported that normalized isometric strength for hip abduction (PFPS= 23.3±6.9 [CI₉₅= 19.8-26.7] %BW; Control= 31.4±6.2 [CI₉₅= 28.4-34.5] %BW) and external rotation (PFPS= 10.8±4.0 [CI₉₅= 8.8-12.8] %BW; Control= 16.8±5.5 [CI₉₅= 14.0-19.6] %BW) was significantly reduced in the subjects with PFPS as compared to the healthy subjects (p<0.001).

Cichanowski et al measured six different hip isometric strength measures (flexion, extension, abduction, adduction, internal rotation, and external rotation) among female collegiate athletes with and without PFPS. They reported that the athletes with PFPS demonstrated with weakness in 5 out of 6 hip movements compared to the healthy athletes (p<0.05); hip adduction strength did not show any group difference (p=0.087).
In addition, the injured leg of the PFPS athletes demonstrated significantly weaker hip abduction and external rotation as compared to their uninjured leg (p<0.05).

The study by Robinson and Nee\textsuperscript{9} assessed limb symmetry index (LSI) for hip abduction, extension, and external rotation strengths among those with and without unilateral PFPS. The results from their study showed that LSI values for all strength measures were significantly lower in the PFPS group (range of differences between groups= 14-29%; p<0.01). They also found that hip abduction (PFPS= 16±8%BW; Control= 22±3%BW; p=0.007), extension (PFPS= 23±9%BW; Control= 48±13%BW; p<0.001), and external rotation (PFPS= 16±6%BW; Control=23±4%BW; p=0.004) strengths normalized to body mass were significantly reduced in the subjects with PFPS compared to the control subjects.

In the study by Boling et al,\textsuperscript{63} concentric and eccentric torque values of the hip (extension, abduction, and external rotation) were measured in subjects with and without PFPS. They reported that the subjects with PFPS demonstrated significantly less peak eccentric hip abduction torque (PFPS=0.048±0.017 %BW⋅height; Control= 0.061±0.015 %BW⋅height) and average concentric (PFPS=0.017±0.007 %BW⋅height; Control= 0.022±0.009 %BW⋅height) and eccentric (PFPS=0.024±0.007 %BW⋅height; Control= 0.031±0.013 %BW⋅height) hip external rotation torque.

The findings from these studies suggest that deficits in neuromuscular control and strength of the lateral hip muscles are contributing to kinematic deficits,\textsuperscript{64} that may put further stress on the patellofemoral joint. However, in all of the studies hip musculature strength values were measured in open kinetic chain, and therefore the lower extremity data and strength data were not collected simultaneously. This may put a critical
limitation to clinical and practical implication, since athletic and daily activities that require balanced neuromuscular control and muscular strength typically occur in closed kinetic chain. Therefore, other measures of neuromuscular control such as muscle activation onset timing and muscle activity duration may provide us with better understanding of lower extremity muscular strength when the neuromuscular data are collected simultaneously using EMG during a functional, closed-chain activity.

2.4.3 The role of hip adductors

Contrary to the recent effort to investigate the involvement of the proximal lateral hip musculature on altered biomechanics in PFPS, the possible association of medial hip musculature has not been extensively explored. The vastus medialis has an anatomical connection to the adductor magnus and longus muscles, via the vastoadductor membrane.\textsuperscript{50, 65-67} From clinical perspectives, this membrane is theorized to act as a pulley to enhance mechanical efficiency of the VMO. Therefore, if the VMO is not firing correctly, the hip adductor group may be required to fire longer or in greater amplitude to maintain the knee extensor mechanism. This over-activity of the hip adductors may be further contributing to increased knee valgus through increased hip adduction and hip internal rotation typically seen in patients with PFPS. However, to our knowledge, investigation to support these concepts has not been conducted.

With regards to strength deficits of the hip adductors, the few studies that have performed the investigation have yielded conflicting results. As described above, Cichanowski et al did not find any hip adductor weakness in PFPS subjects compared to the healthy subjects or the uninjured leg of the PFPS subjects.\textsuperscript{62} Niemuth et al\textsuperscript{68}
investigated the isometric strengths of six different hip muscles between recreational runners with various lower extremity injuries and healthy runners. The results revealed significant interactions between groups and between the involved and uninvolved legs of the injured runners. Post-hoc analysis yielded that flexion, abductor, adductor muscle strengths were different between involved and uninvolved legs for the injured runners. Furthermore, the involved leg of the injured runners demonstrated significantly weaker hip abductor strength as compared with the uninvolved leg of the injured runners or the legs of the healthy runners (interaction $F=34.65; p<0.001$), whereas the involved leg of the injured runners demonstrated significantly stronger hip adductor strength as compared with the uninvolved leg of the injured runners or either leg of the healthy runners (interaction $F=7.2; p<0.01$). They also found that the involved leg hip flexor muscle was significantly weaker than the uninvolved side in the injured runners ($p=0.026$) The authors discuss these imbalances in hip muscle strength may be compensatory mechanisms on the injured runners to provide stiffness or stability of the femur. However, the results of this study should be interpreted with caution, since only 6 out of 30 injured runners (20%) were diagnosed with anterior knee pain.

Due to its structural mechanical connections, incorporation of hip adduction has been considered to enhance the VMO activity during a functional rehabilitation exercise. However, research studies do not seem to support this hypothesis.69, 70 One clinical concept may be that increasing activation of the hip adductors may increase the activity of the VMO since these fibers are connected with each other, and therefore help stabilize the patella medially. The other end of that clinical concept is that the increased hip adductor activation further reduces the VMO activation, resulting in not only the patella
to shift laterally but also the femur to adduct and internally rotate, creating further patellofemoral malfunction and stress. Perhaps the reason for unsuccessful outcomes of the previous intervention studies may be inhibition or reduction of the VMO activity due to increased hip adductor. However, to our knowledge, no research has been done to investigate the direct relationship between hip adductors and VMO activation amplitude or onset timing. The previous work by the author\textsuperscript{71} is the first study that we are aware of, which looked at the EMG activities of the VMO and hip adductor (mainly adductor longus) during a dynamic postural control task. The results revealed that the subjects with PFPS demonstrated significantly increased hip adductor activity normalized to MVC (maximum voluntary isometric contraction) during the Down phase of the anterior-direction SEBT (PFPS= 59.44±20.91 %MVC; Control=44.12±17.25 %MVC; p=0.048). Interestingly, the PFPS group also demonstrated significantly higher VMO activity during the Down (PFPS= 166.81±99.91 %MVC; Control= 103.47±37.66 %MVC; p=0.036) and Up phases (PFPS= 107.56±54.05 %MVC; Control= 65.35±23.91 %MVC; p=0.013) of the SEBT. Although the results of this study support the notion of increased hip adductor activity in PFPS individuals, the increased VMO activity was not expected. The increased activity of the VMO in the PFPS may be a compensatory mechanism to recruit as much muscle fibers as possible via increase in action potentials to perform the dynamic postural control task, the SEBT. Regardless of the VMO activity, the hip adductor activity was different between groups, providing a notion that PFPS may contribute to altered activation of the hip adductor. However, more research is warranted to establish the effect of PFPS on activation of the lower extremity muscles, and how it relates to movement alteration.
Knee valgus can further increase pain about the patellofemoral articulation, and pain may inhibit or causes insufficient VMO firing, leading to further muscular and kinematic abnormality during activities. It is often a dilemma in rehabilitation that exercise interventions strictly focused on VMO “re-education” do not yield effective, long-term pain relief in PFPS patients. A part of the reason may be that the clinicians fail to see the interactions of various muscles of the lower extremity that contribute to dynamic movement, and focus their efforts on improving performance of the VMO. Although the limited investigation of the presence of a hip adductor deficit did not yield any differences between symptomatic and asymptomatic populations, no study has been performed to directly measure the hip adductor activity during a closed-chain dynamic task.

2.5 Effects of PFPS on the lower extremity kinematics and kinetics

Several authors argue that individuals with PFPS seem to demonstrate altered movement strategies to avoid exacerbation of pain via increased patellofemoral joint loading. Crossley et al\textsuperscript{7} investigated stance-phase knee flexion and onset timing of the VMO and VL during stair ambulation among subjects with and without PFPS. The results of their study show that knee flexion angle at heel strike (mean difference = 6.8° during ascent, 2.5° during descent) and peak knee flexion angle during the stance phase (6.0° during ascent, 5.5° during descent) were significantly lower in the PFPS subjects than the control subjects during stair ambulation. The authors also found that worst pain in the preceding week ($r=-0.365; p=0.011$) and duration of current symptoms ($r=-0.301$, $p=0.038$) correlated with peak stance-phase knee flexion during stair descent. Moreover,
after the PFPS group was divided into the individuals with delayed VMO onset compared to VL and those who had equal onset of them, the authors found that the subgroup with delayed VMO demonstrated significantly lower knee flexion at heel strike (delayed VMO group = 12.2°±3.6; control group = 15.8°±4.4; p=0.032) and peak stance-phase knee flexion (delayed VMO = 31.9°±8.2; control = 37.4°±5.0; p=0.019) during stair descent.

The authors discuss that painful symptoms may cause compensatory adaptations to gait kinematics, possibly in order to reduce patellofemoral joint reaction force. Furthermore, the authors discuss that compromised neuromuscular control as presented with delayed onset of the VMO relative to the VL may further contribute to patellar maltracking and altered gait kinematics.

Grenholm et al measured lower extremity kinematics during stair descent in subjects with and without PFPS. The results showed significantly reduced knee angular velocity in the PFPS group compared to the healthy group at the end of the single stance phase (PFPS= 132.2°/s; Control= 164.0°/s; p=0.007; r=0.44). However, no hip and knee kinematic differences at foot contact were observed between groups. The authors suggest a use of global kinematic analyses, which may allow researchers to identify motor control alterations in pathological individuals.

Reduced knee flexion during the stance phase of gait may have an influence on the vertical ground reaction force and therefore on the patellofemoral joint reaction force. Powers et al found that the subjects with PFPS had significantly less knee flexion at the maximum loading response during fast-walking compared to the healthy subjects (16.9°±5.1 and 21.6°±5.2m respectively; p=0.04). They also found that the PFPS group demonstrated the significantly lower average velocity (free walking 77.8±12.0 m/min vs.
lower peak vertical ground reaction force (free walking 129.5±10.2 %BW vs. 141.4±10.7 %BW, p=0.01; fast walking 139.9±19.1 vs. 166.0±16.2 %BW, p=0.001), and lower peak loading rate (free walking 93.6±35.2 BW/s vs. 161.2±72.3 BW/s, p=0.004; fast walking 154.4±65.8 vs. 238.3±102.2 BW/s, p=0.03) at free and fast walking. The authors discuss that reducing the walking velocity to reduce patellofemoral joint loading, rather than reducing the loading response knee flexion, may be the main compensatory response for avoiding pain in those with PFPS during walking at a self-selected speed. As the difficulty of the task increased by increasing the velocity, the loading response knee flexion was significantly less in PFPS subjects, alluding to the notion that compensatory mechanisms may become more apparent as the task constraints increase. Although kinematic variables were not measured, Brechter and Powers suggest that individuals with PFPS exhibit reduced knee extensor moment along with reduced patellofemoral joint reaction force during stair negotiation, possibly as compensatory strategies to reduce patellofemoral joint stress and pain.²⁹

Correlation between hip and knee weakness and frontal plane knee motion has been found in healthy subjects.⁷³ Earl et al found healthy females to display increased knee abduction and hip adduction and internal rotation during drop-jump and step-down tasks.⁷⁴ Although Claiborne et al⁷³ and Earl et al⁷⁴ related the increased knee valgus to the possibility of an ACL injury, it is feasible that frontal plane knee angle plays a role in patellofemoral tracking, patellofemoral joint stress, and propagation of pain.⁷⁵ Willson and Davis measured trunk, hip and knee isometric strength in association with knee and hip kinematics and kinetics during single-leg jump.⁷⁶ The results showed that females
with PFPS demonstrated with significantly weaker hip external rotation (PFPS= 21.1%BW, Control= 24.9%BW, p=0.05, ES=0.64), hip abduction (PFPS= 9.1%BW, Control= 10.8%BW, p=0.04, ES=0.67), and lateral trunk flexion (PFPS= 16.1%BW, Control= 22.6%BW, p=0.02, ES=0.76), compared to the healthy females. During single-leg jump, the subjects with PFPS had greater hip adduction excursion (PFPS=10.7°, Control=8.3°, p=0.05, ES=0.65) and hip abduction impulse (group difference= 18%, p=0.05, ES=0.62) compared to the healthy subjects.

In the case study by Cibulka and Threlkeld-Watkins, reduced hip internal rotation and weak hip internal rotator and abductor muscles of the symptomatic limb compared to the asymptomatic limb were observed in a patient with PFPS. This reduction in hip internal rotation may be a compensatory mechanism to reduce the Q-angle and the patellofemoral joint stress.

Souza and Powers assessed hip kinematics and hip muscle strength and activation patterns during three functional activities (running, drop jump, step-down) in people with and without PFPS. Contrary to the previous research, the results from Souza and Powers et al revealed that, across all activities, the PFPS group demonstrated significantly higher peak hip internal rotation compared to the healthy group (PFPS=7.6°±7.0, Control= 1.2°±3.8; F=16.638; p<0.001) with the largest difference during running (PFPS= 11.8°±6.9, Control= 4.2°±3.4), but no group differences were found for peak hip adduction across all activities (F=1.238; p=0.273). Also, the subjects with PFPS displayed significantly less peak isometric hip abduction torque (PFPS= 1.39±0.41 Nm/kgBW, Control= 1.62±0.26 Nm/kgBW; t=-2.07; p=0.02) and peak isometric extension torque (PFPS= 1.98±0.50 Nm/kgBW, Control= 2.35±0.38 Nm/kgBW; t=-2.69;
p=0.005) compared to the healthy subjects. Furthermore, significantly higher gluteus maximus EMG activities during step-down (PFPS= 44.1±30.6 %MVC, Control= 23.1±11.7 %MVC; p<0.05) and running (PFPS= 15.2±8.8 %MVC, Control= 9.3±4.8 %MVC; p<0.05) were observed in PFPS subjects as compared to the healthy subjects, whereas no group differences in gluteus medius amplitude were observed. Souza and Powers discuss that increased activation of weaker gluteus maximus was made in an attempt to provide hip stability, which did not seem to be very effective from the results of their study.

Dierks et al\(^\text{19}\) measured hip abduction and external rotation isometric strength before and after a prolonged run, as well as lower extremity kinematics at the beginning and end of the run between runners with PFPS and healthy runners. The results show that the runners with PFPS demonstrated significantly weaker hip abduction compared to uninjured runners before (PFPS= 15.3±2.2 kg·cm/bw, Control= 17.3±2.6 kg·cm/bw; p<0.001) and after the run (PFPS= 13.5±2.8 kg·cm/bw, Control= 15.4±2.7 kg·cm/bw; p<0.001). Hip external rotation strength was also significantly decreased after the run compared to pre-running (p<0.001), regardless of the group. Also, there was a strong negative correlation between hip abductor strength and peak hip adduction angle at the end of the prolonged run (r= -0.74; p=0.002).

Bolgla et al also hypothesized that individuals with PFPS demonstrate less hip abductor and external rotator strength and greater hip adduction, hip internal rotation, and knee valgus angles during stair descent.\(^\text{79}\) They found that the normalized hip abductor (group difference= 26%; p=0.006) and hip external rotator strengths (group difference=
were significantly lower in the PFPS group compared to the healthy group; however, they did not find any significant differences in kinematic variables.

