The effect of patellofemoral pain syndrome on the hip and knee neuromuscular control on dynamic postural control task

Shiho Goto

The University of Toledo
A Thesis

Entitled

The Effect of Patellofemoral Pain Syndrome on the Hip and Knee Neuromuscular Control on Dynamic Postural Control Task

By

Shiho Goto, ATC, LAT

Submitted as partial fulfillment of the requirements for The Master of Science degree in Exercise Science

Advisor: Dr. Phillip Gribble

Committee Member: Dr. Charles Armstrong

Committee Member: Dr. Thomas McLoughlin

College of Health Science and Human Service

College of Graduate Studies

The University of Toledo

August 2009
An Abstract of

The Effect of Patellofemoral Pain Syndrome on the Hip and Knee Neuromuscular Control on Dynamic Postural Control Task

Shiho Goto, ATC, LAT

Submitted as partial fulfillment of the requirements for
The Master of Science degree in
Exercise Science

The University of Toledo
August 2009

Context: Patellofemoral pain syndrome (PFPS) is a multifactorial knee condition. It has been suggested that alteration in hip musculature activation and excessive knee valgus are two of the major contributions to PFPS. However, the influence of hip muscle activation and knee kinematics during dynamic activity has not been explored fully. **Objective:** The primary purpose of this study was to compare hip and knee muscle activities and frontal plane knee kinematics during the anterior direction of the Star Excursion Balance Test (SEBT) between a PFPS group and a healthy group. The secondary purpose was to determine whether pain level and performance as measured by the reach distance of the dynamic postural control task may be associated with PFPS. **Design:** Case-controlled cohort study with repeated measures for the VAS. **Setting:** Athletic training research laboratory. **Patients or Other Participants:** Twenty eight subjects participated in this study and completed the test (14 PFPS: Age= 21.07±3.27yrs, Ht= 172.09±10.26cm, Mass= 69.96±9.05kg; 14 Control: Age= 20.93±3.00yrs, Ht= 170.18±8.94cm, Mass=...
Subjects with PFPS reported minimal 2 months of anterior or lateral knee pain with walking, running, ascent and descent of stair climbing, kneeling, squatting, and sitting for long periods of time. **Interventions:** Participants performed 3 maximal voluntary isometric contractions (MVIC) in hip abduction, extension, external rotation, and knee extension and 5 anterior reaches of the SEBT. **Main Outcome Measures:** Frontal plane knee kinematics, anterior reach distance during the SEBT, and normalized average electromyography (Norm Avg EMG (%MVIC)) of the gluteus maximus (GMax), gluteus medius (GMed), and the vastus medialis (VM) were measured. In addition, knee pain was assessed with the Visual Analog Scale (VAS) before, during and after the task. **Results:** Comparing to the control group, PFPS group demonstrated increased knee valgus angle at touchdown, the point of the maximum reach (p=0.047), and significantly less varus displacement during the SEBT (p=.011). When observing the anterior-direction SEBT, reach distances were significantly shorter in PFPS group compared to the healthy group (p=.014). For pain on the visual analogue scale (VAS), there was a statistically significant group by time interaction for VAS ($F_{2,52}=4.70$, $p<.001$). PFPS group demonstrated significantly increased pain at pre, during, and post tasks. In addition, subjects with PFPS demonstrated significantly increased pain during and post tests compared to pre test, and increased pain during test compared to post test. There was a statistically increased VM normalized average EMG in the PFPS group compared to the control group while there was no statistically significant difference in the iEMG of the gluteus medius and gluteus maximus between groups. **Conclusion:** The results derived from our study indicate that PFPS subjects demonstrate increased knee valgus angle in the anterior reach task on the SEBT. In addition, the PFPS group demonstrated shorter
reach distance on the SEBT, along with increased pain on the VAS. On the contrary to our hypothesis, subjects with PFPS demonstrated greater VM activities than healthy subjects. In the sagittal plane movement, VM may play an important role to maintain the balance, while GMed and GMax may not be the primary muscle for the postural control during the task. During a common sagittal plane rehabilitation activity, it may be important for clinicians to observe differences in frontal plane positioning at the knee with PFPS.
Acknowledgement

I would like to give a great thanks to my Advisor, Dr. Phillip Gribble, giving me an opportunity to come to this program. He has spent a lot of time to develop this project and guided me where I am now. Without his support, guidance and encouragement, I would never have finished this thesis.

I would also like to recognize my committee members, Dr. Charles Armstrong and Dr. Thomas McLoughlin. I appreciate for your time and input to assist me in completing this research.

I would like to give a special thanks to Naoko Aminaka as my mentor and long time friend, spending as much time as she could and putting great effort and knowledge on the completion of this study. Without her support, I would not have completed the projects. Thank you for your encouragements and laughs. I also would like to thank Holly Snell and Danielle Dinkelacker, senior athletic training students, for their help throughout data collection.

I would like to express a deepest appreciation to all of the faculties in the department of kinesiology and classmates for their support. Thank you to the all volunteer subjects who participated in this study. Without their participation, I would never have completed this project.

Lastly, I need to thank to my family for understanding, supporting, and encouraging me to complete master’s degree and pursue this career.
# Table of contents

Abstract                                    ii
Acknowledgements                            v
Table of Contents                           vi
List of Tables                              ix
List of Figures                             x

## I. Introduction

Statement of the problem                  4
Statement of the purpose                  5
Specific aims and hypotheses              5

## II. Literature Review

Definition of the patellofemoral pain syndrome  7
Etiology                                    7
Patellofemoral joint functional anatomy     8
Gluteus medius                              10
Gluteus maximus                             10
Dynamic malalignment of the lower extremity  11
  Qudriceps angle                           11
  Gluteus muscles strength deficit          12
  Rehabilitation intervention              19
Star Excursion Balance Test               22
Summary                                    25
III. Methodology 26

Subjects 26

Instrumentation 27

Procedures 27

Data analysis 31

Independent variables 31

Dependent variables 32

Power analysis calculation 33

IV. Results 35

Knee valgus angle 35

Normalized reach distance (%MAXD) 35

Pain on the Visual Analogue Scale (VAS) 36

Normalized average EMG of the vastus medialis during the SEBT (%MVIC) 36

Normalized average EMG of the gluteus medius during the SEBT (%MVIC) 37

Normalized average EMG of the gluteus maximus (hip extensors) during the SEBT (%MVIC) 37

Normalized average EMG of the gluteus maximus (hip external rotators) during the SEBT (%MVIC) 37

V. Discussion 46

Knee kinematic alteration 46

Hip and knee musculature activation 49
Pain on the VAS  52
Normalized anterior reach distance (%MAXD)  53
Summary  54
Limitation  55
Clinical implication  55
Conclusion  56

VI. References  57

VII. Appendix

A. Informed Consent Form  62

B. Visual Analogue Scale  71

C. Star Excursion Balance Test Directions  75

D. Picture of Anterior Reach for the Star Excursion Balance Test  77

E. Data Collection Sheet  79

F. Pictures of Maximal Voluntary Isometric Contraction  82

G. Picture of Motion Monitor  87
List of Tables

Table 1. Demographic data 38
Table 2. Valgus Angle at Touch-down (TD) 38
Table 3. Knee Valgus Angle displacement 38
Table 4. Normalized Reach Distance (MAXD%) 38
Table 5. Pain in Visual Analogue Scale (VAS) 39
Table 6. PFPS pain in VAS 39
Table 7. Normalized Average EMG of Vastus Medialis during the SEBT 39
Table 8. Normalized Average EMG of Gluteus Medius during the SEBT 40
Table 9. Normalized Average EMG of Hip Extensors during the SEBT 40
Table 10. Normalized Average EMG of Hip External Rotators during the SEBT 40
List of Figures

Figure 1. Frontal Knee Kinematic at Touchdown (Knee Valgus) 41
Figure 2. Frontal Knee Kinematics Displacement 42
Figure 3. Normalized Reach Distance (%MAXD) 43
Figure 4. Visual Analogue Scale (VAS) 44
Figure 5. Normalized Average EMG of Vastus Medialis during the SEBT 45
Figure 6. Normalized Average EMG of the Gluteus Medius during the SEBT 45
Figure 7. Normalized Average EMG of the Gluteus Maximus (Hip Extensors) during the SEBT 45
Figure 8. Normalized Average EMG of the Gluteus Maximus (Hip External Rotators) during the SEBT 45
Chapter I

Introduction

Patellofemoral pain syndrome (PFPS) is one of the most common conditions associated with knee pain.\textsuperscript{1} It is described as an anterior or retro patellar pain with stair climbing, squatting, running, jumping, kneeling, or sitting for a long period of time.\textsuperscript{2-4} Although there are no definitive etiologies, previous studies have identified predisposing factors to PFPS such as overuse activities, direct trauma, muscle dysfunction in the knee and hip, lateral knee tightness, patellar hypermobility, pronated foot, and increased quadriceps angle (Q-angle).\textsuperscript{2-10}