Various kinetic differences are also observed in PFPS sufferers. Using healthy subjects, Kowalk et al\textsuperscript{13} found that subjects had a tendency towards knee abduction moment patterns during the stance phases of stair ascent and descent. Authors suggest that projection of ground reaction force passing medial to the knee joint may explain the increased knee abduction moment. Stefanyshyn et al\textsuperscript{80} found that knee abduction impulse (total internal knee abduction moment over the entire stance phase) during running is significantly higher in runners with PFPS compared to asymptomatic runners (PFPS\(=\) 17.0\(\pm\)8.5 Nms, Control\(=\) 12.5\(\pm\)5.5 Nms; p=0.026). They also performed a prospective study on 80 runners and found that the six runners who developed PFPS had significantly higher knee abduction impulses than the matched individuals who remained injury-free (PFPS\(=\) 9.2\(\pm\)3.7 Nms; matched control\(=\) 4.7\(\pm\)3.5 Nms; p=0.042). The authors discuss that increased internal abduction impulse may be a risk factor for development of PFPS in runners, and may be associated with other kinematic alterations such as increased hip adduction. Several limitations include a short injury-free period as an inclusion criterion (no injury 3 months prior to the participation of the study) and history of injuries other than PFPS in the retrospective group, as well as large variability in the abduction impulses within groups.

Although the results of previous studies have demonstrated differences in the lower extremity kinematics, we have yet to reach the consensus, perhaps due to differences in measurement techniques, and tasks in which the kinematic data are collected. Even statistically significant differences in kinematic values between groups
are small, and therefore the clinical implication of these results may not be as strong as researchers and clinicians hope for. Perhaps limitations in laboratory research lie in the fact the movement analyses are limited to generation of single joint angle at a discrete event or time point. Furthermore, due to lack of studies utilizing EMG recording of the muscles while kinematics and moments are measured in a functional activity, there seems to be scarcity of evidence how altered kinematics and kinetics are influenced by or causing neuromuscular control patterns. As muscles are considered to provide dynamic stability to the patellofemoral joint, it may be feasible to suspect that kinematic, kinetic and neuromuscular alterations are related in individuals with PFPS. Therefore, there is a need for more research studies that perform comprehensive investigation of biomechanical and neuromuscular factors simultaneously to provide researchers and clinicians with further understanding of alterations associated with PFPS.

2.6 Movement Coordination in PFPS

Previous researchers have attempted to demonstrate kinematic alterations associated with PFPS during various activities; however, there seems to be inconsistency in the results. This may be due to differences in methodology in data collection and various definitions for kinematic variables. Another explanation for the lack of kinematic differences between pathological and non-pathological groups during various functional activities may be that the previous studies only examined isolated kinematic variables at discrete time points with most of the focus on the patellofemoral articulation. PFPS seems to be a condition that is impacted by abnormalities in the entire lower extremity kinetic chain.\textsuperscript{16,19,75} Although patients with PFPS clinically have shown deficits in
movement at multiple joints, there is little evidence to support these deficits from research laboratory settings. As functional closed-chain tasks often require coordination of multiple joints in all three planes of movement, measurement of isolated joint angles at a discrete point may not provide clinical importance. There is an increasing need for applying techniques to determine intersegmental coordination of lower extremity movement to understand more fully how lower extremity pathology, such as PFPS, may be creating injurious and exacerbating lower body mechanics.

In order to investigate alterations in the human body’s natural ability to adapt to various perturbations in the environment due to injuries and pathologies, the concept of dynamical systems theory (DST) has been employed by several researchers in the last few decades to study variability in movement. This theory was formulated under the concept that the generation of movement patterns is multifactorial and movement involves the coupling of multiple degrees of freedom (e.g., muscles and joints) present in the human body.\textsuperscript{14,16} In contrast to the notion that all variability in movement is associated with instability and pathology, DST proposes that the variations in movement patterns are due to the neuromuscular system’s response to global (changes in environment) and local (proprioception) perturbations.\textsuperscript{14,81} Variability, therefore, indicates the availability or flexibility of utilizing various movement patterns (degrees of freedom in the system).\textsuperscript{15}

Newell\textsuperscript{81} proposed different types of constraints that may reduce the system’s variability: organismic constraint, which pertains to individuals’ characteristics such as morphology and pathology; environmental constraint which includes surface condition; and task constraint, which pertains not only to the task itself, but also to instructions
regarding the task (e.g., performing single-leg stance with eyes open versus eyes closed).

With a pathology or injury, it is possible that the system’s ability to explore boundaries of its stability through various movement patterns, and is forced to produce less variable, more predictable patterns of movement. DST has been utilized in the past to identify various neuromuscular disorders and injuries such as Parkinson’s disease, cerebral palsy, low back pain, ACL tear, and patellofemoral pain syndrome. Therefore, the lack of variability due to reduced degrees of freedom in movement may indicate the presence of pathology or instability, as a possible mechanism to protect oneself from exploring further into ranges of motion that may cause pain, instability or dysfunction. For example, individuals with PFPS may have reduced muscle activity, muscular strength, and range of motion (limited degrees of freedom) due to pain. They may present with more predictable, or less variable, gait patterns in order to prevent themselves from changing their gait patterns to accommodate to external stimuli (e.g., uneven surface, obstacle, etc). A few authors have reported the presence of reduced variability in coordination during locomotive tasks among PFPS participants. Hamill et al suggest that the reduced variability and high repeatability movement pattern may induce excessive wear and tear on the joint structures.

Relative phase analysis is one novel way of quantifying movement coordination based on the DST approach. It incorporates angular displacement and angular velocity of body segments or joints, and therefore provides us with spatiotemporal measure of how a body (system) coordinates two different segments or joints to achieve a task. Relative phase analysis allows the determination of whether one segment is moving faster than the other during periods of the movement cycle, which may allow the assessment of
changes in coordination patterns of the two joint segments during task performance between pathological and healthy populations. This analysis technique provides valuable information beyond the traditional discrete time point kinematic analysis that is commonly used, but does not indicate the temporal factors that can quantify normal and abnormal coordination. The author’s previous work reported that people with PFPS performed poorly on the dynamic postural control task called the Star Excursion Balance Test (SEBT) and reported more pain immediately after the task, although no kinematic differences at the time of maximum reach (touchdown) were reported. However, using the relative phase analysis, the author reported differences in relative phase variables between the pathological and non-pathological subjects, as well as between the symptomatic and asymptomatic limbs during the SEBT performance. This suggests that relative phase analysis may yield more useful information about how pathological subjects are coordinating joints differently from non-pathological subjects, instead of focusing on a single joint kinematic value at a discrete point in time.

Continuous relative phase (CRP), which expresses the relative phase values of two segments throughout the whole time period of a particular task, range between -180° and 180°, with 0° indicating perfectly synchronous, in-phase relative movement between two segments. Dierks et al investigated lower extremity CRP relationship during running in those with and without PFPS. They found that the PFPS subjects demonstrated more out-of-phase CRP between rearfoot eversion/inversion and tibial rotation, and between rearfoot eversion/inversion and knee flexion/extension, but more in-phase CRP between rearfoot eversion/inversion and knee rotation, during the first half of the stance phase. Dierks et al discuss that more in-phase CRP for rearfoot eversion/inversion and knee
rotation may be attributed by the femoral rotation, which may result in increased patellofemoral contact pressure. Ferber et al reported that runners with lower extremity injuries demonstrated more out-of-phase CRP relationship between rearfoot eversion and tibial internal rotation throughout the stance phase of running, as compared with the healthy runners.92

While CRP values provide whether two segments are moving synchronously and hence indication of intersegment stability, variability of the CRP values provide insight into the system’s flexibility to utilize multiple degrees of freedom to provide external stability while attempting to overcome various perturbations.93 In the study by Heiderscheit et al,94 the effect of Q-angle on joint coupling and variability of relative phase between different segments of the lower extremity during the stance phase of running was investigated in healthy, injury-free subjects. Q-angle did not have any significant influence on continuous relative phase (CRP) variability. However, CRP variability for thigh flexion/extension with leg rotation, thigh adduction/abduction with leg rotation, and leg rotation with foot eversion/inversion) at initial part of stance was observed regardless of differences in Q-angle (p<0.05). The authors discuss that this finding may indicate the healthy system’s ability to anticipate various perturbation at the initial foot contact, in order to maintain stability. They propose that if the variability is reduced at this moment, the system’s ability to adapt to perturbations may be reduced and result in an injury.

Despite the increasing number of studies utilizing relative phase to measure movement coordination in pathological populations, to our knowledge, there is currently no study that has quantified the extent of alterations in dynamic movement strategies
between PFPS and healthy people during stair negotiation. In addition, there has been no study combining relative phase analysis with concurrent kinetic or EMG analysis. Studying the relationship among more global movement coordination deficits through relative phase analysis and other neuromuscular deficits may help clinicians implement more effective rehabilitation programs for the patients with PFPS.
Chapter 3

Effects of Patellofemoral Pain Syndrome on Movement Coordination during Stair Ambulation.

3.1 Introduction

As patellofemoral pain syndrome (PFPS) has become a common condition in the general and athletic populations, a substantial amount of research has been published examining the effects of the condition on lower extremity kinematics. Although many authors have found significant kinematic differences between those with and without PFPS during various functional activities, many other have found no kinematic differences. Inconsistency in kinematic findings may be attributable to the fact that these analyses were made by measuring a single joint angle taken at a discrete point during a task. Clinicians visually assess coordination of multiple joints in a multiple planes during an entire task, whether it is squatting, walking, or running. As such, a great need exists to utilize a movement analysis technique which brings in multi-joint movement assessment over a period of time rather than at an isolated time point.

Relative phase analysis aims to quantify a person’s ability to coordinate multiple segments (intralimb or interlimb) during a task. Relative phase analysis has been applied to evaluate movement coordination and variability of movement between different joints during various tasks through incorporation of angular position and angular velocity of two joints. Based on the dynamical systems theory, relative phase analysis suggests that a healthy individual is able to demonstrate coordinated movement, yet is
still able to demonstrate flexibility or variability in movement and respond to various perturbations. For example, a healthy individual would be able to perform a walking task with relatively stable, or coordinated, movement between the knee and the hip, while demonstrating a greater variability in movement pattern. Therefore, variability or flexibility indicates a wider availability of movement patterns, which allows the individual to explore various movement patterns to respond to various perturbations such as an uneven surface, an obstacle, and other external forces. On the other hand, reduced stability and variability may be observed in an individual with pathology such as PFPS, indicating that the ability to coordinate intersegmental movement as well as the available movement patterns are reduced. Previous studies have used relative phase analysis to find differences in movement coordination in those with ACL reconstructed knees, low back pain, chronic ankle instability, and patellofemoral pain syndrome.

The author’s previous work reported that people with PFPS performed poorly on a measure of dynamic postural control task called the Star Excursion Balance Test (SEBT) with simultaneous reports of more pain immediately after the task. However, no kinematic differences at the time of maximum reach (touchdown) were reported. However, using the relative phase analysis, there were differences in relative phase variables between the pathological and non-pathological subjects, as well as between the symptomatic and asymptomatic limbs during the SEBT performance. This suggests that relative phase analysis may yield more useful information about how pathological subjects are coordinating joints differently from non-pathological subjects, instead of focusing on a single joint kinematic value at a discrete point in time. If individuals with PFPS in fact display altered movement coordination and variability during functional
tasks, then clinicians may be able to effectively develop rehabilitation approaches intended to increase movement coordination and variability of movement patterns.

Despite the increasing number of studies utilizing relative phase to measure movement coordination in pathological populations, to our knowledge, there is currently no study that has quantified the extent of alterations in dynamic movement strategies between PFPS and healthy people during stair negotiation, an activity of daily living that commonly exacerbates symptoms of this pathology. In addition, it is not clear whether the duration of pain affects movement coordination. It is logical to assume that the presence of pain would result in altered movement. Therefore, it is feasible to presume that movement coordination patterns are further unstable and inflexible in those with longer duration of PFPS symptoms. While reduction in available movement patterns may be a compensatory strategy to avoid pain, the long term adaptation may further limit the range of available movement and movement coordination pattern. This highly predictable and reproducible movement pattern may put excessive stress on a small area of a joint, and may cause subsequent damage to the articular cartilage and the subchondral bone.16 If clinicians are able to manage their patients’ pain and reestablish a wider variety of movement patterns, excess joint stress may be reduced, in turn deterring the progression of a degenerative disease such as osteoarthritis.

The primary aim of this study was to examine various movement coordination of the lower extremity during stair negotiation in those with and without PFPS. Furthermore, investigated whether duration of knee pain plays a role in reduced coordination and flexibility of inter-joint movement of the knee and hip. We hypothesized that PFPS individuals would demonstrate increased pain and reduced
coordination and variability of movement between the knee and hip in all three planes of movement, as compared with healthy individuals. We also hypothesized that the duration of pain in those with PFPS would be associated with reduced ability and flexibility of inter-joint movement coordination.

3.2 Materials

The following data collection instrumentations were utilized for the study:

1) Passive marker motion capture system with 12 Eagle digital cameras (Motion Analysis Corporation, Santa Rosa, CA) for the kinematic analysis

2) AMTI OR6-5 Force plate (Advanced Motion Technology, Inc., Watertown, MA) integrated with the motion capture cameras through National Instruments NI USB-6218 A/D converter (32-inputs, 16-bit, 250kS/s Isolated Multifunction I/O) (National Instruments, Austin, TX).

3) The four-step stair case with Occupational Safety and Health Administration (OSHA) compliant specifications (Appendix E)

4) Cortex 1.0.0.98 motion capture/processing software (Motion Analysis Corporation)

5) Visual 3D Basic RT (C-Motion, Inc., Germantown, MD) for post-processing data analysis

6) Microsoft Excel 2007 (Microsoft Corporation, Seattle, WA) for relative phase analysis

7) Statistical Package for Social Science (SPSS) version 15.0 (SPSS, Inc., Chicago, IL) for statistical analysis
3.3 Methods

3.3.1 Subjects

This case control study included 20 individuals with PFPS and 20 healthy individuals (Table 3.1). The participants were recruited from the University of Toledo community as well as residents of the Greater Toledo community.

Table 3.1: Subject Demographics.

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Age (years)</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PFPS</td>
<td>20 (13F, 7M)</td>
<td>21.45±3.90</td>
<td>169.96±10.47</td>
<td>71.30±14.50</td>
</tr>
<tr>
<td>Healthy</td>
<td>20 (13F, 7M)</td>
<td>21.35±3.76</td>
<td>172.21±9.24</td>
<td>69.68±9.78</td>
</tr>
</tbody>
</table>

In order to be eligible as a participant in this study, the subjects in each group had to meet the following criteria:

**Patellofemoral Pain Syndrome Group**

*PFPS Inclusion Criteria*

Volunteers were included in the PFPS group if they:

1) were diagnosed with PFPS by a physician, athletic trainer, or physical therapist

2) presented with diffuse anterior knee pain experienced for at least eight weeks,

3) had their knee pain increased by going up or down stairs, and at least one of the following activities: going up or down hills, after sitting for a prolonged period of time, walking, running, and squatting,

4) were between the age of 18 and 35.
Exclusion Criteria

Volunteers were excluded from the PFPS group if they:

1) had previous history of lower extremity injury other than PFPS,
2) had had surgical procedures that would have caused major structural changes to the knee joint,
3) were currently receiving rehabilitation, or have received rehabilitation within the last year.

Healthy Individuals Serving as Controls

Healthy volunteers had no history of lower extremity injury and no history of knee pain. Healthy subjects were matched to the PFPS subjects by gender, age, height and mass, and were assigned “symptomatic” and “asymptomatic” legs according to the matched PFPS subject.

All subjects were free from any neurocognitive deficits that affect postural control and ability to ascend/descend the stairs without ambulatory assistance. Each subject signed an informed consent form (Appendix A), approved by the Biomedical Institutional Review Board at the University of Toledo prior to the participation in the study.

3.3.2 Procedures

Subjects reported to the research laboratory for a single data collection session. After signing the approved informed consent form, the subject’s height and weight were
measured. The subjects were asked to complete the Kujala Anterior Knee Pain Scale (AKPS)\(^9\) and Lower Extremity Functional Scale (LEFS),\(^{100}\) and rate the worst pain in the previous week on a 10-cm visual analogue scale (VASW) and the current level of pain at the beginning of data collection (VASB). A sample of the 10-cm VAS is shown in Appendix B. The AKPS (Appendix C) is comprised of thirteen activity-related questions, and the subject is asked to circle the letter which best describes the level of pain he/she experiences on the symptomatic knee for each activity. If the subject presents with no pain with any of the questions, the maximum score of 100 was awarded. If the subject indicated a history of patellar dislocation, and scored 81 points or above on the 100-point AKPS, the subject was excluded from the study. The LEFS (Appendix D) consists of 20 different activities ranging from activities of daily living (ADLs) to athletic activities. Using the Likert scale of 0-4, the subject is asked to rate the perceived difficulty of each task on the day of testing. The examiner asked the subject to fill the chart using the following directions: “Please rate the difficulty of completing each task, if you are to do it today or if you have already done it today.” For each question, a score of 4 indicates no difficulty, and a score of 0 indicates that the subject was not able or did not think he/she was able to perform the task because of extreme difficulty. Therefore, if the subject did not experience or perceive any difficulty with any of the tasks, the highest score of 80 was awarded.

A passive marker motion capture system with 12 Motion Analysis Eagle digital cameras (Motion Analysis Corporation, Santa Rosa, CA) recorded the kinematic data of the hip and knee at a sampling rate of 100Hz. Subjects were asked to warm up on a stationary bicycle (Monark Ergomedic 828E Exercise Test Cycle, Monark Exercise AB,
Vansbro, Sweden), at a rate between 50 and 60 RPM and a self-selected resistance for 5 minutes. After a 5-minute rest, 25mm-radius retroflective markers for kinematic data collection were placed on the skin. Retroflective markers were placed with double-sided adhesive tape on each leg using the following marker set placements: sacrum, anterior superior iliac spine (ASIS), posterior superior iliac spine (PSIS), greater trochanter, anterior thigh cluster consisting of two medial and two lateral markers, lateral femoral condyle, anterior shank cluster consisting of two medial and two lateral markers, lateral malleolus, heel at the posterior calcaneal tuberosity, fifth metatarsal head, and first metatarsal head (Cappozzo et al IEEE 1997). Markers at the medial malleolus and medial femoral condyle were placed during a static trial. These markers created reflections that were picked up by the motion analysis camera to track the movements of the subject’s joints. Figure 3.1 shows the anterior and posterior views of the marker attachments.

Figure 3.1: The Lower Extremity Marker Sets. A: anterior view. B: posterior view.
The subject’s static data were collected while quietly standing on one of the force plates with their arms crossed in front of the chest for 5 seconds. The middle two seconds were used to obtain the baseline measures of the EMG for each muscle. Then, the subject was asked to walk up and down the 4-step stairs at a self-selected pace. We utilized a self-built stair case with a standard step height, width and depth (Appendix E). The speed of the task was not be controlled, as the angular velocities of segments were critical components of relative phase calculation, which measured how two segments are moving with each other with respect to time (angular velocity) and distance (angular position). Kinematic data during quiet standing and stair ascent and descent were recorded and processed using Cortex 1.0.0.198 motion capture/processing software (Motion Analysis Corporation), and the processed data were exported into Visual 3D Basics/RT motion analysis software (C-Motion, Inc., Germantown, MD). For both stair ascent and descent tasks, the second step was collected for the kinematic data during stair descent. This was done so that the gait events were synchronized to the force plate measures, on which an 80-pound box serving as the second step of the stairs rested (Appendix E). Each stair ambulation task was performed 5 times on each leg. The order of the starting leg was randomized to minimize the effect of fatigue across subjects. Stair trials were repeated if the subject placed more than one foot on a single force plate, or if the subject missed the force plate. Up to one minute of rest was allowed between trials to avoid fatigue. Upon completion of each stair ambulation task for each limb, the subject was asked to rate the maximum perceived pain (VASA for ascent, VASD for descent).
3.3.3 Data Processing

Visual 3D Basic/RT software (C-Motion, Inc., Germantown, MD) was used for data processing. From the original stair ambulation trials, the period during which the foot was in contact with the second step (directly above the force plate) was recorded as the stance phase. Kinematic data were normalized to 100% of the stance phase. Continuous relative phase (CRP) was calculated by first generating a phase-plane portrait of angular velocity versus angular position for proximal and distal segments. Then the phase angle for each point in the phase-plane portrait was calculated in order to transform the phase-angle trajectories from Cartesian (x,y) to polar (r, θ) coordinates using the following formula:

$$\theta(t) = \tan^{-1}(y(t) / x(t))$$

The phase angle at a single point was presented as θ(t). The value y(t) referred to the angular velocity of the time point, and x(t) referred to the angular position of the time point. CRP was then calculated by subtracting the phase angle of the proximal segment from the distal segment. For example, to obtain CRP of the knee relative to the hip (φKNEE-HIP), the following formula was applied:

$$\varphi_{KNEE-HIP} = \theta_{KNEE} - \theta_{HIP}$$

The CRP yielded the range between -180° and +180°. The CRP value closer to 0° indicated that the two segments were closer to being in phase, whereas the value closer to 180° indicated that the two segments are moving out-of-phase with each other (positive value indicates that the proximal segment is moving faster or in greater degree than the distal segment). For the entire stance period during stair ascent and descent, the mean of the absolute CRP angles was calculated to obtain the MARP value. Since the CRP values
were turned into absolute values, the MARP values range between 0° and 180°. The MARP is a somewhat simpler way of analyzing movement coordination, with the value of 180° (out-of-phase relationship between joints) indicating reduced coordination of the movement, typically indicating the presence of pathology. Additionally, a standard deviation of the absolute relative phase values was calculated to obtain a Deviation Phase (DP) for the entire stance period. It provided a measure of stability of the organization of the neuromuscular system. A low DP value, or less variability, indicated a less flexible organization, meaning that the body segments were forced to reduce their available degrees of freedom in order to maintain stability and prevent excursion of the segments that are susceptible to injury or loss of postural control.

3.3.4 Data Analysis

Independent variables included group (PFPS and Healthy), and side (Symptomatic, Asymptomatic) for each of the relative phase variables. For the VAS scores, time (worst week, baseline, ascent and descent) served as an additional independent variable. Dependent variables included the AKPS, LEFS, and VAS pain scores, mean absolute relative phase (MARP) angle and deviation phase (DP) angle between the knee and the hip during the stance phase of stair ascent and descent. Specifically, MARP and DP of the following segments were calculated:

- Knee flexion/extension – Hip abduction/adduction
- Knee abduction/adduction – Hip abduction/adduction
- Knee external/internal rotation – Hip external/internal rotation
The means and standard deviations of each dependent variable were utilized for statistical analysis. For each category of dependent variables (MARP and DP) during stair ascent and descent, a separate one-within (side) one-between (group) repeated measures analysis of variance (ANOVA) was applied. For VAS pain scores, a one-within (time) one-between (group) repeated measures ANOVA was utilized. For the AKPS and LEFS scores, a separate independent samples t-test was performed. For our purposes, stair ascent and descent were being considered as unique tasks that did not have direct statistical comparison. Statistical Package for Social Science version 15.0 (SPSS, Inc.; Chicago, IL) was used for data analysis. Post-hoc univariate analysis was performed in the event of statistically significant interactions. In addition, Pearson’s correlation product moment was applied for correlation between the duration of pain and relative phase angles, if the MARP or DP revealed statistically significant findings.

3.3.5 Power Analysis Calculation

Recently, we completed kinematic analyses of level walking between 16 PFPS and 11 healthy subjects. Our results for frontal plane joint coupling angles between the knee and the hip have shown a statistically significant interaction ($F_{1,25} = 8.60; p=0.007; \text{observed power } = 0.804$) of symptomatic side and group at heel strike, indicating that the symptomatic leg of the PFPS subjects contacted their heel with a more restricted movement pattern compared to their asymptomatic leg or to either leg of the control group (PFPSymp = 56.36±24.60°; PFPSasymp = 76.19±10.84°; CONTymp = 77.89±10.65°; CONTasymp = 67.83±21.09°). Based on the above means and standard deviations and using an online statistical calculator,$^{101}$ we estimate the statistical power to be 0.90 with 15 subjects in each of PFPS and healthy groups.
3.4 Results

3.4.1 Pain and Function Scores

The average duration of painful symptoms for the PFPS subjects was 5.28±3.82 years (minimum = 0.3 years; maximum = 15 years). The scores for the AKPS and LEFS are provided in Table 3.2, and the VAS scores in Table 3.3. The PFPS subjects scored significantly worse on the AKPS (t=12.397; p<0.001; Figure 3.2) and LEFS (t=9.07; p<0.001; Figure 3.3) scores, compared to the healthy subjects. (Table 3.2) As for VAS, multivariate analysis revealed a statistically significant time by group interaction (F₁,₃₈ = 12.729; p<0.001). Univariate analysis revealed that VAS pain scores were significantly different between groups (F₁,₃₈ = 68.92; p<0.001), indicating the PFPS group demonstrated with significantly more pain on the VAS scale compared to the healthy group (Table 3.3, Figure 3.4). Post-hoc univariate analysis revealed that the PFPS subjects reported significantly worse pain in the past week (VASW) compared to other times during the data collection (VASB, VASA, VASD) (p<0.001). Moreover, the PFPS subjects reported significantly more pain during stair ambulation tasks (VASA and VASD) compared to the baseline level of pain (VASB) at the beginning of the data collection session (VASB vs. VASA p=0.005; VASB vs. VASD p=0.009); however, there was no statistically significant difference in pain levels between stair ascending and descending tasks (p=0.974).

Table 3.2: Anterior Knee Pain Scale (AKPS) and Lower Extremity Functional Scale (LEFS) Results.

<table>
<thead>
<tr>
<th></th>
<th>Healthy</th>
<th>PFPS</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>AKPS</td>
<td>99.15±2.08</td>
<td>72.00±9.57</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>LEFS</td>
<td>79.65±0.67</td>
<td>61.50±8.92</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>
Figure 3.2: Anterior Knee Pain Scale.

Figure 3.3: Lower Extremity Functional Scale.
Table 3.3: VAS Pain Scores. The significance values were obtained from the post-hoc univariate between-subject comparison. VASW = worst pain in the previous week; VASB = pain at the beginning of the test session; VASA = worst pain

<table>
<thead>
<tr>
<th></th>
<th>Healthy</th>
<th>PFPS</th>
<th>p-values</th>
</tr>
</thead>
<tbody>
<tr>
<td>VASW</td>
<td>0.24±0.64</td>
<td>4.28±2.11</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>VASB</td>
<td>0.00±0.00</td>
<td>1.20±1.31</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>VASA</td>
<td>0.02±0.09</td>
<td>2.08±1.74</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>VASD</td>
<td>0.00±0.00</td>
<td>2.24±1.83</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

Figure 3.4: Visual Analog Scale Pain Scores.

3.4.2 Continuous Relative Phase

The continuous relative phase angles during the entire stance phases are depicted for the purpose of qualitative analysis.
3.4.2.1 Knee Abduction/Adduction – Hip Abduction/Adduction Continuous Relative Phase during Ascent

The continuous relative phase graphs of knee abduction/adduction relative to hip abduction/adduction during the stair ascending task are shown in Figure 3.5. For both symptomatic and asymptomatic legs, the PFPS individuals demonstrated more out-of-phase angles during the middle 30% of the stance phase. The rest of the CRP graphs look fairly similar between groups; however, on the asymptomatic leg, the PFPS subjects displayed more out-of-phase movement at the end of the stance phase.

![Figure 3.5: Knee Abduction/Adduction – Hip Abduction/Adduction Continuous Relative Phase during Stair Ascent.](image)

3.4.2.2 Knee Abduction/Adduction – Hip Abduction/Adduction Continuous Relative Phase during Descent

The stair descending task created clearly obvious differences between groups on both symptomatic and asymptomatic legs (Figure 3.6). On the symptomatic leg, the PFPS subjects tended to display more negative but fairly in-phase knee-hip coordination in the frontal plane, compared to the healthy subjects. It is clear in the healthy subjects, the knee-hip coordination is synchronous at the initial contact and quickly moves out-of-
phase during the first 10-20% of the stance phase, and returns to completely in-phase at approximately 25 to 30% of the stance phase. The PFPS subjects began stair descent with a slightly more negative out-phase pattern at initial contact, and did not display the quick shift in coordination for the entire stance phase. The PFPS subjects perhaps were compensating for pain by reducing the amount and speed of movement at both knee and hip in the frontal plane.

![Figure 3.6: Knee Abduction/Adduction – Hip Abduction/Adduction Continuous Relative Phase during Stair Descent.](image)

Another group difference is seen in the mid-stance, where the matched symptomatic leg of the healthy subjects displays more positive out-phase knee-hip coordination than the PFPS subjects. During the middle 30% of the stance phase during stair descent, the stance leg bears all the body weight, while the swing leg moves in front of the body to prepare for the contact with the next step. The fact that the knee-hip frontal plane coordination was more positively out-of-phase in the healthy subjects during this period may indicate that the faster or greater knee frontal plane movement may increase the ability to swing the contralateral leg faster in preparation for the subsequent step, thereby achieving a quicker execution of the stair descending task. Finally, there is a short period of negative out-phase knee-hip coordination at the end of
the stance phase in the PFPS symptomatic leg. As the stance leg comes off the step, the PFPS subjects seemed to show greater hip movement relative to the knee.

3.4.2.3 Knee Flexion/Extension – Hip Abduction/Adduction Continuous Relative Phase Ascent

For sagittal plane knee and frontal plane hip movement coordination during stair ascent, there does not seem to be a qualitative difference between groups on either leg (Figure 3.7). Although the PFPS subjects reported more pain during the stair ascending task compared to the healthy subjects, the lack of group difference on this combination of relative phase angles shows that the sagittal plane knee movement in relation to the frontal plane knee movement did not seem to be altered in the pathological subjects compared to the healthy subjects during stair ascent.

Figure 3.7: Knee Flexion/Extension – Hip Abduction/Adduction Continuous Relative Phase during Stair Ascent.
3.4.2.4 Knee Flexion/Extension – Hip Abduction/Adduction Continuous Relative Phase Descent

Contrary to the findings during the stair ascending task, the knee flexion/extension – hip abduction/adduction continuous relative phase showed more obvious group differences during the stair descent task (Figure 3.8). Although the overall patterns were similar for both symptomatic and asymptomatic legs, the PFPS subjects demonstrated significantly more in-phase knee-hip coordination throughout the stance phase, as compared with the healthy subjects. The large group difference was observed during the first one third of the stance phase, where the healthy subjects started out with more out-phase knee-hip relationship than the PFPS subjects, moved drastically out-of-phase at approximately 10-15% of the stance phase, and went more in-phase at approximately 30-35% of the stance phase. Similar to the findings from the frontal plane knee-hip continuous relative phase graphs, the healthy subjects may have shown a greater ability to move their knee relative to the movement of the hip, which may allow them to reduce joint reaction force.
Another marked difference between groups was that, for the PFPS group, there was a short period of time when the frontal plane hip movement was relatively greater than the sagittal plane knee movement during 30-45% of the stance, where as the healthy group never demonstrated greater hip movement. It can be inferred that the healthy subjects are able to move their knee in the sagittal plane at a greater degree and speed with respect to the frontal plane hip movement. Combined with the information from the knee abduction/adduction – hip abduction/adduction continuous relative phase graphs, it can be inferred that the healthy subjects are able to display greater movement at the knee in the frontal and sagittal planes, in relation to the frontal plane movement at the hip.