Recently, several studies have reported that interactions of the hip and patellofemoral joint may contribute to PFPS.\textsuperscript{11-13} Increased Q-angle results in excessive valgus angle at the knee, which may be a predisposing factor for PFPS. It is suggested that weak hip abductors and external rotators may not provide sufficient strength to resist hip internal rotation and hip adduction during dynamic activities.\textsuperscript{6} The increased knee valgus angle, may result in an increased lateral quadriceps muscle force on the patella, resulting in abnormal patellar tracking.\textsuperscript{8}
Previous studies have demonstrated diminished isometric strength in hip abductors and hip external rotators in PFPS subjects compared with healthy subjects.\textsuperscript{11-13} Ireland et al.\textsuperscript{11} determined that individuals with PFPS demonstrated a 26\% decrease in hip abduction and a 36\% decrease in hip external rotation force production compared with those of healthy individuals. Cichanowski et al.\textsuperscript{12} reported that female subjects with PFPS had significant weakness in hip abductors and hip external rotators compared with healthy subjects. Robinson and Nee\textsuperscript{13} found that in PFPS subjects isometric muscle force production of the hip extensors, hip abductors and hip external rotators was 52\%, 27\%, and 30\% less, respectively, than that of healthy subjects. Other studies have demonstrated that physical therapy including hip muscular strengthening significantly decreased anterior knee pain in PFPS subjects.\textsuperscript{14-17} Examining these studies\textsuperscript{11-17} could lead to a hypothesis that there is a relationship between weak hip muscles, which do not provide sufficient resistance to hip internal rotation and hip adduction, and an increased knee valgus angle which results in patellar mal-tracking. However, this relationship has not been realized fully, perhaps because these studies were conducted in static or non-weight bearing conditions, making it challenging to help explain weight-bearing mechanisms of injury.

Brindle et al.\textsuperscript{18} conducted one of the first studies to examine the relationship between gluteus medius, vastus medialis oblique (VMO) and vastus lateralis (VL) and anterior knee pain during dynamic postural control. They report that PFPS subjects had delayed onset and shorter durations of gluteus medius activation during ascending and descending stairs compared with those of VMO and VL; while there was no significant difference in duration and onset between VMO and VL. However, they did not quantify
the frontal knee kinematics during the task. While there seems to be an increased focus on hip muscle weakness to help correct knee valgus and decrease PFPS pain in clinical practice, there are a limited number of controlled studies that have quantified this relationship in dynamic activities.\textsuperscript{19} Since most activities are dynamic in daily life and in athletic participation, additional investigation of the relationship of neuromuscular alteration in the knee and hip in PFPS patients during dynamic tasks is needed.

The Star Excursion Balance Test (SEBT) has been used to quantify lower extremity function and dynamic postural control. The task involves incorporating a single leg squat while attempting to reach as far as possible with the opposite leg along eight separate lines oriented 45° from each other.\textsuperscript{20-22} The ability to reach farther while maintaining the single leg position is used as an indicator of more lower extremity function and dynamic postural control.\textsuperscript{20-22} With a strong level of reliability associated with this task,\textsuperscript{23,24} the SEBT has been effective in detecting deficits in lower extremity injury,\textsuperscript{22,25} as well as predict other lower extremity injuries\textsuperscript{21}. While the majority of work with the SEBT has been associated with ankle instability,\textsuperscript{22,25} recent investigation has applied the test in evaluating PFPS. Aminaka and Gribble\textsuperscript{26} demonstrated a decrease in dynamic postural control during the anterior directions of the SEBT in subjects with PFPS compared with healthy subjects, along with an associated increase in pain. In addition, Ebersole et al.\textsuperscript{27} reported a shorter reaching distance in the posterior direction in PFPS subjects compared with healthy subjects. Earl et al\textsuperscript{28} quantified the amount of EMG activation in a variety of lower extremity muscles in the thigh and lower leg during performance of the SEBT by healthy subjects. However, the relationship between hip musculature EMG activation and reach distance to our knowledge has not been explored. Furthermore, the influence of
the activation of the gluteus medius and gluteus maximus on the deficits in performance of a dynamic postural control task in PFPS subjects has not been quantified.

The gluteus medius is a primary hip abductor and a secondary hip external rotator; while the gluteus maximus is a primary hip extensor and external rotator.29 The two muscles are activated during a single leg squat in a concentric and eccentric manner to control knee kinematics in the frontal plane.30 Considering that the knee and hip movements occurring in the SEBT are similar to those of a single leg squat, the SEBT will be an appropriate method to measure the activation of those two muscle groups, while adding additional challenges related to the production of dynamic postural control.

Previous authors14,18,19 have studied the activation of hip muscles and knee kinematics separately during dynamic activity; but the measurements have not been combined to examine how the two contributing factors to PFPS may be associated with deficits in dynamic postural control. Therefore, the primary purpose of this study is to determine the effects of PFPS on hip neuromuscular control of knee frontal plane kinematics during a dynamic postural control task. Because previous work from our research laboratory26 demonstrated an increased level of pain in PFPS subjects while performing the SEBT, it is important to investigate this symptom’s influence on the task performance as a secondary purpose. The results from our study may help to establish rehabilitation and prevention protocols for individuals suffering from PFPS.

Statement of the problem

While previous studies have found the presence of gluteal and knee muscle weakness in the subjects with PFPS, the relationship of the muscle weakness and the
knee and hip kinematics has not fully been investigated. The previous studies have been conducted in open kinetic chain or non-weight bearing condition. More recently, several researchers have observed the relationship of the gluteus muscle strength and the knee and hip kinematics during different activities. However, the outcomes were inconclusive.

**Statement of the purpose**

The purpose of this study was to examine the effects of PFPS on measures of knee and hip neuromuscular control during a dynamic postural control task.

**Specific aims and hypotheses**

- **Specific Aim #1**: To determine if individuals with PFPS would present with a reduction in dynamic postural control compared to healthy control subjects.
  
  *Hypothesis #1*: Healthy subjects would reach farther than PFPS subjects during the SEBT, indicating a reduction in dynamic postural control in the PFPS subjects.

- **Specific Aim #2**: To determine if subjects with PFPS had an alteration in hip function during a dynamic postural control task.
  
  *Hypothesis #2*: PFPS subjects would demonstrate reduced muscle activation of the gluteus medius and maximus during performance of the SEBT compared to the healthy subjects.

- **Specific Aim #3**: To determine if subjects with PFPS had an alteration in knee function during a dynamic postural control task.
  
  *Hypothesis #3*: PFPS subjects would demonstrate reduced muscle activation of the vastus medialis during performance of the SEBT compared to the healthy
subjects.

- **Specific Aim #4**: To determine if subjects with PFPS had an alteration in knee positioning during a dynamic postural control task.

  *Hypothesis #4*: PFPS subjects would demonstrate an increased knee valgus angle during performance of the SEBT compared to the healthy subjects.

- **Specific Aim #5**: To determine the amount of pain at rest as well as associated with performance of a dynamic postural control task.

  *Hypothesis #5a*: PFPS subjects would experience more knee pain presented by the visual analogue scale (VAS) at rest compared to the Healthy subjects

  *Hypothesis #5b*: The VAS score would increase during performance of the test in the PFPS subjects compared to before and after the test performance.
Chapter II

Literature Review

Definition of patellofemoral pain syndrome

Patellofemoral pain syndrome (PFPS) is a common condition presenting with anterior and retropatellar knee pain.\(^1\) Its onset is generally insidious, and pain develops with knee flexion and extension associated with walking, running, ascending and descending stairs, kneeling, prolonged sitting, and squatting. Pain is experienced by the activity and becomes consistent over time.\(^2-4\)

Etiology

The etiology of PFPS is not clarified and remains controversial.\(^2-10\) Several previous studies have suggested that pain is generated after articular cartilage is worn due to patellar maltracking on the femoral trochlea with increasing compressive force across the patellofemoral (PF) joints.\(^4,5\) There are many predisposing factors to PFPS reported, such as a pronated foot, excessive tibial internal rotation, increased valgus knee angle, excessive femoral internal rotation, inflexibility of surrounding soft tissues, leg length discrepancy, and strength deficit of the quadriceps and hip muscles.\(^2-10\)
Patellofemoral joint functional anatomy

The patellofemoral (PF) joint is the least congruent joint in the body, comprised of the patella and distal part of the anterior femur.\textsuperscript{31} Dynamic stability is provided by the quadriceps tendon, patellar tendon, vastus medialis oblique (VMO), vastus lateralis (VL), and iliotibial band, while the articular capsule, femoral trochlea, medial and lateral retinacula and patellofemoral ligament provide static stability.\textsuperscript{4,31} The posterior aspect of the patella articulates with the distal part of the femur.\textsuperscript{32} The patella works as a pulley to reduce friction between the patellar tendon and the femur. The quality of its function depends on the patellar tracking on the femur during knee flexion and extension.

The patella is the largest sesamoid bone in the body, and surrounded by the quadriceps muscle group: vastus medialis, VL, vastus intermedius, and rectus femoris.\textsuperscript{29,31} The posterior surface of the patella is covered with the thickest articular cartilage (7mm at the midpoint of the ridge) in the body.\textsuperscript{32} The vertical ridge divides the surface into two facets: the larger lateral facet and the smaller medial facet. Furthermore, the odd facet separates the medial facet and the extreme medial edge.\textsuperscript{31,32} The posterior surface is convex toward the center of the patella and concave superior to inferior, and medial to lateral.\textsuperscript{31,32} The patella sits between the femoral condyles, with its vertical ridge corresponding to the intercondylar groove of the femur.\textsuperscript{29,31}

With the knee fully extended, the articular cartilage of the patella has minimal or no contact with the femoral groove. The inferior parts of the lateral and medial facets
make the first contact to the femur when the knee flexes to 10-20 degrees. The contact area increases as the knee goes into more flexion.\textsuperscript{31, 32}

Most of the surface, with the exception of the odd facet, experiences some contact with the femur by 90 degrees of knee flexion.\textsuperscript{31, 32} The initial contact of the odd facet with the femur begins at past 90 degrees of knee flexion, as the medial facet enters the intercondylar notch.\textsuperscript{31, 32} The medial facet no longer has contact after 135 degrees of knee flexion although the lateral and odd facets still remain in contact with the femur.\textsuperscript{31, 32} As the patella tracks on the femur distally and proximally, medial tilt of the patella also occurs. The average medial tilt is about 11 degrees and occurs as the knee flexes from 25-135 degrees.\textsuperscript{31, 32}

Medial and lateral rotation of the patella on the frontal plane occurs with the rotations of the femur. The inferior aspect of the patella is fixed to the tibial tuberosity via the patellar tendon, therefore only the superior portion of the patella moves with the femoral rotation.\textsuperscript{31, 32} Medial rotation of the patella occurs with the lateral rotation of the femur on the tibia, while lateral rotation occurs with the medial rotation of the femur.\textsuperscript{31, 32} The medial-lateral stability of the patella may be influenced by the surrounding tissues, especially by the VMO and VL.\textsuperscript{4, 29, 31, 32} The VMO and the VL have to contract with equivalent force in order to achieve normal patellar tracking.\textsuperscript{29, 31, 32}

Joint reaction forces increase as the knee flexes.\textsuperscript{31, 32} The patella is simultaneously pulled by the quadriceps tendon proximally and the patellar tendon distally.\textsuperscript{31, 32} When these pulls are equivalent, which happens with full extension of the knee, the patella does not experience the compressive force.\textsuperscript{31, 32} The compressive force increases across the patellofemoral joint when the force from the quadriceps tendon and
patellar tendon become oblique, which occurs as the knee goes into flexion.\textsuperscript{31, 32} The lower extremity malalignment, such as genu valgum, femoral internal rotation and lateral tibial torsion, results in an increase in joint reaction forces across the patellofemoral joint.\textsuperscript{31, 32} Failure of tracking or movement of the patellar, and excessive forces being applied at the patella with knee flexion results in wear and tear of the articular cartilage.\textsuperscript{31, 32}

**Gluteus medius**

The primary function of the gluteus medius is hip abduction, while the anterior fibers serve as a secondary hip internal rotator, and the posterior fibers serve as a secondary hip external rotator and hip extensor.\textsuperscript{29} The gluteus medius originates from the external surface of the superior ilium, the anterior gluteal line, and the gluteal aponeurosis and inserts in the greater trochanter of the femur.\textsuperscript{29, 33} It is known that the gluteus medius functions as a pelvic stabilizer during stance, especially single leg stance.\textsuperscript{29} Electromyography (EMG) study reported that the maximal activation of all three parts of the gluteus medius was observed at full stance during the gait cycle along with the tensor fascia latae.\textsuperscript{34}

**Gluteus maximus**

The gluteus maximus primarily functions as a hip extensor and hip external rotator while the anterior fibers serve as a secondary hip abductor.\textsuperscript{29, 35} It attaches at the posterior aspect of the ilium, sacrum, coccyx, sacrotuberous, posterior sacroiliac ligament and fascia, and inserts into the iliobibial band of the tensor fascia latae, and the gluteal tuberosity of the femur.\textsuperscript{29, 33} According to the literature review by Ferris et al.,\textsuperscript{35} the
gluteus maximus also supports the lower extremity against the ground reaction force from full stance to contralateral toe off during gait. In the same literature review, EMG study observed the maximal activation in the isometric contraction of the hip extensor, abduction with the resistance, hip external rotation, and hyperextension of the trunk and hip in a standing. 36 Strong contraction was also observed at 60-90 degrees of hip flexion. The gluteus maximus is known as a pelvic stabilizer along with the gluteus medius. 35

**Dynamic malalignment of the lower extremity**

*Quadriceps angle*

Quadriceps angle (Q-angle) is the measurement to quantify the knee and hip alignment. 29 Q-angle is the angle between two lines, one is from the anterior superior iliac spine to the center of the patella, and the other line is from the center of the patella to the tibial tuberosity. 29, 31 Its normal range is 10-15 degrees in a supine anatomical position, and it has been suggested that more than 15 degrees of Q-angle may lead to knee injury. 29 During dynamic activities, such as squat, single leg squat, and jump-landing, increased Q-angle is a combination of increased femoral adduction and internal rotation. Q-angle indicates the lateral force vectors acting on the patella, therefore, increased Q-angle may result in more lateral force on the patella. 8, 31 When excessive femoral internal rotation occurs, the patella shifts more laterally, and the articular surface diminishes its contact area against the femur while the contact pressure increases. 31, 32 One cadaver study observed that a 10 degree increase in knee valgus angle resulted in a 45 % increase in peak contact pressure across the patellofemoral joint at 20 degrees of knee flexion. 37
Powers et al.,\textsuperscript{38} using MRI, revealed when knee flexion and extension occurs in weight bearing conditions, a maximal 13 degrees of femoral internal rotation was observed during full knee extension, while the average femoral internal rotation was 5.2 degrees in non weight bearing conditions. Minimal patellar rotation was recorded during weight bearing conditions, while a maximal 16 degrees of patellar rotation was observed at full knee extension in non weight bearing condition. This difference occurs due to screw home mechanism. In a non-weight bearing conditions, the tibia externally rotates on the femoral condyles as the knee goes into extension while the femur internally rotates to fit femoral condyles into the tibia; the tibia is unable to rotate because the distal part is fixed. Therefore, excessive femoral internal rotation increases contact pressure across the PF joint which may lead to anterior and lateral knee pain.

**Gluteus muscles strength deficit**

Previously, it was generally accepted that PFPS results from patellar maltracking and patellar malalignment.\textsuperscript{4,6,8} Recent studies reported that femoral rotation influences patellofemoral joint mechanics.\textsuperscript{38} Weak hip muscle strength has been believed to be associated with increased Q-angle.\textsuperscript{11-13} The gluteus maximus controls external rotation of the femur, therefore, a weak gluteus maximus does not resist femoral internal rotation. The excessive rotation of the femur underneath the patella results in patellar lateral shift; the patella shifts laterally as the femur goes into excessive internal rotation.\textsuperscript{38}

The presence of weak gluteus medius also contributes to increased adduction angle.\textsuperscript{30} Hip abductors include the gluteus medius and the anterior part of the gluteus maximus.\textsuperscript{29,34} The functions of the gluteus medius are primarily to serve as a hip abductor
in an open kinetic chain, and as pelvic stabilizer in a closed kinetic chain.\textsuperscript{29,34} Gottschalk et al.\textsuperscript{34} reported that the maximal activation of all three parts of the gluteus medius was observed at full stance during the gait cycle along with intense activity of the tensor fascia latae. Furthermore, it is generally accepted that the primary function of the gluteus medius is hip abduction; however, isolated hip abduction did not show strong gluteus medius EMG activity while the tensor fascia latae demonstrated more activity than the gluteus medius.\textsuperscript{34}

Since the gluteus medius has been known as a hip stabilizer, torque produced by the gluteus medius is very important to stabilize the pelvis in the frontal plane and the horizontal plane during activity. Therefore, a weak gluteus medius and gluteus maximus may not have sufficient strength to resist hip adduction and internal rotation torque, resulting in increasing femoral internal rotation and adduction and contralateral pelvic drop, subsequently resulting in an increased Q angle in a closed kinetic chain.

Several studies reported a strength deficit in hip abduction, hip extension and hip external rotation in PFPS subjects compared to healthy subjects.\textsuperscript{11-13} In 2003, Ireland et al.\textsuperscript{11} conducted one of the first studies on the relationship between hip strength and PFPS in thirty female subjects. They reported that the maximal isometric voluntary contraction (MVIC) of the hip abduction was 26\% (P < .001) lower and hip external rotation was 36\% (P < .001) lower in the subjects with PFPS than those of healthy subjects. Cichanowski et al.\textsuperscript{12} observed the peak hip torque of all hip directions (flexion, extension, abduction, adduction, internal rotation, and external rotation) between the symptomatic side and the asymptomatic side of the PFPS subjects, and between the symptomatic side of the PFPS subjects and the healthy subjects. The symptomatic side of the PFPS subjects
demonstrated significant weakness in all directions (flexion P=.033, extension P= .029, abduction P=.01 internal rotation P=.049, external rotation P=.033) except for hip adduction (P=.087) compared to randomly selected legs of the control group. Furthermore, weaker hip abduction (P=.003) and external rotation (P=.049) strength were observed in the symptomatic side of PFPS subjects compared to those of the asymptomatic side of the PFPS subjects with no significant difference in other muscles. Robinson et al.\textsuperscript{13} assessed the strength in the hip abduction, extension, and hip external rotation in twenty female subjects with PFPS. The strength was described as MVIC and limb symmetry index (LSI: MVIC of symptomatic side divided by MVIC of asymptomatic side x 100 for PFPS subjects, MVIC of non-dominant side divided by MVIC of dominant side x 100 for control subjects). PFPS subjects presented with weaker hip abduction (P=.007), hip extension (P< .001), and hip external rotation (P= .004) in the symptomatic side compared to the healthy subjects. In addition, the LSI score was found to be significantly different in each motion; hip abduction (P < .001), hip extension (P < .001), and hip external rotation (P= .007) between PFPS subjects and the healthy group. Additionally, the strength of the symptomatic side of the PFPS subjects was significantly decreased compared to the weaker side of the control group in all three muscle groups (the hip abductors, the hip extensors, and the hip external rotators).