3.4.2.5 Knee External/Internal Rotation – Hip External/Internal Rotation

Continuous Relative Phase Ascent

Figure 3.9: Knee External/Internal Rotation – Hip External/Internal Rotation Continuous Relative Phase during Stair Ascent.

For the transverse plane knee-hip coordination during stair ascent, there seem to be two periods that showed some qualitative difference between groups on the symptomatic leg (Figure 3.9). During the first 15% of the stance phase, the PFPS subjects displayed negative coordination (greater hip rotation) while the healthy subjects
displayed positive coordination (greater knee rotation). Conversely, during 40-60% of the stance phase, the PFPS subjects displayed more positive coordination, while the healthy subjects displayed more negative coordination.

3.4.2.6 Knee External/Internal Rotation – Hip External/Internal Rotation

Continuous Relative Phase Descent

The CRP graphs between the transverse plane knee-hip movement during stair descent seemed to be most perplexed in our study (Figure 3.10). Qualitative patterns are significantly different between groups, although the PFPS subjects seem to follow the similar pattern of knee-hip coordination between the symptomatic and asymptomatic sides. The fact that the healthy subjects’ coordination changes from positive to negative relative phase angles rather quickly, without specific patterns, was somewhat unexpected. However, it may be suggestive that the healthy subjects were able to interchange the relative phase angles and thereby displaying the flexibility of movement variation. Also,

Figure 3.10: Knee External/Internal Rotation – Hip External/Internal Rotation Continuous Relative Phase during Stair Descent.
the PFPS subjects’ CRP graphs may be suggestive of a reduced pattern of movement coordination, perhaps in an effort to reduce pain.

3.4.3 Mean Absolute Relative Phase

3.4.3.1 Ascent

Table 3.4 and Figure 3.11 depict the mean absolute relative phase (MARP) angles between the knee and the hip during the stance phase of stair ascent. For the MARP between knee abduction/adduction and hip abduction/adduction, there was no group by side interaction ($F_{1, 38} = 0.865; p=0.358$) or main effect of side ($F_{1, 38} = 0.061; p=0.807$). During the ascending task, PFPS subjects displayed a slightly more out-phase coordination between knee abduction/adduction and hip abduction/adduction; however, this difference did not reach statistical significance (between-group $F_{1, 38} = 3.169; p=0.08; ES = 0.41$).

For the MARP between knee flexion/extension and hip abduction/adduction during stair ascent, there was no significant group by side interaction ($F_{1, 38} = 1.489; p=0.230$). Similarly, there were no main effects for group ($F_{1, 38} = 0.854; p=0.361; ES=-0.21$) or side differences ($F_{1, 38} = 0.057; p=0.812$).

For the MARP between knee external/internal rotation and hip external/internal rotation, no significant group by side effect was observed ($F_{1, 38} = 0.346; p=0.560$). There was no statistically significant main effect of side ($F_{1, 38} = 2.222; p=0.144$). The PFPS subjects tended to demonstrate more in-phase MARP between knee external/internal rotation and hip external/internal rotation, although the difference did not show any statistical significance (between-group $F_{1, 38} = 3.758; p=0.06; ES=-0.49$).
Table 3.4: Mean Absolute Relative Phase Angles during Stair Ascent.

<table>
<thead>
<tr>
<th>MARP Ascent</th>
<th>Healthy</th>
<th>PFPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>KAHA Symp</td>
<td>77.95±18.75</td>
<td>82.15±20.49</td>
</tr>
<tr>
<td>KAHA Asym</td>
<td>75.16±17.16</td>
<td>86.95±20.17</td>
</tr>
<tr>
<td>KFHA Symp</td>
<td>82.18±17.45</td>
<td>73.23±17.81</td>
</tr>
<tr>
<td>KFHA Asym</td>
<td>78.19±23.37</td>
<td>79.16±15.50</td>
</tr>
<tr>
<td>KRHR Symp</td>
<td>77.59±19.95</td>
<td>69.68±15.08</td>
</tr>
<tr>
<td>KRHR Asym</td>
<td>85.80±22.15</td>
<td>73.24±24.96</td>
</tr>
</tbody>
</table>

3.4.3.2 Descent

The results of the MARP angles between the knee and the hip during the stance phase of the stair descending task are shown in Table 3.5 and Figure 3.12. For the MARP between knee abduction/adduction and hip abduction/adduction during stair descent, no significant side by group interaction ($F_{1, 38} = 0.316; p=0.578$) or side main

Figure 3.11: Mean Absolute Relative Phase (MARP) during Stair Ascent.
effect \( (F_{1, 38} = 0.003; p=0.958) \) was observed. Similarly, the PFPS subjects and the healthy subjects displayed fairly similar MARP between knee abduction/adduction and hip abduction/adduction \( (\text{between-group } F_{1, 38} = 1.234; p=0.274; \text{ES}=-0.22) \).

For the MARP between knee flexion/extension and hip abduction/adduction, no significant side by group interaction was observed \( (F_{1, 38} = 0.363; p=0.550) \). Also, there was no main effect for side \( (F_{1, 38} = 0.041; p=0.841) \). However, a statistically significant group main effect was observed \( (F_{1, 38} = 76.649; p<0.001; \text{ES}=-1.09) \). The PFPS group demonstrated with significantly more in-phase MARP between knee flexion/extension and hip abduction/adduction, as compared with the healthy group.

For the MARP between knee external/internal rotation and hip external/internal rotation during stair descent, there was a statistically significant group by side interaction \( (F_{1, 38} = 7.384; p=0.01) \), while no main effect for group \( (F_{1, 38} = 0.357; p=0.554) \) or side \( (F_{1, 38} = 1.051; p=0.312) \) was observed. Post-hoc univariate analysis revealed that there was a significant difference in the MARP angle between knee external/internal rotation and hip external/internal rotation in the PFPS group \( (F_{1, 38} = 7.002; p=0.012; \text{ES}=0.67) \). Moreover, there was a significant group difference on the asymptomatic side \( (F_{1, 38} = 4.757; p=0.035; \text{ES}=-0.67) \).
Table 3.5: Mean Absolute Relative Phase Angles during Stair Descent. *Indicates a significant group main effect regardless of sides. †Indicates a significant side by group interaction.

<table>
<thead>
<tr>
<th>MARP Descent</th>
<th>Healthy</th>
<th>PFPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>KAHA Symp</td>
<td>81.20±18.35</td>
<td>79.63±17.52</td>
</tr>
<tr>
<td>KAHA Asym</td>
<td>83.69±14.76</td>
<td>77.58±16.43</td>
</tr>
<tr>
<td>KFHA Symp*</td>
<td>78.21±10.85</td>
<td>52.38±24.92</td>
</tr>
<tr>
<td>KFHA Asym*</td>
<td>75.89±11.20</td>
<td>57.03±27.18</td>
</tr>
<tr>
<td>KRHR Symp†</td>
<td>80.49±22.54</td>
<td>88.05±21.29</td>
</tr>
<tr>
<td>KRHR Asym†</td>
<td>87.19±18.15</td>
<td>73.26±22.18</td>
</tr>
</tbody>
</table>

Figure 3.12: Mean Absolute Relative Phase during Stair Descent.

3.4.4 Deviation Phase

3.4.4.1 Ascent

The results of the deviation phases (DP) between the knee and the hip during stair ascent are shown in Table 3.6 and Figure 3.13. For the DP between knee abduction/adduction and hip abduction/adduction during stair ascent, no statistically
significant side by group interaction was observed (F_{1, 38} = 0.112; p=0.740). Additionally, there was no significant side (F_{1, 38} = 0.190; p=0.665) or group difference (F_{1, 38} = 2.124, p=0.153, ES=-0.37).

For the DP between knee flexion/extension and hip abduction/adduction, there was no significant side by group interaction (F_{1, 38} = 0.156; p=0.695). Similarly, there was no significant side (F_{1, 38} = 1.134; p=0.294) or group difference (F_{1, 38} = 1.131, p=0.294, ES=0.26).

Similar to findings with other DP values, the DP between knee external/internal rotation and hip external/internal rotation did not reveal any side by group interaction (F_{1, 38} = 1.909; p=0.175). Furthermore, there was no significant main effect of side (F_{1, 38} = 1.451; p=0.236) or group (F_{1, 38} = 2.093, p=0.156, ES=-0.35).

Table 3.6: Deviation Phase Angles during Stair Ascent.

<table>
<thead>
<tr>
<th>DP Ascent</th>
<th>Healthy</th>
<th>PFPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>KAHA Symp</td>
<td>60.02±5.96</td>
<td>56.48±9.96</td>
</tr>
<tr>
<td>KAHA Asymp</td>
<td>60.18±7.86</td>
<td>57.66±8.37</td>
</tr>
<tr>
<td>KFHA Symp</td>
<td>54.73±6.58</td>
<td>55.84±5.65</td>
</tr>
<tr>
<td>KFHA Asymp</td>
<td>53.01±5.63</td>
<td>55.05±6.04</td>
</tr>
<tr>
<td>KRHR Symp</td>
<td>54.67±9.16</td>
<td>53.93±8.73</td>
</tr>
<tr>
<td>KRHR Asymp</td>
<td>55.02±10.09</td>
<td>48.88±10.82</td>
</tr>
</tbody>
</table>
3.4.4.2 Descent

The results of the DP between the knee and the hip during stair descent are shown in Table 3.7 and Figure 3.14. During the stair descending task, there was no side by group interaction for the DP between knee abduction/adduction and hip abduction/adduction ($F_{1,38} = 0.117; p=0.734$). There was no significant main effect for side ($F_{1,38} = 0.057; p=0.879$) or group ($F_{1,38} = 0.640; p=0.429; ES=0.19$).

For the DP between knee flexion/extension and hip abduction/adduction, there was no significant side by group interaction ($F_{1,38} = 0.023; p=0.879$) or main effect of side ($F_{1,38} = 0.048; p=0.828$). However, there was a significant group difference on the DP between knee flexion/extension and hip abduction/adduction during stair descent ($F_{1,38} = 82.52; p<0.001; ES=-1.22$).

For the DP between knee external/internal rotation and hip external/internal rotation, no significant side by group interaction ($F_{1,38} = 1.036; p=0.315$) or main effect
of side ($F_{1,38} = 1.172; p=0.286$) was observed. The DP seemed to be less in the PFPS subjects than the healthy subjects; however, the group main effect was not statistically significant ($F_{1,38} = 3.327; p=0.076; ES=-0.45$).

Table 3.7: Deviation Phase Angles during Stair Descent. *Indicates a significant group main effect.

<table>
<thead>
<tr>
<th>DP Descent</th>
<th>Healthy</th>
<th>PFPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>KAHA Symp</td>
<td>56.38±13.96</td>
<td>59.28±11.17</td>
</tr>
<tr>
<td>KAHA Asym</td>
<td>57.72±10.03</td>
<td>59.03±8.52</td>
</tr>
<tr>
<td>KFHA Symp*</td>
<td>56.76±5.06</td>
<td>40.31±15.51</td>
</tr>
<tr>
<td>KFHA Asym*</td>
<td>57.00±6.70</td>
<td>41.67±18.56</td>
</tr>
<tr>
<td>KRHR Symp</td>
<td>54.36±6.68</td>
<td>51.96±11.75</td>
</tr>
<tr>
<td>KRHR Asym</td>
<td>54.24±8.45</td>
<td>48.15±9.70</td>
</tr>
</tbody>
</table>

Figure 3.14: Deviation Phase during Stair Descent.
3.4.5 Correlation between Duration of Pain and Relative Phase Angles

For the relative phase angles that displayed statistical significance, Pearson’s product correlation moment was applied to investigate if the changes in the relative phase angles were correlated with the duration of pain. The results showed that, when all the subjects from both the PFPS and the healthy groups were entered, there was a significant correlation between the duration of pain and the MARP between the knee flexion/extension and hip abduction/adduction during stair descent on the symptomatic leg (Pearson $r = -0.471$; $p=0.002$). Also, there were significant correlations between the duration of pain and the DP between the knee flexion/extension and hip abduction/adduction during stair descent on the symptomatic leg (Pearson $r = -0.456$; $p=0.003$) and on the asymptomatic leg (Pearson $r = -0.329$; $p=0.038$). However, when only the PFPS subjects were entered, there was no significant correlation between the pain duration and any of these relative phase angles (pain duration to MARP between knee sagittal and hip frontal plane movement Pearson $r = -0.130$, $p=0.585$; pain duration to DP on the symptomatic leg Pearson $r = -0.071$, $p=0.766$; pain duration to DP on the asymptomatic leg Pearson $r = 0.031$, $p=0.896$).

3.5 Discussion

3.5.1 Pain and Function Levels

Overall, the PFPS subjects reported more pain and reduced functional levels compared to the healthy subjects. The PFPS subjects reported more pain during both stair ascending and descending tasks, as compared to their baseline level of pain.
However, pain levels during the stair negotiation tasks were about a half of their worst pain experienced in the previous week. Although our experiment produced increases in pain during the stair navigation, the results and anecdotal reports from our subjects indicate that the pain level remains fairly low while the tasks lasted only a few minutes. While rating their worst pain in the previous week, the subjects reported that their worst pain was felt when they were doing a prolonged activity (i.e., sitting in class for a long period of time, running or doing other athletic activity for more than half an hour, walking from the parking lot to classrooms).

Another interesting finding was that pain levels between stair ascending and descending tasks did not differ significantly in the PFPS subjects, while movement coordination stability and variability demonstrated more significant group differences during the descending task, which will be discussed in the following section. Both ascending and descending tasks were performed at a self-selected speed, and therefore it is speculated that the subjects altered movement coordination between the tasks in order to keep their pain level at a minimum level. Obviously the goals of the tasks were different, with the stair ascent task being able to exert enough power to overcome the force of gravity, and the stair descent task being able to absorb energy to control the rate of movement. We did not separate the PFPS group into those who reported more pain during ascending and descending tasks; however, it may be of future interest to divide the PFPS patients into those who experienced more pain during stair ascent and those who experienced more pain during stair descent. Depending on when the pain was experienced, our treatment approach should be different.
3.5.2 Movement Coordination and Variability during Stair Ascent

3.5.2.1 MARP

To our knowledge, this is the first study to examine the inter-joint relationship of the lower extremity during stair negotiation tasks. The mean absolute relative phase (MARP) values from this study indicated that the three combinations of the knee and hip movement relationship did not demonstrate any statistically significant group differences during stair ascent. However, there was a weak trend toward out-phase knee and hip relationship in the frontal plane as well as a trend toward in-phase knee and hip relationship in the transverse plane. Although direct comparisons with other previous studies\textsuperscript{16, 87} cannot be made for relative phase analysis, the lack of statistically significant findings related to the lower extremity kinematics during stair ascent has been consistent with other studies.\textsuperscript{7} Although stair ascent is a more demanding task than level walking, participants from this study were able to coordinate the movement between segments. However, it was interesting that no statistically significant differences existed for the frontal plane (knee and hip abduction/adduction) MARP values during stair ascent, even though the continuous relative phase graph demonstrated some marked differences in the patterns and magnitude of the CRP curves between groups. Since the MARP was taken over the entire stance period, these observable differences may have been washed out. Therefore, the future analysis should divide the stance periods to multiple periods, in order to identify the group differences in movement coordination more precisely.
3.5.2.2 DP

Similar to our MARP findings, there were no statistically significant group or side differences on the DP angles during the stair descent task. It seems that the PFPS subjects were able to demonstrate similar variability of movement, thereby exhibiting similar ability as the healthy subjects to vary their movement patterns.