The findings were consistent with weaker hip abductors in PFPS subjects compared to the healthy subjects. Additionally, hip extensors and hip external rotators were also reported to be weak in PFPS subjects compared to healthy subjects. However, there were limited numbers of studies observing hip musculature strength in subjects with PFPS. Although the authors hypothesized that the weak hip musculature strength caused
hip and knee malalignment, resulting in PFPS, they did not observe this relationship. One of the limitations of previous studies is that the relationship between hip muscle strength and PFPS has been investigated only in the open kinetic chain, and the relationship of the knee and hip kinematics in the frontal plane have been observed separately.

In 2003, Brindle et al.\textsuperscript{18} conducted one of the first studies to identify EMG activation of the gluteus medius, VMO and VL in relation with knee and hip kinematics during stair ascent and descent in sixteen anterior knee pain (AKP) subjects. PFPS subjects had demonstrated later onset of the gluteus medius EMG onset (P=.035) and shorter duration of EMG activity (P=.032) compared to the healthy group during stair ascent. The stair descent test did not show significant delay of the onset, however, shorter duration of EMG activity was observed in the gluteus medius (P=.049), VMO (P=.023), and VL (P=.032). No significant difference in the knee flexion angle and hip orientation at toe contact was observed between groups in stair descent or ascent conditions (P> .05). Additionally, the task difference did not change the pain perception on the visual analogue scale (VAS) in AKP subjects. No alternation of knee and hip kinematics was observed regardless of the changes in duration and onset of the gluteus medius during stair descent. The investigators suggested that stair descent may not require high demand on neuromuscular control of the knee and hip joint.

Bolgla et al.\textsuperscript{19} examined the relationship between the gluteus medius and gluteus maximus MVIC and knee and hip kinematics including knee valgus, hip adduction and hip internal rotation angles during stair descent in eighteen subjects with PFPS. The strength was normalized by the body mass. PFPS subjects demonstrated weaker MVIC
of the hip external rotators (P=.002) and hip abductors (P=.006) than those of healthy subjects. The average percentile of the strength in each muscle compared to the healthy subjects was 26% less strength in the hip abductor and 24% less strength in the hip external rotator. The knee and hip angles during the stance phase were measured and averaged. The study demonstrated PFPS subjects had no significant kinematic differences in hip internal rotation (P=.60), hip adduction (P=.15), and knee valgus (P=.28) angles during the stance phase compared to the control group. Although the results were not statistically significant, PFPS subjects demonstrated a 5.7 degree greater knee varus angle (P=.28) compared to healthy subjects, while hip internal rotation was slightly greater (P=.67) and hip adduction was slightly less (P=.15) compared with healthy subjects. In the study, hip strength was measured in the same way that Ireland et al. did in their study to compare whether the hip strength obtained were similar to those of Ireland et al. The study demonstrated similar strength in hip abductors (22.5 % with Brindle et al. VS 23.3% with Ireland et al.), and hip external rotators (11.1% with Brindle et al. VS 10.8% with Ireland et al.).

This study did not demonstrate the relationship that weak hip abductor and external rotators may result in increased hip adduction and hip internal rotation angle. The authors suggested that lack of relationship between hip strength and hip and knee kinematics may have happened because of the task demands chosen in their study, such as stair height, numbers of the trial, and speed, were not sufficient enough to cause the kinematic changes. In addition, since the subjects have been sustaining pain for an average of fourteen months, which indicates a chronic condition, they may have adjusted their knee and hip kinematics to avoid the pain.
Willson et al.\textsuperscript{39} assessed the lower extremity kinematics with various activities including single leg squat, running, and single leg jump in twenty female subjects with PFPS. Throughout the activities, PFPS subjects demonstrated an average of 3.5 degrees greater hip adduction (P=.012), 3.9 degrees less hip internal rotation (P=.01) and 4.3 degrees greater knee external rotation angle than the healthy subjects. These results indicated that the task demand did not change the lower extremity kinematics. Although some kinematic changes were observed in this study, it is difficult to draw the conclusion from the result. For example, the authors have suggested that the kinematic data may have included errors, and these may have resulted in decreased hip internal rotation along with increased knee external rotation, which is controversial.

Another study by Wilson et al.\textsuperscript{40} observed the influence of fatigue on trunk and hip strength and single leg jump mechanics in the subjects with PFPS. Subjects performed five consecutive single leg jumps, followed by the exertion protocol of ten single leg squats and five single leg jumps to cause fatigue. Immediately after the fatigue protocol, subjects performed another five consecutive single leg jumps. The exertion protocol did not alter the knee and hip kinematic patterns. Both the control and PFPS groups demonstrated similar changes in almost all kinematics except for contralateral pelvic drop. PFPS subjects demonstrated a significantly greater pelvic drop compared to the healthy subjects, and it became more significant at the end of the exertion protocol (P=.003). However, group differences were observed during the investigation with PFPS subjects compared to the control group: PFPS group demonstrated 5.8 degrees greater in hip flexion (P=.05), 4.2 degrees greater in hip adduction (P=.02), and 4.5 degrees less in hip internal rotation (P=.02) at peak knee extension moment compared to
healthy subjects. MVIC strength of the PFPS subjects was 21% less in hip abduction (P< .001), 10% less in trunk lateral flexion (P= .03), and 10% less in hip external rotation (P=.07) than those of healthy subjects. Investigators suggested that the hip and trunk strength is an important factor to PFPS, however, they did not confirm the relationship between hip strength and increased hip external rotation as opposed to the general hypothesis that weak abductor and external rotator may result in increased hip internal rotation.

Dierks et al. observed the knee and hip kinematics in association with hip musculature strength before and after prolonged running with twenty recreational runners. Both PFPS and healthy groups demonstrated significant reduction in hip abductor and hip external rotator MVIC over time (P<.001). PFPS group demonstrated weaker hip abduction before and at the end of running, compared to healthy subjects (P=.045, ES = 0.405). Their study also found a strong relationship between hip frontal plane kinematic and hip abductor MVIC: the hip adduction angle increased as the hip abduction MVIC decreased at the end of running (r = - 0.74). However, there was no statistically significant relationship between hip external rotator strength and hip internal rotation angle (P= .331, ES = 0.190). MVIC in the hip external rotators decreased at the end of running in both PFPS and healthy subjects, but no difference between groups was found. While hip abductor strength showed significant difference before and after running, hip external rotator had no significant difference. In addition, the study found interesting changes in the hip abduction angle between PFPS subjects and healthy subjects from heel strike to full stance during running cycle. Both groups demonstrated a similar hip abduction angle at the heel strike, while hip abduction angle increased toward
the mid to late stance and increased hip adduction at the full stance. Conversely, healthy
subjects demonstrated increased hip adduction angle toward the mid stance and then
increased hip abduction toward the late stance to full stance. At the full stance, hip
adduction angle was greater in PFPS subjects than healthy subjects. The authors
suggested that this movement occurred in PFPS subjects due to the compensation
mechanics of hip abduction. The opposite side of the pelvis tends to elevate in order to
abduct the weaker side’s limb, decreasing compressive pressure across the PF joint, and
consequently decreasing pain perceived by the PFPS subjects.

Several studies assessed the presence of weak hip muscle strength in the
subjects with PFPS, which have led to the need to investigate how the knee and hip
kinematics in frontal and transverse plane are associated with hip muscle strength.
Several studies have investigated this relationship; however, the findings are not
consistent enough to draw the conclusions. The outcomes included some errors and
contradictories. The interventions were different from each other. Task demands may not
sufficient enough to cause the kinematic change or muscle activity change. Therefore,
few outcomes were available to compare, which makes it difficult to validate. Further
study needs to be conducted to establish the efficient task demands, intervention, and to
investigate the relationship between hip muscle strength and the knee and hip kinematics
in the subjects with PFPS.

Rehabilitation intervention

Considering the hypothesis that hip muscle strength may influence the knee and
hip kinematics, a hip strength program is commonly included in the rehabilitation
intervention for PFPS. Boling et al.\textsuperscript{14} investigated the differences in EMG activation of the gluteus medius and VMO and VL muscles after six weeks of weight bearing rehabilitation intervention in twenty eight subjects. Weight bearing exercises included stretching and double stance and single leg stance exercises so that hip and thigh muscles were recruited in a concentric and eccentric manner, and lower extremity stretching was performed throughout the intervention. The program was gradually progressed in intensity and repetition over six weeks. EMG activities of the gluteus medius, VMO, and VL onset and duration were measured during stair ascent and descent pre and post rehabilitation. After six weeks of rehabilitation, there was no difference in the EMG onset (\(P = .386\)) or duration (\(P = .48\)) of gluteus medius during stair ascent or descent. Additionally, no significant difference was observed in onset timing of VMO and VL (VL onset – VMO onset) (\(P = .077\)) and duration of the gluteus medius activation (\(P = .343\)) in PFPS subjects after six weeks rehabilitation. In contrast, post rehabilitation measurement revealed that the PFPS subjects had significant improvement of the VMO onset, with no significant change in VL onset; therefore, the difference of the VMO and VL onset timing was significantly improved after six weeks of rehabilitation (\(P = .001\)).