Taking both of the MARP and DP results over the entire stance phase together, it seems that the PFPS subjects were able to perform the stair ascending task with similar movement coordination patterns as compared with the healthy subjects. As mentioned earlier, the goal of the stair ascending task is to keep the leg stable enough so that it can create enough energy to overcome the force of gravity and move the body upwards. The PFPS subjects seemed to be able to achieve this task, although experiencing more pain, with sufficient stability and variability of intersegmental movement.

3.5.3 Movement Coordination and Variability during Stair Descent

3.5.3.1 MARP

Contrary to our findings from the stair ascending task, the PFPS subjects demonstrated with significantly different movement patterns compared to the healthy subjects. The PFPS group showed significantly more in-phase MARP between knee flexion/extension and hip abduction/adduction during the descending task. This finding is inconsistent with other research studies that reported more out-phase MARP angles in pathological subjects during other functional tasks such as level walking,\textsuperscript{20} single-leg squat and reach task,\textsuperscript{90} and running.\textsuperscript{16, 20} Perhaps there is a compensatory strategy that was demonstrated in the PFPS group, in order to keep the pain level at minimum during
the stair descending task. From the CRP graphs, we can detect that the PFPS demonstrated more in-phase relationship between the knee flexion/extension and hip abduction/adduction during the first 30% of the stance period, which would correspond with the loading response period. Pathological individuals tend to demonstrate with less knee flexion during this period, which indicates that these individuals land with stiffer knee. More positively out-phase knee to hip coordination in the healthy subjects indicate that they were able to absorb the ground reaction force by flex the knee in a greater degree or speed relative to the hip frontal plane movement; which may decrease the knee (both tibiofemoral and patellofemoral) joint reaction force. Knee joint reaction force during stair descending task is known to be greater than that of walking or stair ascent. Therefore, the movement coordination strategy may be naturally different during stair descent than other tasks.

3.5.3.2 DP

During the stair descending task, the PFPS subjects displayed significantly less variability in movement coordination between the knee flexion/extension and hip abduction/adduction, as compared with the healthy subjects. This finding is consistent with the other authors’ work with other functional tasks. A low DP angle is indicative of reduced variability, which in turn suggests that the available movement patterns are reduced in the individual. With reduced variability, the individual may be forced to repeat the same movement pattern over and over, thereby putting continuous stress on the same area of the joint. This increased stress could be a contributing factor of PFPS.
An interesting finding was observed with the DP between the knee external/internal rotation and hip external/internal rotation on the asymptomatic side during the stair descending task. The PFPS subjects presented with significantly less DP on the asymptomatic limb, as compared with the healthy subjects; while the symptomatic leg showed no difference in the DP angle between groups. One possible reason for this finding could be that 11 out of 20 subjects reported bilateral PFPS. For those with bilateral PFPS, the symptomatic side was determined to be the side which elicited more intense and more frequent pain. However, some subjects reported more pain on the asymptomatic or less symptomatic side during our data collection session. Therefore, it is possible that the “asymptomatic” leg displayed more altered relative phase angles than the “symptomatic” leg at the time of data collection. It may be possible that the less symptomatic leg was displaying more altered relative phase angles due to compensation from pain on the contralateral leg. Bilateral effects of pathology have been reported in previous studies,\textsuperscript{103} which may help to explain the effects of PFPS on the contralateral side during the stair descending task. While the asymptomatic side of the PFPS group may not have been truly symptom-free, subjectively the selected side was what the subject felt to be more symptomatic in general. Future studies may need to more specifically consider and categorize bilateral contributions of PFPS.

3.5.4 Correlation between Pain Duration and Relative Phase Angles and Variability

Our results showed that the stair descent MARP between the knee flexion/extension and hip abduction/adduction on the symptomatic leg was negatively
correlated with the duration of pain. This indicates that more in-phase knee and hip coordination on the symptomatic leg is correlated with a longer duration of pain. As discussed in the previous section, the more in-phase coordination between the sagittal plane knee movement and the frontal plane hip movement may be a compensatory strategy to minimize pain.

Additionally, we found that the variability of movement coordination (DP) between the knee flexion/extension and hip abduction/adduction during descent on the symptomatic and asymptomatic legs during stair descent was negatively correlated with the duration of pain. In other words, the reduced movement variability appears to be related to the longer duration of pain. This finding supports our hypothesis that the duration of pain is associated with reduced variability of movement. Although only discrete sagittal plane knee angles were used, Crossley et al\textsuperscript{7} reported similar correlation between the duration of pain and reduced peak knee flexion during stair descent. The authors conclude that gait alterations may become more apparent with the longer duration of painful symptoms. Many researchers have conflicting opinions whether the painful symptoms in PFPS are a result or a cause of kinematic abnormality. A longitudinal prospective study would be the best way to answer this cause-and-effect question; however, our results may indicate that longer duration of pain may contribute to altered movement coordination and reduced variability of movement. The findings from this study would further advocate that early initiation of treatment and rehabilitative programs may prevent longer-lasting kinematic alterations that may lead to increased joint stress.
3.5.5 Limitations

One of the known limitations in the study was the excess clothing. Any subtle movement of the reflective markers placed on the clothing could have affected our kinematic results. We have attempted our best to eliminate this by having the subjects wear spandex shorts or tighter-fitting clothing or applying elastic tape to secure loose clothing as close to the skin as possible.

Visual analog assessment (VAS), AKPS and LEFS are objective tools used commonly to quantify pain and perceived level of function, which are subjective in nature. Pain is affected by many factors, some of which we may not have been able to control. Not only does pain tolerance differ between subjects, it can fluctuate within a subject across multiple assessments as well, making the subjective assessment of pain rather difficult. Although it is not ethical to purposely induce pain, a longer data collection period with increased number of stair ambulation tasks may have elicited more pain and perhaps more clear changes in movement coordination.

3.5.6 Conclusion

Our current study was the first to investigate alterations in movement coordination and variability of movement coordination during stair negotiation tasks among those with and without PFPS. We did not find any significant group difference on the relative phase measures between the knee and the hip in various planes of movement during stair ascent. However, our findings during stair descent are consistent with previous studies which utilized other functional tasks, that movement coordination is different in individuals with PFPS, as compared with healthy individuals. The tendency
in PFPS subjects of more in-phase knee-hip coordination and reduced variability of movement between the two joints may indicate that chronic knee pain may further force the pathological individuals to reduce the degrees of freedom with extremely synchronous movement pattern. This information can be useful in implementing treatment and rehabilitative strategies that address movement coordination and variability, so that the patients are able to utilize multiple coordination patterns to achieve different functional tasks.
Chapter 4

Manuscript #2: Onset Timing and Duration of the Lower Extremity Musculatures and Knee Kinetics during Stair Ambulation Tasks in Those with and without Patellofemoral Pain Syndrome.

4.1 Introduction

PFPS is a condition in which active people have diffuse pain in the anterior part of the knee caused by excessive irritation on the underside of the patella as it moves on the femur.\(^1\)\(^,\)\(^2\) It is one of the most common orthopedic injuries, affecting approximately 25% of the general population.\(^3\)\(^,\)\(^4\) The exact etiology of PFPS has not yet been fully understood. However, the excessive patellofemoral joint loading placed repeatedly over a long period of time has been suggested to result in biomechanical and neuromuscular alterations, such as increased knee adduction moment, increased knee valgus, reduced knee flexion, and weakness in the lower extremity musculatures. Additionally, pain may change neural input that are relayed to the central nervous system and change the output signal to the muscles. This may cause people to become more selective in their movement pattern, thereby limiting the degrees of freedom through which they achieve the task. Therefore, regardless of whether PFPS is caused by static structural abnormalities, prolonged pain experienced by the individuals with PFPS may result in alterations in neuromuscular control.
Alterations in firing patterns of the lower extremity muscles have been recognized in those with PFPS. Numerous studies have reported the delayed activation onset of the VMO during various tasks in those with PFPS as compared with healthy individuals.\(^7,53-55\) It has been widely recognized that the abnormal function of the VMO contributes to abnormal patellar tracking on the femur,\(^104\) which presumably increases patellofemoral joint stress and pain in PFPS patients.\(^60\)

In the light of global changes contributed by local patellofemoral pain, more recent researchers have started to investigate the influence of PFPS on proximal muscular function during activities. Brindle et al\(^11\) found that the PFPS subjects had shorter duration of the vasti activities compared to the healthy subjects. Additionally, the authors found the delayed onset and shorter duration of gluteus medius activity during stair ascent, and shorter duration of gluteus medius activity during stair descent in the PFPS subjects as compared with the healthy subjects. Cowan et al\(^61\) also detected delayed gluteus medius and VMO activation during the stair stepping task in those with PFPS. Other studies reported that isokinetic or isometric hip muscle strengths are associated with altered kinematics during various tasks.\(^9,19,79\)

While the influences of lateral hip musculatures on PFPS have gained more understanding, the influences of medial thigh musculature, the hip adductor group, on PFPS have not been widely studied. The VMO and the hip adductor group, mainly adductor magnus and longus, are connected through a thin membrane known as the vastoadductor membrane.\(^50,65-67\) Because of this anatomical connection, the hip adductor group is theorized to act as a pulley to increase the mechanical efficiency of the VMO. While this function of the hip adductor group may provide some mechanical advantage, it
could also be a compensatory mechanism for altered VMO function, contributing factor to weakening or inhibition of the VMO in those with PFPS. However, this theory has not been established yet, as previous studies that have investigated the hip adductor strength have yielded inconsistent results.\textsuperscript{62, 68} The previous work by the author of this current study has revealed that the hip adductors and the VMO normalized activities (% maximum voluntary contraction [MVC]) were significantly larger in PFPS subjects compared to healthy subjects during a dynamic postural control task.\textsuperscript{105} However, there has been no study to date which has investigated the onset timing and duration of the hip adductor group compared to other muscles of the lower extremity (VMO and lateral hip muscles), as well as between those with and without PFPS. If the muscle imbalances between the lower extremity muscles are detected, then clinicians may be able to implement rehabilitative exercises that are aimed to reestablish the proper firing patterns (onset timing and duration) of the muscles, which may help reduce kinematic and kinetic anomalies.

One of the limitations in the current research lies in the fact that no study has investigated the joint moments in conjunction with electromyographic (EMG) measures of the lower extremity muscle activation pattern. Because the hip muscle strengths are measured in an open kinetic chain, association of these strengths deficits to biomechanical factors during a closed-chain functional task may not be as strong. However, in all of the studies hip musculature strength values were measured in open kinetic chain, and therefore the lower extremity data and strength data were not collected simultaneously. This may present a critical limitation to clinical and practical implication, since athletic and daily activities that require balanced neuromuscular control and
muscular strength typically occur in closed kinetic chain movements. Therefore, other measures of neuromuscular control such as muscle activation onset timing and muscle activity duration may provide us with better understanding of lower extremity muscular strength when the neuromuscular data are collected simultaneously using EMG during a functional, closed-chain activity.

Joint internal moments and impulses can yield useful information regarding the muscle functions in response to the amount of load which is placed on the joint. When excess joint loads are placed, the surrounding muscles may respond to them by producing an opposing internal joint moment. The amount of the joint moment, therefore, can provide information regarding the joint angles and strength of the muscles which resists that movement. On the other hand, joint impulse is a product of joint moment and time, and therefore it provides information regarding the total joint load during a given period of time. Because PFPS seems to be associated with increased knee abduction (valgus), one can speculate that the internal knee adduction moment and knee adduction impulse are increased in these patients. However, to our knowledge, only one study\textsuperscript{80} has investigated knee abduction impulses in those who developed PFPS. The authors of the prospective study stated that internal knee abduction impulse was larger in those who later developed PFPS (6 out of 80 subjects), which is inconsistent with others who proposed that knee adduction moment and impulse are larger in the PFPS individuals. Since Stefanyshyn et al\textsuperscript{80} did not report any kinematic findings, it is not known if the PFPS individuals present with altered frontal plane kinetics along with altered frontal plane kinematics. More importantly, no current research has investigated the frontal plane knee joint kinetics and EMG activation onset and duration of the lower extremity muscles.
simultaneously during a functional task, such as stair ambulation. Combining these variables would provide more insight into muscular contributions to altered knee moment and impulse. This information will help clinicians develop therapeutic exercise programs that not only address the muscle imbalance but also the excessive joint loading that may be observed during functional activities in patients with PFPS.

The aims of the current study are 1) to find imbalance in muscle activation onset timing and activation duration in the VMO, adductor longus, gluteus medius and gluteus maximus muscles, and 2) to investigate differences in knee adduction moment and impulse, during stair ascending and descending tasks. Specifically, we hypothesize that adductor longus onset occurs earlier and has longer activation duration compared to three other muscles in PFPS subjects during both stair ascent and descent. Also, we hypothesize that knee adduction moment and impulse are greater in those with PFPS during both stair ascent and descent.

4.2 Materials

The following data collection instrumentations were utilized for the study:

1) An 8-channel telemeterized EMG system (Noraxon U.S.A., Inc. Scottsdale, AZ) with baseline noise of > 1 microvolt, input impedance of > 100 m Ohms, and a common-mode rejection ratio of > 100 dB.

2) An AMTI OR6-5 Force plate (Advanced Motion Technology, Inc., Watertown, MA) integrated with the motion capture cameras through National Instruments NI USB-6218 A/D converter (32-inputs, 16-bit, 250kS/s Isolated Multifunction I/O) (National Instruments, Austin, TX).
3) The four-step stair case with Occupational Safety and Health Administration (OSHA) compliant specifications (Appendix E)

4) Cortex 1.0.0.198 motion capture/processing software (Motion Analysis Corporation, Santa Rosa, CA)

5) Visual 3D Basic/RT (C-Motion, Inc., Germantown, MD) for post-processing data analysis

6) Microsoft Excel 2007 (Microsoft Corporation, Seattle, WA) for relative phase analysis

7) Statistical Package for Social Science (SPSS) version 15.0 (SPSS, Inc., Chicago, IL) for statistical analysis

4.3 Methods

4.3.1 Subjects

This case control study included 20 individuals with PFPS and 20 healthy individuals (Table 4.1). The participants were recruited from the University of Toledo community as well as residents of the Greater Toledo community.

<table>
<thead>
<tr>
<th>Table 4.1: Subject Demographics</th>
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<tbody>
<tr>
<td>N</td>
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<tr>
<td>---------</td>
</tr>
<tr>
<td>PFPS</td>
</tr>
<tr>
<td>Healthy</td>
</tr>
</tbody>
</table>

In order to be eligible as a participant in this study, the subjects in each group had to meet the following criteria:
Patellofemoral Pain Syndrome Group

PFPS Inclusion Criteria

Volunteers were included in the PFPS group if they:

1) were diagnosed with PFPS by a physician, athletic trainer, or physical therapist
2) presented with diffuse anterior knee pain experienced for at least eight weeks,
3) had their knee pain increased by going up or down stairs, and at least one of the following activities: going up or down hills, after sitting for a prolonged period of time, walking, running, and squatting,
4) were between the age of 18 and 35.

Exclusion Criteria

Volunteers were excluded from the PFPS group if they:

1) had previous history of lower extremity injury other than PFPS,
2) had had surgical procedures that would have caused major structural changes to the knee joint,
3) were currently receiving rehabilitation, or have received rehabilitation within the last year.

Healthy Individuals Serving as Controls

Healthy volunteers would have no history of lower extremity injury and no history of knee pain. Healthy subjects were matched to the PFPS subjects by gender, age, height and mass, and were assigned “symptomatic” and “asymptomatic” legs according to the matched PFPS subject.
All subjects were free from any neurocognitive deficits that affect postural control and ability to ascend/descend the stairs without ambulatory assistance. Each subject signed an informed consent form (Appendix A), approved by the Biomedical Institutional Review Board at the University of Toledo prior to the participation in the study.

4.3.2 Procedures

Subjects reported to the research laboratory for a single data collection session. After signing the approved informed consent form, the subject’s height and weight were measured. Ground reaction force, which was used to calculate the knee moments, was collected at 1000Hz using one 50cm x 50cm AMTI force plates (Advanced Mechanical Technology Inc., Watertown, MA), and recorded using Cortex 1.0.0.198 (Motion Analysis Corporation, Santa Rosa, CA). The subject was asked to warm up on a stationary bicycle (Monark Ergomedic 828E Exercise Test Cycle, Monark Exercise AB, Vansbro, Sweden), at a rate between 50 and 60 RPM and a self-selected resistance for 5 minutes. After a 5-minute rest, surface electromyography (EMG) data for the gluteus maximus, gluteus medius, adductor longus, and VMO was collected using an 8-channel telemeterized EMG system (Noraxon U.S.A., Inc. Scottsdale, AZ) at a sampling rate of 1000Hz, which was recorded in Cortex 1.0.0.198. Unit specifications for the EMG system included the baseline noise of > 1 microvolt, input impedance of > 100 m Ohms, and a common-mode rejection ratio of > 100 dB. A pair of disposable 0.8cm diameter Ag/AgCl surface electrodes with a center-to-center inter-electrode distance of 1.5cm, (Noraxon U.S.A., Inc.) were placed after the skin is cleaned, lightly debrided with sand paper, and shaved if necessary, over the gluteus medius (GMed), adductor longus (AL)
and vastus medialis oblique (VMO). For the gluteus medius, the electrode pads were placed half way between the highest point of the iliac crest and the greater trochanter of the femur.\textsuperscript{106, 107} Initially, the electrodes for the adductor longus were to be placed over the muscle 8cm distal to the pubic symphysis, according to the electrode placement for the adductor magnus as suggested by Winter.\textsuperscript{108} However, during pilot work, it was determined that the signals contained less noise when the electrodes were placed more distally, which makes the electrode placement closer to the center of the muscle belly. As a result, the electrodes for the adductor longus group were applied on the anteromedial thigh at the proximal one third of the distance between the pubic symphysis and the medial femoral condyle. For the VMO, the electrodes were placed 4cm proximal to the superior medial angle of the patella at a 55 degree angle from the line of the femur.\textsuperscript{106, 109}

The subject’s static data were collected while quietly standing on one of the force plates with their arms crossed in front of the chest for 5 seconds. The middle two seconds was used to obtain the baseline measures of the EMG for each muscle. Then, the subject was asked to walk up and down the 4-step stairs at a self-selected pace. We utilized a self-made stair case with a standard step height and depth (Appendix E). Kinetic and EMG data during quiet standing and stair ascent and descent were recorded and processed using Cortex 1.0.0.198 motion capture/processing software (Motion Analysis Corporation), and the processed data were exported into Visual 3D Basics/RT motion analysis software (C-Motion, Inc., Germantown, MD). For both stair ascent and descent tasks, the second step was used for data analysis. The second step of the stairs consisted of an 80-pound box, which was placed directly on top of the force plate. The pre-loading
of the stair was done to minimize any motion artifacts when the subject stepped on the box (the second step). The rest of the stairs were made with a square opening, so that the box serving as the second step would remain without contacting the staircase (Appendix E).

Each stair ambulation task was performed 5 times on each leg. The order of the starting leg was randomized to minimize the effect of fatigue across subjects. Stair trials were recollected if the subject placed more than one foot on the force plate, or if the subject missed the force plate. Up to one minute of rest was allowed between trials to avoid fatigue.

4.3.3 Data Processing

Visual 3D Basic/RT software (C-Motion, Inc., Germantown, MD) was used for data processing. From the original stair ambulation trials, the period during which the foot was in contact with the second step (directly above the force plate) was recorded as the stance phase. Knee kinetics were automatically calculated in Visual 3D Basic/RT using inverse dynamics, and normalized to the subject’s height (in meters) and mass (in kg). Peak knee moment was found by identifying the maximum value during the stance phase. The positive value was determined as the knee adduction moment, and the negative value as the knee abduction moment. Knee adduction (positive) or abduction (negative) impulses were calculated as the area under the curve of the knee adduction moment over the entire stance period.

The EMG signals for quiet standing and stair ambulation trials were full-wave rectified, band-pass filtered at 20-500Hz, and processed using the root mean square
(RMS) calculation over the 55-msec window. Muscle onset (milliseconds) for GMed and AL during the stair ambulation trials was defined as the time when the EMG amplitude exceeded 3 standard deviations (SDs) of baseline for a minimum of 25msec prior to or after the initial foot contact.\textsuperscript{11,53,59} For the VMO, many subjects exceeded this original threshold value for the entire data collection period. Therefore, the new threshold value for the VMO was set as the 10\% of the mean peak amplitude across the ascending or descending trials for each subject. The negative onset value would indicate that the muscle activation onset occurred prior to the foot contact, and the positive value would indicate that the muscle activation onset occurred after the foot contact. Baseline for each muscle was determined as the mean EMG amplitude during a 2-second quiet standing trial. Muscle activation duration (seconds) for each muscle was defined as the time between the muscle onset (as described above) and when the EMG amplitude fell below 3 SDs of baseline for a minimum of 25msec after the initial foot contact.

4.3.4 Data Analysis

Independent variables included group (PFPS and Healthy), and side (Symptomatic, Asymptomatic) for each of the dependent variables. Dependent variables for each of the stair ambulation tasks (ascent and descent) included peak knee adduction moment, knee adduction impulse during the stance phase, activation onset and duration of the vastus medialis oblique (VMO), adductor longus (AL), and gluteus medius (GMed). The means and standard deviations of each dependent variable were utilized for statistical analysis. For our purposes, stair ascent and descent were being considered as unique tasks that did not have direct statistical comparison. Statistical Package for Social
Science version 15.0 (SPSS, Inc.; Chicago, IL) was used for data analysis. Post-hoc univariate analysis was performed in the event of statistically significant interactions.

4.4 Results

4.4.1 Knee Kinetics

4.4.1.1 Peak Knee Frontal Plane Moment

The results of the peak knee frontal plane moment are shown in Table 4.2 and Figure 4.1. There was no statistically significant side by group interaction for both stair ascent and descent (Ascent: $F_{1,38} = 0.143, p=0.707$; Descent: $F_{1,38} = 0.075, p=0.786$). Similarly there was no main effect of side for the peak knee frontal plane moment for stair ascent and descent (Ascent: $F_{1,38} = 0.054, p=0.817$; Descent: $F_{1,38} = 0.008, p=0.927$). During stair descent, no group difference was observed for the peak knee frontal plane moment ($F_{1,38} = 1.718, p=0.198$). However, there was a statistically significant group difference on the peak knee frontal plane moment during stair ascent ($F_{1,38} = 7.806$, $p=0.008$, effect size (ES) = 0.76). Regardless of sides, the PFPS group displayed significantly higher knee abduction moment compared to the healthy group.

Table 4.2: Peak Knee Frontal Plane Moment (Nm/kg·m) during Stair Ambulation.

<table>
<thead>
<tr>
<th></th>
<th>Ascent*</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Symp</td>
<td>Asymp</td>
<td>Symp</td>
<td>Asymp</td>
</tr>
<tr>
<td>Healthy</td>
<td>0.0081±0.019</td>
<td>0.0098±0.022</td>
<td>-0.011±0.017</td>
<td>-0.0098±0.024</td>
</tr>
<tr>
<td>PFPS</td>
<td>-0.0050±0.017</td>
<td>-0.0054±0.014</td>
<td>-0.0033±0.018</td>
<td>-0.0039±0.017</td>
</tr>
</tbody>
</table>

*Indicates a significant group main effect.
4.4.1.2 Knee Frontal Plane Impulse

The results of the knee frontal plane impulse (Nm/kg⋅m\*s) during the stance phase of gait during the stair ambulation tasks are shown in Table 4.3 and Figure 4.2. During both stair ascent and descent, no significant side by group interaction was observed (Ascent: F\(_{1, 38} = 0.877\), p=0.355; Descent: F\(_{1, 38} = 0.546\), p=0.464). Similarly, no main effect of side was observed for both tasks (Ascent: F\(_{1, 38} = 0.062\), p=0.805; Descent: F\(_{1, 38} = 0.512\), p=0.478). However, for both ascending and descending tasks, there were statistically significant group differences in the knee frontal plane impulse (Ascent: F\(_{1, 38} = 8.596\), p=0.006, ES=0.78; Descent: F\(_{1, 38} = 4.329\), p=0.044, ES=0.54). The PFPS group, for both stair ascent and descent, demonstrated more knee abduction impulse, rather than adduction impulse, as compared to the healthy group.
Table 4.3: Knee Frontal Plane Impulse (Nm/kg·m*s) during Stair Ambulation. †Indicates the significant group main effect.

<table>
<thead>
<tr>
<th></th>
<th>Ascent†</th>
<th></th>
<th>Descent†</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Symp</td>
<td>Asymp</td>
<td>Symp</td>
</tr>
<tr>
<td>Healthy</td>
<td>0.11±0.21</td>
<td>0.14±0.28</td>
<td>0.078±0.20</td>
</tr>
<tr>
<td>PFPS</td>
<td>-0.041±0.24</td>
<td>-0.085±0.21</td>
<td>-0.023±0.23</td>
</tr>
</tbody>
</table>

Figure 4.2: Knee Frontal Plane Impulse (Nm/kg·m*s) during Stair Ambulation. The positive value indicates knee adduction impulse, while the negative value indicates knee abduction impulse.

4.4.2 Muscle Onset and Duration

4.4.2.1 Ascent

The results of the lower extremity muscle onset and duration during stair ambulation tasks are presented in Table 4.4, and Figures 4.3 (onset) and 4.4 (duration).
Table 4.4: Lower Extremity Muscle Onset and Duration during Stair Ascent. PFPS = patellofemoral pain syndrome; symp = symptomatic leg; asymp = asymptomatic leg; VMO = vastus medialis oblique; AL = adductor longus; GMed = gluteus medius
*Indicates a significant group difference. ^ Indicates a significant side difference.
† Indicates a significant side by group interaction.

<table>
<thead>
<tr>
<th></th>
<th>Healthy</th>
<th>PFPS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Symp</td>
<td>Asymp</td>
</tr>
<tr>
<td>Onset (ms) VMO</td>
<td>25.83 ±67.89</td>
<td>23.69 ±56.45</td>
</tr>
<tr>
<td>AL^</td>
<td>-100.88</td>
<td>-124.53</td>
</tr>
<tr>
<td></td>
<td>±134.45</td>
<td>±129.18</td>
</tr>
<tr>
<td>GMed*†</td>
<td>69.50 ±37.78</td>
<td>57.30 ±63.09</td>
</tr>
<tr>
<td>Duration (ms) VMO*</td>
<td>899.07 ±357.35</td>
<td>839.49 ±243.00</td>
</tr>
<tr>
<td>AL^</td>
<td>521.11 ±318.51</td>
<td>590.91 ±278.85</td>
</tr>
<tr>
<td>GMed*</td>
<td>706.55 ±122.59</td>
<td>680.75 ±182.65</td>
</tr>
</tbody>
</table>

Figure 4.3: Muscle Activation Onset at the Initial Contact during Stair Ascent.
The results showed that the VMO onset during stair ascent did not have any side by group interaction ($F_{1, 38} = 1.728, p=0.197$). Similarly, there was no significant main effect of side ($F_{1, 38} = 1.528, p=0.224$) or group ($F_{1, 38} = 1.728, p=0.197$).

For the VMO activation duration during stair ascent, no side by group interaction was observed ($F_{1, 38} = 0.194, p=0.662$). There was no main effect of side ($F_{1, 38} = 0.884, p=0.353$). However, a significant difference was observed for the activation duration of the VMO between groups ($F_{1, 38} = 14.639, p<0.001$). The PFPS subjects demonstrated significantly shorter activity duration of the VMO, as compared with the healthy subjects.

**Adductor Longus**

For the AL onset during stair ascent, no significant side by group interaction was observed ($F_{1, 29} = 2.031, p=0.165$). While no significant group differences were observed ($F_{1, 29} = 0.002, p=0.961$), a significant side main effect was observed ($F_{1, 29} = 4.729, p=0.038$). The effect of side was more significant for PFPS subjects, in that the
asymptomatic leg displayed a significantly earlier onset of the AL prior to the initial contact, compared with the symptomatic side (p=0.012).

As for the AL activation duration during stair ascent, no side by group interaction was observed (F₁, 29 = 0.689, p=0.662). The side main effect for the AL activation duration was statistically significant (F₁, 29 = 4.556, p=0.041), although there was no group difference for the AL activation duration (F₁, 29 = 2.041, p=0.164). The AL duration was significantly longer on the asymptomatic leg than the symptomatic leg in the PFPS group (p=0.035).

**Gluteus Medius**

A significant side by group interaction was observed for the activation duration of the GMed during stair ascent (F₁,38 = 5.223, p=0.028). Post-hoc pairwise comparison with SIDAK adjustment revealed that the PFPS group demonstrated with significantly later onset of the GMed than the health group on the asymptomatic leg (p=0.005); however the group difference in the GMed activation onset on the symptomatic was not statistically significant (p=0.08). There was no main effect of side (F₁, 38 = 0.163, p=0.689); however a significant group main effect was observed (F₁, 38 = 7.398, p=0.01).

As for the GMed activation duration during stair ascent, no significant side by group interaction was observed (F₁, 38 = 0.888, p=0.352). Similarly, no significant main effect of side was observed (F₁, 38 = 3.329, p=0.076), although the symptomatic side regardless of the groups seemed to show shorter activation duration compared to the asymptomatic side. However, a significant group main effect on the GMed activation duration was observed (F₁, 38 = 4.923, p=0.033). The GMed activation duration was significantly shorter in the PFPS subjects than in the healthy subjects.
4.4.2.2 Stair Descent

The results of the lower extremity muscle onset and duration during stair descent are presented in Table 4.5, and Figures 4.5 (onset) and 4.6 (duration).

Table 4.5: Lower Extremity Muscle Onset and Duration during Stair Descent. PFPS = patellofemoral pain syndrome; symp = symptomatic leg; asymp = asymptomatic leg; VMO = vastus medialis oblique; AL = adductor longus; GMed = gluteus medius
*Indicates a significant group difference. ^Indicates a significant side difference.

<table>
<thead>
<tr>
<th></th>
<th>Healthy</th>
<th></th>
<th>PFPS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Symp</td>
<td>Asymp</td>
<td>Symp</td>
<td>Asymp</td>
</tr>
<tr>
<td>Onset</td>
<td>VMO</td>
<td>-75.19 ±117.33</td>
<td>-75.47 ±117.90</td>
<td>-32.57 ±133.17</td>
</tr>
<tr>
<td></td>
<td>AL</td>
<td>-1.93 ±85.35</td>
<td>0.77 ±78.50</td>
<td>-11.30 ±172.96</td>
</tr>
<tr>
<td></td>
<td>GMed*</td>
<td>-50.91 ±93.12</td>
<td>-69.95 ±88.20</td>
<td>38.38 ±49.05</td>
</tr>
<tr>
<td>Duration</td>
<td>VMO^</td>
<td>810.88 ±239.60</td>
<td>913.95 ±246.14</td>
<td>754.91 ±319.34</td>
</tr>
<tr>
<td></td>
<td>AL</td>
<td>331.96 ±270.46</td>
<td>283.76 ±173.77</td>
<td>422.69 ±274.89</td>
</tr>
<tr>
<td></td>
<td>GMed*</td>
<td>526.33 ±227.55</td>
<td>510.74 ±231.26</td>
<td>274.43 ±115.00</td>
</tr>
</tbody>
</table>
Figure 4.5: Muscle Activation Onset at the Initial Contact during Stair Descent.