Boling’s study also reported that the pain decreased in VAS in stair ascent and descent, and functional skills improved in the functional index questionnaire while the control group did not show significant change in pre and post rehabilitation. The study reported no alternation of the gluteus medius muscle in duration or onset difference on stair descent and ascent tasks.

The major limitation of this study is that the subjects had to perform the exercises on their own with no supervision. Although EMG activation of the hip muscle
did not change from the baseline, the combination of quadriceps and hip muscles weight bearing rehabilitation program improved the function, and altered the onset and duration of the VMO and VL. Additionally, and perhaps most importantly, it decreased the self-perceived pain level. Authors of the study suggested that changes in the EMG amplitude may have influenced the pain reduction in VAS, and increased FIQ score, although the difference between pre and post rehabilitation was not statistically significant.

Mascal et al.\textsuperscript{17} conducted a case study including 14 weeks of rehabilitation, focusing on hip and trunk muscle strengthening with two PFPS subjects. Great improvement was observed in the gluteus medius and gluteus maximus strength in both subjects. One subject demonstrated a 50% increase in the gluteus medius, a 55% increase in the gluteus maximus, a 317% increase in external rotators, and a 20% increase in the quadriceps strength. The other subject demonstrated a 110% increase in the gluteus medius, a 90% increase in the gluteus maximus, a 15% increase in external rotators, and 10% increase in the quadriceps. Along with these results, both subjects also demonstrated kinematic improvement. One subject demonstrated increased hip external rotation from 1.4 degrees internal rotation to 2.6 degrees external rotation and decreased hip adduction angle from 8.7 degrees to 2.3 degrees during step down. Additionally, kinematic assessment demonstrated a decrease in hip adduction, hip internal rotation, and contralateral pelvic drop during gait. The hip adduction angle increased at the last 85% of the stance phase during step down activity, however, post rehabilitation data indicated that the hip adduction angle was decreased at the last 80% of the stance phase. Similar kinematic changes were observed in step down activity compared with the pre rehabilitation measurement. Pain perception was improved in both subjects, with one
subject being able to stand, walk, ascend and descend stairs without pain. The other subjects reported great reduction in pain to ascend and descend stairs with occasional minimal discomfort.

The intervention was effective to these subjects.\textsuperscript{17} The ideal outcomes may be because of the close attention on the subjects during on site rehabilitation. The subjects were closely monitored by the therapist so that the subjects were able to collect their kinematics if they were not appropriate. In addition, a deficit of hip strength was the factor contributing to PFPS for those subjects. Although the result was based on the case studies of two PFPS subjects, outcomes could support the concept that hip muscle weakness may contribute to PFPS. Future study should be conducted with larger population for validation.

There are limited studies that have been done to observe the effect of hip muscle strengthening to PFPS. Although the relationship between weak hip muscle strength and hip and knee kinematics changes has not been fully investigated, clinicians have included hip muscle strengthening for treating PFPS. It is not clearly understood which interventions are effective to treat PFPS. This may be because PFPS is a multifactorial condition, and each subject receives intervention may have different factors that caused PFPS. Further studies are needed to observe this relationship.

**Star Excursion Balance Test**

The star excursion balance test (SEBT) is a functional test to quantify the ability to maintain balance during dynamic postural control. The SEBT requires the subject to stand in the middle of the separated eight lines extending from the center at a 45-degree
angle from each other. The subject performs single leg squats with the opposite leg reaching as far as possible and making a contact on the line with the most distal part of the foot.20

The SEBT has been used to detect the deficit of the lower extremity function with chronic ankle instability and PFPS. The longer reach distance indicates the better lower extremity function and dynamic postural control.22,25 Olmstead et al.25 observed the reach distance in eight directions in subjects with chronic ankle instability. Lateral and anterolateral reaches had significantly shorter reach than all other directions, and a longer reach in the posterior and postelomedial directions compared with the healthy limbs. The researchers also found the sum of the reaching distances in all eight directions for the chronic ankle instability subjects was shorter than that of healthy subjects as well as healthy limb of the chronic ankle instability subjects. Gribble et al.25 observed a shorter reach distance and less knee flexion angle with subjects with chronic ankle instability compared with healthy subjects. The SEBT has also been used to predict the lower extremity injuries in a high school basketball team. Pliskey et al. measured three directions of the SEBT (anterior, posteromedial, and posterolateral). Subjects with an average of four centimeters reach difference between right and left leg had 2.5 times more of a chance of sustaining a lower extremity injury during the season. They also found 6.5 times more chance of lower extremity injuries in females, with less than 94% of the average of all three directions normalized to the limb length.21

While most studies of the SEBT had been done with the ankle, there are only few studies that had investigated the influence of knee pathology during the SEBT. Aminaka and Gribble24 demonstrated a decrease in the normalized reach distance in the
anterior direction, along with an associated increase in pain, in twenty subjects with PFPS, compared with twenty healthy subjects. Ebersole et al\textsuperscript{27} reported a shorter reach distance in the posterior direction in PFPS subjects compared with healthy subjects. Earl and Hertel\textsuperscript{28} quantified the integrated electromyographic (iEMG) activation patterns of the VMO, vastus lateralis, medial hamstrings, biceps femoris, anterior tibialis, and gastrocnemius, and knee and ankle sagittal plane kinematics during the SEBT. They found that quadriceps activity was greatest in anterior reach direction while hamstrings activity was greatest in posterior direction. The gastrocnemius did not change its activities, regardless of the direction. Knee flexion angle was greater in the anterior, anteromedial, medial, and posterolateral directions (P < .05) than the other directions. Ankle dorsiflexion was greater in anterior, anteromedial, and medial directions than that of other directions (P < .0005).

Gluteus medius is a primary hip abductor and secondary hip external rotator; while the gluteus maximus is a primary hip extensor and external rotator. EMG studies have observed these two muscles are activated during a single leg squat in concentric and eccentric manner to control knee and hip kinematics in the frontal plane.\textsuperscript{30} Considering that the knee and hip movements occurring at the SEBT are similar to those of a single leg squat, the SEBT will be an appropriate method to measure the activation of those two muscle groups, while adding additional challenges related to the production of dynamic postural control.
Summary

PFPS is a common knee problem. Because of its multifactorial condition, the etiology is not completely understood. Recent studies have investigated the presence of hip muscle weakness in subjects in non weight bearing condition, and drawn the hypothesis that the weak hip muscle strength may cause increased hip adduction and femoral internal rotation. This results in decreasing patellar articular contact area and increasing compressive force across the PF joint, which cause patellofemoral pain. Several kinematic studies have been conducted in PFPS subjects; however, findings are not consistent across the studies. Furthermore, findings are contradictory within the literature. This may occur due to the limited number of the study. Extensive study needs to be conducted to investigate the relationship weak hip muscle strength and knee and hip kinematics.
Chapter III

Methodology

Subjects

Twenty eight subjects participated in this study and completed the test (PFPS: Age= 21.07±3.27yrs, Ht= 172.09±10.26cm, Mass= 69.96±9.05kg; Control: Age= 20.93±3.00yrs, Ht= 170.18 ±8.94cm, Mass= 70.25 ±8.57kg) (Table 1). The subjects were recruited from the University of Toledo student and faculty population, and local sports medicine clinics. All subjects had no history of osteoarthritis, surgery (including arthrosocopy), fracture, patellar dislocation/subluxation, or ligamentous or other soft-tissue injury, or a concussion within the last year. Additionally, the PFPS subjects presented with diffuse, unilateral anterior knee pain for at least 8 weeks, exacerbated by stair climbing, sitting, walking, running, squatting, knee flexion and isometric quadriceps contraction.\textsuperscript{26} In addition, none of the subjects could be participating in physical therapy 30 days prior to the study. Control subjects were matched for sex, age, weight, and mass. Additionally, control subjects were designated a matched “injured side” for the purposes of between group comparisons. For instance, if the first PFPS subject had a symptomatic
right side, then the right limb of the subsequent matched control subject was used. The subjects read and sign the informed consent before participating in the study (Appendix A). The study was approved by the University of Toledo institutional review board.

**Instrumentation**

Knee and hip kinematics were measured with MotionMonitor™ data acquisition system (Innovative Sports Training, Inc., Chicago, IL) with 5 Ascension "Flock of Birds" magnetic trackers (Ascension Technology Corporation, Burlington, VT) and a Standard Range Transmitter. A 16-channel telemeterized EMG system (Noraxon U.S.A., Inc. Scottsdale, AZ) was integrated with MotionMonitor™ and collected the electromyographic activation of the GMed and GMax during the SEBT. A custom-made mat with tape measures secured to the mat at 45° angles to each other was placed on the floor for the SEBT reach distance measurement.