Figure 4.6: Muscle Activation Duration during Stair Descent.

**Vastus Medialis Oblique**

The results showed that there was no statistically significant side by group interaction ($F_{1,35} = 1.564$, $p=0.219$). No group difference was observed for the activation
onset of the VMO during stair descent (F\(_{1, 35} = 0.097, p=0.758\)). Similarly, there was no statistically significant effect of side on the VMO onset (F\(_{1, 35} = 1.591, p=0.216\)).

For the activation duration of the VMO during stair descent, there was no side by group interaction (F\(_{1, 35} = 0.672, p=0.418\)). Similarly, there was no statistically significant group difference (F\(_{1, 35} = 0.004, p=0.947\)). However, statistically significant side main effect was observed (F\(_{1, 35} = 6.247, p=0.017\)). Regardless of group, the symptomatic leg demonstrated significantly shorter activation duration of the VMO compared to the asymptomatic leg, during the stair descending task.

*Adductor Longus*

For the AL activation onset during stair descent, there was no statistically significant side by group interaction (F\(_{1, 29} = 0.267, p=0.609\)). Similarly, no statistically significant side (F\(_{1, 29} = 0.387, p=0.539\)) or group (F\(_{1, 29} = 0.014, p=0.906\)) difference was observed for the activation onset during stair descent.

For the AL activation duration during stair descent, no statistically significant side by group interaction was observed (F\(_{1, 29} = 0.381, p=0.542\)). Similarly, there was no statistically significant side (F\(_{1, 29} = 0.076, p=0.785\)) difference. The group difference for the AL activation duration did not reach statistical significance (F\(_{1, 29} = 3.228, p=0.083\)), although the PFPS group seemed to display a longer AL activation duration compared to the healthy group.

*Gluteus Medius*

For the GMed activation onset during stair descent, no significant side by group interaction was observed (F\(_{1, 35} = 0.053, p=0.819\)). A significant main effect of group was observed (F\(_{1, 35} = 18.835, p<0.001\)), although no significant effect of side was
observed ($F_{1, 35} = 0.635, p=0.431$). Regardless of leg, the PFPS subjects demonstrated significantly later onset of the GMed as compared with the healthy group during stair descent.

As for the GMed activation duration during stair descent, no significant side by group interaction was observed ($F_{1, 35} = 0.739, p=0.396$). However, significant group difference was observed for the GMed activation duration ($F_{1, 35} = 18.127, p<0.001$), while there was no significant side difference across the groups ($F_{1, 35} = 0.158, p=0.694$). The PFPS group demonstrated with significantly shorter GMed activation duration, compared to the healthy group.

4.5 Discussion

4.5.1 Frontal Plane Knee Moment and Impulse

The purpose of the current study was to simultaneously assess knee kinetics and EMG activation patterns of the lower extremity muscles between those with and without PFPS. Our results rejected the hypothesis that the PFPS subjects would display higher knee adduction moment and impulse compared to the healthy subjects during both stair ascending and descending tasks. In fact, our subjects with PFPS demonstrated with more knee abduction moment during the stance phase of stair ascent, as well as more knee abduction impulse during both stair ascent and descent. Our findings are consistent with the findings from the studies by Stefanyshyn et al$^{89}$ and by McClay and Manal,$^{110}$ both of which found that the patients with PFPS had higher knee abduction impulses during the stance phase of running. One possible explanation for our findings is that the PFPS subjects may have used a compensatory strategy. While the results are not reported in the
current study, a companion study demonstrated that those with PFPS utilize restricted movement coordination strategies. Therefore, the increased knee abduction moment and impulse may be a strategy which was utilized by the PFPS subjects to provide stability of the lower extremity during dynamic tasks.

Although it is only speculative that those with restricted movement coordination would demonstrate altered kinetics, it would be of benefit in the future to further verify the relationship between the kinematic and kinetic variables that are commonly presented in those with PFPS. In addition, internal frontal plane knee moment can be affected by the location of the ground reaction force vector in relation to the center of the knee joint. Perhaps the PFPS subjects adapted their stair ambulation strategies so that the line of the ground reaction force would pass medial to the knee joint center, thereby increasing the knee abduction moment and impulse. An increase in internal knee abduction moment and impulse could indicate that the knee is placed in more varus or adduction during the stance phase, subsequently causing the knee to experience a higher external knee adduction moment.

4.5.2 Lower Extremity Muscle Onset and Duration

Contrary to previous results, our current study did not find significantly different onset timing for the VMO between groups during stair ascent and descent. However, the activation duration of the VMO was significantly shorter in the PFPS subjects compared to the healthy subjects during both tasks. The similar results are seen in the study by Brindle et al, which examined the lower extremity muscle onset and duration during stair ambulation tasks, and found that the subjects with PFPS had a shorter duration of the
VMO during stair descent. Our results also revealed that the asymptomatic legs of the PFPS subjects demonstrated a significantly earlier activation onset and longer duration of the AL compared to the matched “asymptomatic” legs of the healthy subjects, while the symptomatic legs showed no statistically significant differences. The results of the increased knee abduction moment and impulse may explain the longer activation duration of the AL. The AL, because of the pulley function as suggested, 66 may be activated sooner and longer in compensation for the diminished activation of the VMO. However, the longer activation of the AL may have contributed to the increase in the internal knee abduction moment throughout the stance phase, which increased the knee abduction impulse. To our knowledge, this is the first study which investigated the activation patterns of the medial thigh musculature, combining the activation patterns of the other lower extremity muscles and the frontal plane kinetic measures during stair ambulation. Our study may provide some evidence to the theory of the functional connection between the VMO and AL, as stated by the authors of the previous cadaver studies which found the anatomical connection between the two muscles. 65, 66 However, it is curious that the group differences were more pronounced in the asymptomatic leg, rather than in the symptomatic leg. This finding may support the theory of bilateral neuromuscular alterations due to pain or pathology. 111 The current theory is that altered afferent input from one joint due to an injury may cause altered motor output at joints away from the source of pain or dysfunction. Also, the central nervous system may send inhibitory efferent signals to both sides despite the unilateral source of pain. Although the experiment was performed on the upper extremity, Falla et al112 found that induced pain on the right upper trapezius muscle affected activation of multiple divisions of trapezius
muscles on both the right and left sides. Other studies discuss that arthrogenic muscle inhibition, a measure of decreased motor neuron pool excitability, has been observed not only unilaterally,\textsuperscript{113} but also bilaterally.\textsuperscript{114} If the motor neuron pool excitability is diminished due to injury, muscle activation patterns may be disrupted, further contributing to movement dysfunction. Although no direct comparison can be made between the current study which examined individuals with PFPS to the aforementioned studies, it is possible that our PFPS individuals displayed bilateral deficits on the muscle activation patterns regardless of the source of painful symptoms. Further research is warranted to establish central effects of pain on muscle activation during functional tasks in this population.

Our study also revealed that during both stair ascent and descent, the subjects with PFPS displayed significantly delayed activation onset and shorter activation duration of the GMed compared to the healthy subjects. These findings are similar to the findings in the study by Brindle et al.\textsuperscript{11} However, our study is the first to have measured the activities of medial and lateral hip musculature during stair ambulation tasks using both healthy and pathological groups. Due to the threshold methods being different between the VMO and the rest of the LE muscles, we cannot make comparisons of activation onset and duration between muscles, especially between the VMO and AL, and VMO and GMed. However, in general, GMed activation during stair ascent is markedly later than AL activation, and these differences are more pronounced in the PFPS subjects. Since statistical comparisons between muscle activations was not appropriate and was not performed, the direct relationship between these two muscles cannot be established in this study. Regardless, because of the earlier onset of the AL during stair ascent and the
longer duration of the AL during stair ascent and descent, along with our findings regarding the GMed onset and duration, this may be a new insight to the development of rehabilitation exercise programs. Many clinicians utilize “ball squeezes” or knee extension exercises with hip internal rotation or adduction in the exercise program for PFPS patients, under the idea that adding hip internal rotation or adduction may enhance VMO activation or strength. However, some researchers have found no increase in the VMO activity with those exercises.\cite{70} Our findings may suggest that the AL in the PFPS patients are turned on longer already, which may bring the knee in more valgus or abduction, causing further maltracking of the patella and subsequent pain. Therefore, the exercises that have been used to help PFPS patients may be creating more pain and dysfunction. On the other hand, our results further confirmed that the lateral hip musculature such as GMed is not activating properly, likely further contributing to the knee valgus or abduction due to increased hip adduction. Our findings support the recent ideas of incorporating exercise programs that would reestablish proper neuromuscular control of the lateral hip musculature. Clinicians should therefore be careful when selecting appropriate exercise regimens for patients with PFPS, so that the proper neuromuscular control is restored.

4.6 Conclusion

To our knowledge, this study is the first to investigate the differences between those with and without PFPS on the muscle activation onset and duration of the GMed, AL, and VMO, as well as the frontal plane knee kinetics, during stair ambulation tasks. Our results revealed that the VMO and GMed activation duration were shorter and GMed
onset was delayed in the PFPS subjects, while the AL displayed earlier onset and longer duration during both stair ascending and descending tasks, compared to the muscle activation patterns of the healthy subjects. Furthermore, the knee abduction impulse was higher in the PFPS subjects than the healthy subjects during both stair ascent and descent. These findings may provide additional insights to neuromuscular control alterations in those with chronic knee pain, and suggest implementation of therapeutic exercises which enhance the GMed activity relative to the AL. Further research is warranted to confirm these findings.
Chapter 5

Summary of the Findings

The aims of the studies were to compare movement coordination and variability, combined with simultaneous measurement of muscle activation patterns and frontal plane kinetic values, during stair negotiation tasks in those with and without PFPS. The results of the first study (Chapter Three) indicate that the subjects with PFPS demonstrated more in-phase movement and less variability of movement between the knee and the hip, compared to the healthy subjects. These movement coordination alterations were observed mainly during stair descent, and were more prominent in the asymptomatic side. Furthermore, the more in-phase relationship between the knee and the hip and the less variable movement coordination were correlated with the longer duration of pain.

In the second study (Chapter Four), we found that the PFPS subjects displayed increased knee abduction moment and impulse and altered muscle activation patterns during both stair ascending and descending tasks, as compared with the healthy subjects. More specifically, while the onset timing of the vastus medialis oblique (VMO) was not significantly different between groups during either direction of stair ambulation, the subjects with PFPS demonstrated with shorter activation duration of the VMO compared to the healthy subjects. Furthermore, during both stair ascent and descent, the PFPS subjects had a significantly earlier onset and longer duration of the adductor longus (AL), while the gluteus medius (GMed) had a later activation onset and a shorter duration,
compared to the healthy subjects. Interestingly, these muscular function alterations seemed to be more notable in the asymptomatic side. Perhaps this is due to bilateral changes in neuromuscular control capability. Also, as mentioned earlier in Chapter Four, more than half of the PFPS subjects complained of bilateral symptoms, so the less symptomatic leg which was classified as the “asymptomatic” leg may have displayed more neuromuscular alterations than the more symptomatic leg.

The findings from the two studies may be closely related to each other, as neuromuscular alterations would influence or be influenced by kinematic and kinetic characteristics during functional tasks. The individuals with PFPS showed more synchronous movement between the knee and the hip in different planes of movement, while they showed less variability, indicating that they coordinated their knee and hip movement in a more predictable manner. The results of the kinetic and EMG analysis suggest that an imbalance in the muscle activation onset and duration of the medial and lateral thigh muscles may force the PFPS individuals into performing tasks in a less variable, or more predictable, coordination pattern. In addition, our results regarding the increased peak knee abduction moment and knee abduction impulse during the stance phase may further explain the observed neuromuscular alterations in the PFPS subjects. Our findings may also suggest that the subjects with PFPS were walking with more predictable and overly synchronous movement patterns in three planes of movement, which may have influenced the frontal plane internal moment throughout the stance phase and muscle activation patterns that produce the internal knee abduction moment.

Putting this all together, we can speculate that the individuals with PFPS in our study seemed to move their knee and hip in a pattern which created an increased knee
abduction moment and altered muscle activation onset and duration patterns. Specifically, the PFPS individuals demonstrated imbalance in the lower extremity muscle activation patterns that may have made them more susceptible to an increased knee abduction moment, and subsequent knee abduction (valgus) kinematic patterns relative to the hip. Clinical importance lies in the fact that our individuals with PFPS have already presented with earlier and longer activation of the AL and later and shorter activation of the GMed as well as shorter activation of the VMO, and therefore some of the exercises that are targeted to increase the AL activation to enhance the VMO function may not be providing any benefit to the patients with PFPS. Our results further advocate the use of rehabilitative exercise programs that focus on the earlier activation of the lateral hip musculature. While proper function of the AL is important in providing stability of the knee and the hip during dynamic activities, we found that overactivity of the AL is associated with kinetic and kinematic alterations in those with PFPS. Therefore, clinicians should use caution when implementing therapeutic exercises which may cause imbalance of the muscle activation patterns between various lower extremity muscles.

Future Directions

Our study did not examine the kinematic and neuromuscular characteristics of the swing (trailing) leg during stair ambulation tasks. When the initial contact of the leading leg occurs during stair negotiation, the trailing leg is still bearing weight and in contact with the previous step to provide stability. This stability from the trailing leg is critical as the leading leg comes to the contact with the subsequent step, so that the leading leg can establish proper contact with the step to transfer the body weight up or down. Future
research should investigate the movement coordination relationship between the leading and trailing legs during stair negotiation.

Due to our discovery that the muscle activity for the VMO in many individuals has exceeded the originally set threshold value taken from quiet standing during the entire data collection period, we had to utilize a different method for finding a new threshold value for the VMO. Because of this, we were unable to make direct comparisons between the three muscles to calculate activation onset latencies. In the future, it may be helpful for researchers to establish a calculation method which can be utilized for any muscle to identify its threshold value consistently across all subjects.

Finally, whilst our findings suggest that the longer duration of pain is associated with more restricted movement patterns, our study does not explain whether pain is a cause or result of movement coordination alterations. A prospective study would be necessary to establish whether these biomechanical and neuromuscular alterations are present before or after painful symptoms develop. In addition, it would be of interest to investigate at what point these biomechanical and neuromuscular alterations become irreversible in those people with longer symptoms of PFPS.
References


87. Dierks TA, Davis IS, Scholz JP, Hamill J. Continuous relative phase within the lower extremity in with patellofemoral pain during a prolonged run. Paper presented at: American Society of Biomechanics, 2006; Blacksburg, VA.


98. Bracken M. *Relative phase analysis of lower extremity kinematics among subjects with chronic ankle instability* [Master's Thesis]. Toledo, OH, University of Toledo; 2009.