**Procedures**

Subjects reported to Athletic Training Research Laboratory at the University of Toledo for one session. They read and signed the informed consent approved by the Institutional review board (Appendix A). The subjects were evaluated for 1) static kinematics in anatomical position (i.e. knee valgus and knee varus angle), 2) normalized average EMG of the GMed, GMax, and VM activities during SEBT, 3) normalized reaching distance (MAXD) during the SEBT, 4) kinematic changes of the knee in frontal plane at the touchdown of the SEBT, and 5) VAS for measuring subjective pain pre-test, during test and post-test. These measures were assessed on the injured limb of the PFPS
subjects and a matched limb of the Control group, designated for both groups as the “test limb”. For instance, if the symptomatic side/test limb of a PFPS subject was the right limb, then the matched limb of a matched Control group subject was also the right limb, and served as the test limb.

Subjects were asked to report their knee pain on the visual analogue scale (VAS) (Appendix B) before test. Leg length of the test limb was recorded (cm) at the beginning of the session while lying supine on a plinth from the ASIS to the middle of the medial malleolus. The skin areas for placement of the EMG electrodes on the test limb were cleaned with an alcohol swab, shaved and debrided with sandpaper. A pair of disposable Ag/AgCl surface electrodes (0.8cm diameter, center-to-center inter-electrode distance=1.5cm, (Noraxon U.S.A., Inc. Scottsdale, AZ )) were used. The electrodes were placed at one-half of the distance between the iliac crest and greater trochanter for the GMed, and at half of the distance between the greater trochanter and ischial tuberosity for the GMax. The electrode placement for VM was approximately 4cm from the superomedial angle of the patella, at 45° to the long axis of the femur. Maximum voluntary isometric contraction (MVIC) of both muscle groups for the testing leg were measured according to previously published methods (Appendix E). GMed MVIC was measured with subjects in the side-lying position on a treatment table. Subjects were asked to abduct the hip approximately 30° with slight hip external rotation and extension and hold it in place against the strap at the distal posterior thigh. The MVIC of GMax for hip extension was measured in the prone position with 90° knee flexion while the pelvis is stabilized by the strap. Subjects performed 30° of hip extension against the other strap positioned at the distal posterior thigh. The MVIC of GMax for hip external rotation was
performed while the subject was seated on a treatment table with the hip and knee flexed to 90°. The subject was asked to bring the foot toward the midline of the body against the strap positioned at the medial malleolous. Knee extension MVIC was performed in a sitting position similar to the hip external rotation MVIC. The subject was asked to bring the knee into approximately 30° flexed position, and then held the position against the strap. The MVICs were performed three times for five seconds for each muscle. For each MVIC trial, the three seconds that showed the highest amplitude of activation were recorded for data analysis. Following five minutes rest after completing the MVIC measurement, electromagnetic sensors were attached at the sacrum, lateral thigh, lateral shank, and foot. The wires and sensors were secured to the skin with an elastic tape or a strap.

For the SEBT, subjects were asked to stand on the middle of the SEBT mat on the test limb in bare feet with their hands on their hips. Subjects were instructed to reach into the anterior direction along the tape measure, using the toes of the non-standing leg to make a touch as lightly as possible, and then return to the starting point, resuming a double-leg stance. The speed of the task was selected at subjects’ preference. For this study, the anterior direction was used as the reaching directions (Appendix C, D). The reaching distance was marked and measured in centimeters. All measures were recorded by the same investigator. Prior to the test, after demonstration by the PI, subjects were allowed to complete four practice trials to reduce the learning effect. Following five minutes of rest, subjects performed five test trials reaches. Each trial was separated by 15 seconds of rest. Subjects were asked to repeat the trial if the stance foot was lifted while reaching, the subject did not make a touchdown on the designated line, or the
subject lost balance and shifted the stance foot or touched down in an attempt to recover
during the trials.\textsuperscript{20-26} The recorded reach distance was normalized to the measured leg
length and reported as a percentage, based on previous study (%MAXD).\textsuperscript{20}

During the testing session, subjects were asked to report the amount of perceived
pain associated with the SEBT task using a VAS (Appendix B). The VAS instrument
was administered before the practice trials begin, immediately upon completion of all the
test trials (rating their worst pain during the test performance), and also five minutes after
completing the test. The subjects were asked to place a mark on the horizontal line that
corresponded with the level of pain they perceived in their injured limb for each of these
assessments. The placement of the mark was measured in millimeters from the left side
of the line (No Pain) and recorded as the pain score.

The EMG of three muscle groups during the MVICs and the SEBT was collected
through the 16-channel telemeterized EMG system integrated with the MotionMonitor\textsuperscript{™}
data acquisition system, using a sampling rate of 1000 Hz. The EMG data was measured
from the beginning of the SEBT to the end of the SEBT. The mean iEMG data during
the SEBT was normalized by the mean iEMG value of three seconds of MVIC.

The EMG data was filtered with a band pass filter (low pass 500Hz, high pass of
20 Hz). The data was exported to a custom made Excel (Microsoft Corp, Redmond, WA)
spreadsheet to calculate the iEMG value. The iEMG was defined as the area under the
linear envelope of each EMG activation.\textsuperscript{34} iEMG data of the MVIC was divided by 3000
ms to obtain average EMG. iEMG of the SEBT was divided by the amount of time (ms)
which each subject needed to complete the task to calculate average EMG during the
SEBT. The average EMG of the GMed, GMax (hip extensor and hip external rotator)
and VM from the five trials for each muscle were calculated and normalized by the average EMG from the MVICs of each muscle.

Simultaneously, knee kinematics were collected by with the electromagnetic tracking system and a standard range transmitter using a sampling rate of 100 Hz, and integrated with the MotionMonitor software. The frontal plane angle of the knee was recorded at the furthest reach during the SEBT. A 3\textsuperscript{rd} order low pass Butterworth filter with a cut off at 20 Hz was applied to the kinematic data. A virtual event marker was placed in the data by a co-investigator observing the trials so that the point of maximum reach is designated and the kinematic and EMG data may be time-matched. A virtual marker was placed at the beginning and the end of the task as well. The knee valgus angle was recorded as a frontal plane kinematic value at the point of touch down (visually noted and annotated with a virtual event marker during testing), and from the beginning to touch-down during the SEBT.

**Data analysis**

*Independent variables*

1. Group
   a. PFPS
   b. Control

2. Time (VAS only)
   a. Pre-test
   b. During-test
   c. Post test
**Dependent variables**

1. EMG during the SEBT
   a. EMG of GMed
   b. EMG of GMax (Hip extensor)
   c. EMG of GMax (Hip external rotator)
   d. EMG of VM

2. SEBT
   a. Normalized reaching distance (%MAXD)

3. Knee kinematic data
   a. Knee valgus/varus angle at touch down during the SEBT
   b. Knee valgus/varus displacement

4. VAS
   a. Pre-test
   b. During-test
   c. Post-test

For the dependent variables #1-3, the means and standard deviation were used for statistical analysis. For each of these variables, paired t-test were employed to compare the data between the PFPS and control groups for EMG, SEBT and Knee valgus angle. For dependent variable #4, the VAS data was a single assessment at each time point. A one-between (Group) and one-within (Time) repeated measures ANOVA was performed for the VAS data. Level of significance was set at p < .05 for all analyses. In the event of statistically significant interaction (VAS only), a Tukey’s post-hoc test was applied.
All statistical analysis were performed using SPSS 15.0 (SPSS, Inc. Chicago, IL.). Cohen’s $d$ was used to indicate effect size.

**Power analysis calculation**

The power analysis was based on data collected from the research laboratory of the faculty advisor and published work by other authors that utilized similar dependant variables (GMed EMG, MAXD, knee valgus angle) and comparisons that were used in this proposed study. Using these data and an online statistical calculator, sample size with a desired level of statistical significance at $p<.05$ and a power level equal to or greater 0.80 was calculated.

**%MAXD**

In a recently published study under the direction of the faculty advisor, subjects with (n=20) and without PFPS (n=20) performed the anterior reach of the SEBT. Those with PFPS produced significantly less normalized reaching distance ($63.15\pm1.3\%$) compared to Healthy control subjects ($65.2\pm1.3\%$). Based on this relationship, to achieve a power of .80, 8 subjects per group were needed.

**Knee Valgus Angle**

Claiborn et al. reported the amount of maximum knee valgus angle during a single-leg squat in healthy subjects to be ($3.21\pm4.92^\circ$). Assuming that the SEBT is a series of single-leg squats, this task could be used as a comparison to the SEBT. In that study, only healthy subjects were examined. In our study, we would hope to observe at
least a 10% difference in knee valgus angle between the PFPS and healthy subjects. Based on this desired relationship and the control subject data from Claiborn et al., we would need to include 11 subjects in each group to achieve a level of statistical power = .80 in our study.

**GMed EMG**

Brindle et al. examined the difference in GMed duration during a stair descent task between those with and without PFPS. The control subjects produced a significantly increased duration in GMed activation (758±115.7 ms) compared to the PFPS subjects (758±115.7 ms). Based on these means and standard deviations, to achieve a power level of .80, 14 subjects/group were needed in our study.

**Summary of power analyses**

Based on these calculations, we needed 14 subjects with PFPS and 14 healthy control subjects to achieve a statistical power level of .80. Therefore, a total of 28 subjects were enrolled in our study.
Chapter IV

Results

Knee valgus angle

There was a significant difference between groups for knee valgus angle at touch down during the anterior reach on the SEBT (p = .022, t = -2.40) (Figure 1). The PFPS group demonstrated greater knee valgus angle (-2.266±10.278°) compared to the control group (7.081±10.008°) (Figure 1). There was a large effect size associated with this difference (d=0.92) (Table 2).

During the SEBT, the PFPS group also demonstrated significantly less knee varus displacement (1.953±9.933°) compared to the control group (11.689 ± 8.920°) (p=.011, t=-2.70) (Figure 2). There was a large effect size with this difference (d=1.03) (Table 3).

Normalized reach distance (%MAXD)

There was a statistically significant difference between groups for normalized reach distances in the anterior reach (p=.014, t=-2.60). The PFPS group demonstrated shorter MAXD (66.17 ± 5.0%) compared with the control group (70.84 ± 4.40%) (Figure 3). There was a large effect size associated with this difference (d=0.97) (Table 4).
Pain on the Visual Analogue Scale (VAS)

There was a statistically significant group by time interaction for VAS (F_{2,52}=4.70, p<.001). Tukey’s post hoc revealed that the PFPS group demonstrated significantly increased pain at pre-, during, and post- test compared to the control group (PFPS: pre=0.807 ± 1.136, during=2.607 ± 1.477, post=1.714 ± 1.310, Control: pre=0.079±0.267, during=0.243±0.539, post=0.086±0.266) (Figure 4). Large effect sizes were associated with these differences (pre-test: d=0.88, during test: d=2.13, post-test: d=1.72) (Table 5). Furthermore, the PFPS group demonstrated that pain during the test as well as during the post-test was significantly higher compared to pre-test pain; additionally post-test pain was significantly less compared to the pain during the test. (Figure 4). There was also moderate to large effect size related to these results (pre vs. during: d=1.37, pre vs. post: d=0.76, during vs. post: d=0.62) (Table 6).

Normalized average EMG of the vastus medialis during the SEBT

The PFPS group demonstrated significantly greater normalized average EMG compared to the control group (p=.048, t=2.072, PFPS=132.5±77.2%, Control=87.7±23.0%) (Figure 5). There was a large effect size associated with this difference (d=0.89) (Table 7).

Normalized average EMG of the gluteus medius during the SEBT (%MVIC)
There was no statistically significant group difference (p= .790, t=-0.270, PFPS=42.91±23.22%, Control=45.41±25.77%) (Figure 6). A small effect size was associated with this result (d=0.10) (Table 8).

Normalized average EMG of the gluteus maximus (hip extensors) during the SEBT (%MVIC)

There was no statistically significant difference in the EMG of the gluteus maximus for the hip extensor between groups (p= .136, t=1.537, PFPS= 28.6±10.51%, Control= 15.7±68.6%) (Figure 7). There was a moderate effect size associated with this difference (d=0.58) (Table 9).

Normalized average EMG of the gluteus maximus (hip external rotators) during the SEBT (%MVIC)

There was no statistically significant difference observed in the EMG of the gluteus maximus for the hip external rotator (p= .171, t=1.409, PFPS= 229.83±133.03%, Control= 166.56±102.61 %) (Figure 8). There was a small effect size was associated with this result (d=0.53) (Table 10).
### Table 1. Demographic data

<table>
<thead>
<tr>
<th>Group</th>
<th>Sex</th>
<th>Age</th>
<th>Height (cm)</th>
<th>Mass (Kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PFPS</td>
<td>M=4, F=10</td>
<td>21.07 (±3.27)</td>
<td>172.09 (±10.26)</td>
<td>69.96 (±9.05)</td>
</tr>
<tr>
<td>Control</td>
<td>M=4, F=10</td>
<td>20.93 (±3.00)</td>
<td>170.18 (±8.94)</td>
<td>70.25 (±8.57)</td>
</tr>
</tbody>
</table>

### Table 2. Knee Valgus Angle at Touch-down (TD) (degrees)

<table>
<thead>
<tr>
<th>Group</th>
<th>Mean</th>
<th>SD</th>
<th>ES</th>
</tr>
</thead>
<tbody>
<tr>
<td>PFPS</td>
<td>-2.266*</td>
<td>10.278</td>
<td>0.92</td>
</tr>
<tr>
<td>Control</td>
<td>7.081</td>
<td>10.008</td>
<td></td>
</tr>
</tbody>
</table>

* indicates significant difference between groups (p=.22).

### Table 3. Knee Valgus Angle displacement (degrees)

<table>
<thead>
<tr>
<th>Group</th>
<th>Mean</th>
<th>SD</th>
<th>ES</th>
</tr>
</thead>
<tbody>
<tr>
<td>PFPS</td>
<td>1.953*</td>
<td>9.933</td>
<td>1.03</td>
</tr>
<tr>
<td>Control</td>
<td>11.689</td>
<td>8.920</td>
<td></td>
</tr>
</tbody>
</table>

* indicates significant difference between groups (p=.011).

### Table 4. Normalized Reach Distance (%MAXD)

<table>
<thead>
<tr>
<th>Group</th>
<th>Mean</th>
<th>SD</th>
<th>ES</th>
</tr>
</thead>
<tbody>
<tr>
<td>PFPS</td>
<td>66.17*</td>
<td>5.00</td>
<td>0.97</td>
</tr>
<tr>
<td>Control</td>
<td>70.84</td>
<td>4.39</td>
<td></td>
</tr>
</tbody>
</table>

* indicates significant difference between groups (p=.014).
Table 5. Pain in Visual Analogue Scale (VAS)

<table>
<thead>
<tr>
<th>Condition</th>
<th>Group</th>
<th>Mean</th>
<th>SD</th>
<th>ES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre</td>
<td>PFPS</td>
<td>0.807*#†</td>
<td>1.136</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>0.079</td>
<td>0.267</td>
<td></td>
</tr>
<tr>
<td>During</td>
<td>PFPS</td>
<td>2.607*%</td>
<td>1.477</td>
<td>2.12</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>0.243</td>
<td>0.539</td>
<td></td>
</tr>
<tr>
<td>Post</td>
<td>PFPS</td>
<td>1.714*</td>
<td>1.310</td>
<td>1.72</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>0.086</td>
<td>0.266</td>
<td></td>
</tr>
</tbody>
</table>

* indicates significant difference between groups (F_{2.52}=4.70, p<.001)
# indicates significant difference between pre- and during tests within the PFPS group.
† indicates significant difference between pre- and post-tests within the PFPS group.
% indicates significant difference between during and post-test within the PFPS group.

Table 6. PFPS pain in VAS

<table>
<thead>
<tr>
<th>Time</th>
<th>Time</th>
<th>ES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre</td>
<td>During</td>
<td>1.37</td>
</tr>
<tr>
<td>Pre</td>
<td>Post</td>
<td>0.76</td>
</tr>
<tr>
<td>During</td>
<td>Post</td>
<td>0.62</td>
</tr>
</tbody>
</table>

Table 7. Normalized Average EMG of Vastus Medialis (%MVIC)

<table>
<thead>
<tr>
<th>Group</th>
<th>Mean</th>
<th>SD</th>
<th>ES</th>
</tr>
</thead>
<tbody>
<tr>
<td>PFPS</td>
<td>132.5*</td>
<td>77.2</td>
<td>0.89</td>
</tr>
<tr>
<td>Control</td>
<td>87.7</td>
<td>23.0</td>
<td></td>
</tr>
</tbody>
</table>

* indicates significant difference between groups (p=.048).
Table 8. Normalized Average EMG of Gluteus Medius (%MVIC)

<table>
<thead>
<tr>
<th>Group</th>
<th>Mean</th>
<th>SD</th>
<th>ES</th>
</tr>
</thead>
<tbody>
<tr>
<td>PFPS</td>
<td>42.91</td>
<td>23.22</td>
<td>0.10</td>
</tr>
<tr>
<td>Control</td>
<td>45.41</td>
<td>25.77</td>
<td></td>
</tr>
</tbody>
</table>

Table 9. Normalized Average EMG of Hip Extensors (%MVIC)

<table>
<thead>
<tr>
<th>Group</th>
<th>Mean</th>
<th>SD</th>
<th>ES</th>
</tr>
</thead>
<tbody>
<tr>
<td>PFPS</td>
<td>20.86</td>
<td>10.51</td>
<td>0.58</td>
</tr>
<tr>
<td>Control</td>
<td>15.70</td>
<td>6.86</td>
<td></td>
</tr>
</tbody>
</table>

Table 10. Normalized Average EMG of Hip External Rotators (%MVIC)

<table>
<thead>
<tr>
<th>Group</th>
<th>Mean</th>
<th>SD</th>
<th>ES</th>
</tr>
</thead>
<tbody>
<tr>
<td>PFPS</td>
<td>229.83</td>
<td>133.03</td>
<td>0.53</td>
</tr>
<tr>
<td>Control</td>
<td>166.56</td>
<td>102.61</td>
<td></td>
</tr>
</tbody>
</table>
Figure 1. Frontal Knee Kinematic at Touchdown (Knee Valgus)

* indicates group difference (p= .022, t= -2.40, ES=0.92).
Figure 2. Frontal Knee Kinematics Displacement

* indicates group difference (p=.011, t= -2.70, ES=1.03).
Figure 3. Normalized Reach Distance (%MAXD)

* indicates group difference (p= .014, t=-2.60, ES=0.97).