Appendix A
Informed Consent Form

ADULT RESEARCH SUBJECT INFORMATION AND CONSENT/AUTORIZATION FOR USE AND DISCLOSURE OF PROTECTED HEALTH INFORMATION FORM

EFFECTS OF KNEE PATHOLOGIES ON KNEE BIOMECHANICS AND NEUROMUSCULAR CONTROL DURING STAIR AMBULATION TASKS

Principal Investigator: Phillip A. Gribble, Ph.D., ATC
Sub-Investigators: Brian G. Pietrosimone, Ph.D., ATC
Naoko Aminaka, MS, ATC
Phone numbers: (419) 530-2764

What you should know about this research study:
• We give you this consent/authorization form so that you may read about the purpose, risks, and benefits of this research study. All information in this form will be communicated to you verbally by the research staff as well.

• Routine clinical care is based upon the best-known treatment and is provided with the main goal of helping the individual patient. The main goal of research studies is to gain knowledge that may help future patients.

• We cannot promise that this research will benefit you. Just like routine care, this research can have side effects that can be serious or minor.

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

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

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

• Your participation in this research is voluntary.
PURPOSE (WHY THIS RESEARCH IS BEING DONE)

You are being asked to take part in a research study that will examine the relationship among different types of knee injuries. The angles of your joints and muscle activity will be assessed while walking up and down a set of stairs. We believe that certain characteristics of movement may cause some people with knee problems when they are younger to develop arthritis (osteoarthritis) in their knees when they are older. The purpose of the study is to determine what movement patterns occur in young people with knee pain or previous knee injuries and people with knee osteoarthritis. If we are able to identify these patterns, researchers may be able to develop types of rehabilitation that may decrease the risk of developing knee osteoarthritis.

You were selected as someone who may want to take part in this study because you have experienced or been diagnosed by a physician with patellofemoral pain syndrome or knee osteoarthritis (OA). We believe that persons with patellofemoral pain syndrome may be likely to develop OA in the future. You may also be asked to participate in this study if you have no knee pain. We need to compare people with knee pain to people without knee pain in order to detect differences in movement patterns.

This research study will be conducted in the Biomechanics Research Laboratory in the Health Science and Human Services Building at The University of Toledo. We will be enrolling a total of 60 participants ages 18 to 65 years old at the University of Toledo.

DESCRIPTION OF THE RESEARCH PROCEDURES AND DURATION OF YOUR INVOLVEMENT

After consenting to participate in this study, you will be asked to fill out a knee pain questionnaire to allow us to better understand your knee history. You will also be asked to rate the worst pain in the last week as well as the current level of pain on a 10-cm visual analog scale (VAS). In order to classify you as a member of groups with knee pain, you have to score 80 or lower on the knee pain questionnaire. Once your eligibility for participating in this study is established, your height, weight, ankle width, knee width, leg length, and foot length and width will be measured.

Next, electromyography (EMG) electrodes will be placed on the skin of your inner thigh, front of the thigh, and hip to record muscle activity. These electrodes will record muscle activity of the underlying muscle. Prior to placing them on the skin, your skin must be prepared by shaving it, lightly rubbing it with fine sandpaper, and cleansing it with alcohol. By doing this, we are removing surface hair, dead skin cells, and oils that may interrupt the data collection. These electrodes will be secured on your skin with adhesive tape. You will not feel anything from these electrodes during testing.

You will walk for 5 minutes on a treadmill at your own pace. This is done to warm your muscles up and to help prevent injury during the testing. Once your warm-up is complete, reflective markers will be placed with double-sided tape on your foot, inner and outer ankle, outer lower leg (shank), inner and outer knee, outer thigh, hip (pelvis), and lower back using double-sided tape. When participating in the study, twelve cameras mounted near the ceiling will track your motions by recording the movements of the reflective marker. The computer will then be able to draw a stick-figure of your movements. These cameras do not take actual pictures of
you when testing. They only record the reflections of the reflective markers placed on your body.

You will then be asked to perform 5 trials each of going up and down the stairs for each leg. If you are unable to perform these activities, please tell the researcher. The researcher will tell you when to start and stop each activity. If you need rest in between trials, please tell the researcher. After completing all the stair climbing trials, the electrodes and markers will be removed and you will be asked to report to Human Performance and Fatigue Laboratory.

You will then be asked to stand near the testing chair and two electrodes treated with some gel will be placed on your thigh. One of the electrodes will be placed above your knee and the other will be given to you to place below your hips so that it lies flat when you are sitting. The electrodes will be held in place with an elastic bandage. These electrodes will be used to deliver a brief, mild electrical stimulus to your thigh muscles. The electricity will be approximately a half second in duration and will contract your thigh muscle for that half second and relax.

You will be asked to sit in a chair that resembles a car seat. You will have a seat belt applied so that you do not move as you are contracting your leg muscles as hard as you can. You will then be asked to extend your leg as hard as you can and hold it for five seconds. While you are extending out the electrical stimulus will be delivered to your thigh. This stimulus feels similar to a static electric shock that you could get from walking across a carpet in a dry room and then touching a doorknob, although the voltage is lower. You will be asked to perform this at least three times at 5 different periods throughout each session at 3 different positions on both legs. You will be allowed up to 1 minute of rest between each repetition.

The whole procedure will be completed in one day and the session will last approximately one and a half hours. All of the testing performed in your session is for research purposes only. This test session is not designed to treat your existing knee pain.

The researchers encourage you to ask any questions you have prior to or during the study. If at any time you feel unable to participate in the study, for whatever reasons, please tell the researcher and you will be kindly dismissed from the study.

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

When participating in any research study, you may encounter some risks. Although the risk for taking part in this study is very low, you may experience one or more of the following:

1. Because you are participating in a functional activity, there is a chance that you could fall during the treadmill warm-up or testing. However, since you are being asked to perform everyday activities, this risk is minimal. The treadmill has railings on the side and a hand-rail in the front to grab if you feel unsteady.

2. You may experience minor muscle soreness for two or three days following the study as you would after exercising. Participating in the five minute warm-up will decrease this risk.
3. Adhesives are used to secure the reflective markers and the electrodes. If you have had a skin reaction (mild redness or itchiness) to adhesives before, there is a chance your skin may be sensitive to the adhesives used here.

4. After your skin is rubbed lightly with fine sandpaper to remove the dead skin cells, your skin may have some mild redness and mild surface scratches on it. These will go away in about 24 hours.

If you are pregnant, it is advised that you remove yourself from the study during your pregnancy. You may be able to participate following your pregnancy if volunteers are still needed. It is unknown how the EMG electrodes and reflective markers may or may not affect your pregnancy. Additionally, due to balance changes during pregnancy you may have an increased risk of falling. There are no known additional risks for pregnant women taking part in this study.

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

We cannot and do not guarantee or promise that you will receive any benefits from this research. The benefit of participating in this study is to help further research regarding knee pain.

COST TO YOU FOR TAKING PART IN THIS STUDY

You are not directly responsible for making any type of payment to take part in this study. However, you are responsible for providing your own means of transportation to and from the Health Science and Human Services Building at The University of Toledo. You will not be compensated for gas for travel or any other expenses to participate in this study.

PAYMENT OR OTHER COMPENSATION TO YOU FOR TAKING PART IN THIS RESEARCH

This study is currently submitted for the application of funding through the National Athletic Trainers' Association Research and Education Foundation. If the funding application is approved, we will be able to provide small compensation for your participation in this study. Otherwise, no compensation including money, free treatment, free medications, or free transportation will be provided for this study.

PAYMENT OR OTHER COMPENSATION TO THE RESEARCH SITE

The University of Toledo is not receiving money or other benefits from the sponsor of this research as reimbursement for conducting the research.

ALTERNATIVE(S) TO TAKING PART IN THIS RESEARCH

There is no alternative to taking part in this research. Exclusion from the study, however, will not affect the quality of care you may receive at the sports medicine/physical therapy facility, doctor’s office, or other medical facilities.

CONFIDENTIALITY - (USE(S) AND DISCLOSURE(S) OF YOUR PERSONAL INFORMATION)

By agreeing to take part in this research study, you give to The University of Toledo, the Principal Investigator and all personnel associated with this research study your permission to use or disclose health information that can be identified with you that we obtain in connection
with this study. We will use this information solely for the purpose of conducting the research study as described in the research consent/authorization form.

The information that we will use or disclose includes movement and muscle activity data from the stair ascending/descending tasks which will be recorded at Athletic Training Research Laboratory in the Health Science and Human Services building at The University of Toledo. Your data and other information will remain confidential and will be used for research purposes only. Under some circumstances, however, the Institutional Review Board, Research and Grants Administration of the The University of Toledo may review your information for compliance audits.

The University of Toledo is required by law to protect the privacy of your health information, and to use or disclose the information we obtain about you in connection with this research study only as authorized by you in this form. There is a possibility that the information we disclose may be re-disclosed by the persons we give it to, and no longer protected. However, we will encourage any person who receives your information from us to continue to protect and not re-disclose the information.

Your permission for us to use or disclose your personal health information as described in this section is voluntary. However, you will not be allowed to participate in the research study unless you give us your permission to use or disclose your personal health information by signing this document.

You have the right to revoke (cancel) the permission you have given to us to use or disclose your personal health information at any time by giving written notice to Naido Aminaka, MS, ATC, 2801 W. Bancroft, Mail Stop #119, Toledo, OH 43606. However, a cancellation will not apply if we have acted with your permission, for example, information that already has been used or disclosed prior to the cancellation. Also, a cancellation will not prevent us from continuing to use and disclose information that was obtained prior to the cancellation as necessary to maintain the integrity of the research study.

Except as noted in the above paragraph, your permission for us to use and disclose personal health information will expire at the end of the research study.

A more complete statement of University of Toledo’s Privacy Practices is set forth in its Joint Notice of Privacy Practice. If you have not received this Notice, a member of the research team will provide this to you. If you have any further questions concerning privacy, you may contact the person identified in the Notice.

IN THE EVENT OF A RESEARCH-RELATED INJURY

In the event of injury resulting from your taking part in this study, treatment can be obtained at a health care facility of your choice. You should understand that the costs of such treatment will be your responsibility. Financial compensation is not available through The University of Toledo or the University Medical Center. By signing this form you are not giving up any of your legal rights as a research subject.
In the event of an injury, contact Naoko Aminaka, MS, ATC at (727)642-3558, Brian Pietrosimone, PhD, ATC at (419) 530-4467 or Phillip Gribble, PhD, ATC at (419) 530-4271.

VOLUNTARY PARTICIPATION
Taking part in this study is voluntary. If you decide not to take part in this study, your decision will not affect your future relations with the University of Toledo, their personnel, and associated hospitals. If you do decide to take part in this research, you are free to withdraw your consent and to discontinue your participation at any time without a penalty.

NEW FINDINGS
You will be notified of new information that might change your decision to be in this study if any becomes available.

OTHER IMPORTANT INFORMATION
There is no additional information.

ADDITIONAL ELEMENTS
There are no additional elements to the study.

CONTINUED NEXT PAGE
OFFER TO ANSWER QUESTIONS

Before you sign this form, please ask any questions on any aspect of this study that is unclear to you. You may take as much time as necessary to think it over.

SIGNATURE SECTION (please read carefully)

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

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

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

<table>
<thead>
<tr>
<th>Name of Subject (please print)</th>
<th>Signature of Subject or Legally Authorized Representative</th>
<th>Date</th>
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<td>Relationship to the Subject</td>
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YOU WILL BE GIVEN A COPY OF THIS SIGNED FORM TO KEEP.

If you have any questions concerning this study or consent/authorization form beyond those answered by the investigator, including questions about the research, your rights as a research subject or research-related injuries, please feel free to contact the Chairperson of the University of Toledo Institutional Review Board at (419) 383-6796.
Appendix B

Visual Analogue Scale (VAS)

Visual Analog Scale (VAS)

No Pain

Pain as bad as it could possibly be
Appendix C

Anterior Knee Pain Scale

ANTERIOR KNEE PAIN SCALE

Subject #: ________  Group: _________  Symptomatic Knee: L / R

Duration of symptoms: ______ years ______ months

For each question, circle the latest choice (letter), which corresponds to your knee symptoms.

1. Limp
   (a) None (5)  
   (b) Slight or periodical (3)  
   (c) Constant (0)

2. Support
   (a) Full support without pain (5)  
   (b) Painful (3)  
   (c) Weight bearing impossible (0)

3. Walking
   (a) Unlimited (5)  
   (b) More than 2 km (3)  
   (c) 1-2 km (2)  
   (d) Unable (0)

4. Stairs
   (a) No difficulty (10)  
   (b) Slight pain when descending (6)  
   (c) Pain both when descending and ascending (5)  
   (d) Unable (0)

5. Squatting
   (a) No difficulty (5)  
   (b) Repeated squatting painful (4)  
   (c) Painful each time (3)  
   (d) Possible with partial weight bearing (2)  
   (e) Unable (0)

6. Running
   (a) No difficulty (10)  
   (b) Pain after more than 2 km (8)  
   (c) Slight pain from start (8)  
   (d) Severe pain (3)  
   (e) Unable (0)

7. Jumping
   (a) No difficulty (10)  
   (b) Slight difficulty (7)  
   (c) Constant pain (2)  
   (d) Unable (0)

8. Prolonged sitting with the knees flexed
   (a) No difficulty (10)  
   (b) Pain after exercise (8)  
   (c) Constant pain (6)  
   (d) Pain forces to extend knees temporarily (4)  
   (e) Unable (0)

9. Pain
   (a) None (10)  
   (b) Slight and occasional (8)  
   (c) Interferes with sleep (6)  
   (d) Occasionally severe (3)  
   (e) Constant and severe (0)

10. Swelling
    (a) None (10)  
    (b) After severe exertion (8)  
    (c) After daily activities (6)  
    (d) Every evening (4)  
    (e) Constant (0)

11. Abnormal painful kneecap (patellar) movements (subluxations)
    (a) None (10)  
    (b) Occasionally in sports activities (6)  
    (c) Occasionally in daily activities (4)  
    (d) At least one documented dislocation (2)  
    (e) More than two dislocations (0)

12. Atrophy of thigh
    (a) None (5)  
    (b) Slight (3)  
    (c) Severe (0)

13. Flexion deficiency
    (a) None (5)  
    (b) Slight (3)  
    (c) Severe (0)

TOTAL SCORE: ________

Appendix D.

Lower Extremity Functional Scale

LOWER EXTREMITY FUNCTIONAL SCALE

Subject #: __________  Group: __________  Symptomatic Leg: L / R

Today do you or would you have any difficulty at all with these activities?

<table>
<thead>
<tr>
<th>Activities</th>
<th>Unable to perform activity or extreme difficulty (0)</th>
<th>quite a bit of difficulty (1)</th>
<th>moderate difficulty (2)</th>
<th>a little bit of difficulty (3)</th>
<th>no difficulty (4)</th>
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<tbody>
<tr>
<td>1. Any of your usual work housework or school activities</td>
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<td>2. Your usual hobbies recreational or sporting activities</td>
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<td>3. Getting into or out of the bath</td>
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<td>4. Walking between rooms</td>
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<td>5. Putting on your shoes or socks</td>
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<td>6. Squatting</td>
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<td>7. Lifting an object like a bag of groceries from the floor</td>
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<td>8. Performing light activities around your home</td>
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<td>9. performing heavy activities around your home</td>
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<td>10. getting in or out of a car</td>
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<td>11. walking 2 blocks (about 1/8th mile or about 250 meters)</td>
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<td>12. walking 1 mile (1.6 km)</td>
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<td>13. going up or down 10 steps (about 1 flight of stairs)</td>
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<td>14. standing for 1 hour</td>
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<td>15. sitting for 1 hour</td>
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<td>16. running on even ground</td>
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<td>17. running on uneven ground</td>
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<td>18. making sharp turns while running fast</td>
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<td>19. hopping</td>
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<td>20. rolling over in bed</td>
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Appendix E

Stair Configuration on the Force Plate

E.1 Box specification on the force plate

E.2 Stair configuration