Normalized reach distance (%MAXD) = (Reach distance / leg length)*100
Figure 4. Visual Analogue Scale (VAS), Group by time interaction (F_{2,52}=4.70, p<.001)

* indicates group difference at pre- during, and post- tests.

# indicates significant difference between pre- and during tests within the PFPS group.

† indicates significant difference between pre- and post- tests within the PFPS group.

% indicates significant difference between during and post-test within the PFPS group.
Figure 5. Normalized Average EMG of Vastus Medialis (%MVIC)
* indicate group difference
(p= .048, t=2.072, ES=0.89).

Figure 6. Normalized Average EMG of the Gluteus Medius (%MVIC)
(p= .790, t= -.270, ES=0.10)

Figure 7. Normalized Average EMG of the Gluteus Maximus (%MVIC) (Hip Extensors)
(p= .136, t= 1.537, ES=0.58)

Figure 8. Normalized Average EMG of the Gluteus Maximus (%MVIC) (Hip External Rotator)
(p= .171, t= 1.409, ES=0.53)
Chapter V

Discussion

The purpose of this study was to examine the effects of PFPS on hip and knee neuromuscular control during a dynamic postural control. The results partially supported our hypotheses.

Knee kinematic alteration

It was hypothesized that PFPS subjects would demonstrate an increased knee valgus angle during performance of the SEBT compared to the healthy subjects. Our results support this hypothesis, since the PFPS group demonstrated increased valgus angle at the touchdown during the anterior direction of the SEBT. In addition, the PFPS group demonstrated significantly smaller varus displacement from the initiation of the touchdown event during the reaching task compared to the control group. Large effect size helps to support these findings.

It has been suggested that insufficient hip abductor and hip external rotator strength might be associated with dynamic malalignment, such as increased knee valgus
Weak hip abductor and external rotators may not resist hip adduction and hip internal rotation during a dynamic postural control task, allowing an increased knee valgus angle. This malalignment increases contact pressure on the patellofemoral joint, which may contribute to wearing of patellar articular cartilage as the patella slides superiorly and inferiorly on the internally rotated femur as knee flexes and extends, potentially resulting in PFPS.

Our result supported our hypothesis, but the finding is contradictory to a previous study that investigated knee valgus angle during the stair descent task between PFPS and healthy subjects. Bolgla et al. found that there was no statistically significant difference in hip and knee frontal and transverse plane angles during stair descent between PFPS and control groups. Contrary to our results, PFPS subjects in their study demonstrated greater varus angle during the stair descent, although it was not statistically significant (p = .06). One of the reasons for the discrepancy in the results may be the different tasks that were performed. In Bolgla’s study, the subjects descended 20 cm-high steps with controlled speed (96 bpm). Stair descent is essentially a different task than a single leg reach task such as the SEBT. The duration of single leg support during stair descent would be much shorter, as the non-stance limb is allowed to touch the lower step before the stance limb goes into the position beyond its ability to maintain the body’s posture. Although subjects performed the task in our study at their preferred speed, they were not allowed to rest their foot as they made a touchdown, which was more challenging for the subjects to maintain the balance during the test. Another reason for the discrepancy may be due to different time points of quantifying the angle during the tasks. Bolgla et al. measured the mean knee and hip angles during the stance phase of
stair descent while we assessed knee valgus displacement from the beginning to touch-down of the SEBT and discrete knee valgus angle at the touch-down.

Frontal knee kinematics have been measured in different segments in the previous literature. For example, Willson and Davis\textsuperscript{39} have reported the significantly increased hip adduction angle and decreased hip internal rotation angle in subjects with PFPS compared to control subjects during single leg squats, running, and single leg jumps. Another study by Willson and Davis\textsuperscript{40} measured hip adduction and internal rotation, and knee adduction angles tasks during five consecutive single leg jump tasks. They observed that the PFPS group demonstrated significantly increased hip adduction angle and decreased hip internal rotation angle at the peak knee extension moment during the single leg jump compared to the healthy subjects. In addition, they did not find significant difference in knee adduction angle. Dierks et al.,\textsuperscript{41} assessing hip adduction and internal rotation angles as frontal and transverse plane kinematics in a PFPS group during prolonged running, reported that the PFPS group demonstrated significantly increased hip adduction angle compared with the healthy group (p=.044) while there was no significant difference in hip internal rotation angle between groups. Another study by Willson and Davis\textsuperscript{47} demonstrated that pelvic drop, posterior pelvic rotation, hip adduction, hip internal rotation, tibial abduction, and tibial external rotation were significantly correlated with the medial knee displacement, but ultimately hip adduction angle had the highest correlation with medial knee displacement. Findings from previous studies may indicate that increased hip adduction angle may increase knee valgus angle, therefore, our result may be able to support the previous findings; however, since we observed the knee valgus angle as one segment these comparisons cannot be made.
directly. Future study should assess all lower extremity segments to identify kinematic alterations in PFPS subjects.

**Hip and knee musculature activation**

It was hypothesized that PFPS subjects would demonstrate reduced muscle activities of GMed, GMax and VM during performance of the SEBT compared to the healthy subjects. Our hypotheses were not supported as our study did not find significant differences in GMed and GMax EMG activities during the anterior reach of the SEBT, while subjects with PFPS demonstrated increased VM normalized average EMG compared with the healthy subjects during the anterior reach of the SEBT. In addition, there was a large effect size associated with VM activation, which may help to supports this significant difference between groups.

It was unexpected that the subjects with PFPS, who have been presumed to have weakness of the VM, would demonstrate significantly higher VM activity during the SEBT compared to the healthy group. Several studies have shown significantly delayed onset of VM relative to the vastus lateralis in subjects with PFPS compared with that of healthy subjects during stair ascent and descent tasks.\(^{10,14}\) Furthermore, previous studies have demonstrated that the quadriceps strengthening decreased knee pain in the VAS although the rehabilitation protocol included knee and hip muscle strengthening.\(^{14,51}\) Considering that, we expected less VM activities during the SEBT in the PFPS subjects. Our results may be due to the increased VM eccentric contraction during the down phase of the SEBT. The evidence that subjects with PFPS reported increased pain during the SEBT in our study could help to explain this result. Because PFPS is a chronic condition,
most subjects with PFPS likely would know that knee flexion or extension would cause knee pain. In addition, a previous study observed that the subjects with PFPS reported increased knee pain during stair descent compared to the stair ascent.\textsuperscript{49, 50} Therefore, subjects with PFPS tend to be cautious to flex their knees by slowing down this movement (increasing the duration), which may be eventually increasing the duration of the reach task and total normalized average EMG activation of the eccentric contraction of the VM. Future study should investigate the duration and activation of the eccentric and concentric contraction phase separately in both PFPS and healthy groups for the comparison.

It was also unexpected that the PFPS group would demonstrate similar normalized average EMG s of GMed and GMax to those of the healthy group during the SEBT. Previous studies\textsuperscript{11-13} observed a significant reduction in the MVIC of the hip abductor, hip extensor, and hip external rotator groups. The authors assumed that this weakness lead to the increased knee valgus angle during activities, subsequently causing PFPS symptoms. However, there continues to be discrepancies regarding the neuromuscular contribution of PFPS, possibly due to the different tasks selected and different EMG data processing methods. Some studies investigated EMG onset while the others observed the duration of EMG activity. Brindle et al.,\textsuperscript{18} observing the onset of GMed EMG during stair ascent and descent activities, found a significant difference between PFPS and control groups. The PFPS group demonstrated later onset and shorter duration of the GMed during the stair ascent, and shorter duration of GMed, VM, and VL during stair descent compared to the healthy subjects.

Our study did not find a significant difference in normalized average EMG
activation of GMed or GMax during the SEBT. The reason that we did not find the
significant difference might be the selected task. Earl and Hertel\textsuperscript{28} observed that the
tibialis anterior and the VM were activated more than the other muscles in the lower
extremity during the anterior reach of the SEBT. Although GMed or GMax activations
were not investigated in their study, it is speculated that perhaps the VM and the tibialis
anterior are the primary muscles for maintaining posture during the anterior reach task on
the SEBT, therefore the anterior reach task is not demanding enough for eliciting high
activation of GMed and GMax muscles.\textsuperscript{30} It has been reported that GMed is activated
greatly with isometric hip abduction and internal rotation.\textsuperscript{48} As the GMed is a primary
hip abductor and the GMax is a primary hip extensor and hip external rotator, these
muscles are presumed to be more active during movements in the frontal and transverse
planes.\textsuperscript{30,48} Therefore, the anterior reach of the SEBT, which is primarily a sagittal plane
activity, may not be an appropriate enough task to capture those hip muscle activations.

Although we did not find a statistically significant difference in GMax activation
as a hip extensor or hip external rotator, there were moderate effect sizes associated with
these results. In our study, the PFPS subject demonstrated increased hip extensors and
external rotators EMG activities compared to the control subjects. It may indicate that
the increased hip extensors’ or external rotators’ activities may be associated with the
kinematic and VM EMG alteration. It should be noted that the normalized average EMG
of hip external rotators exceeded 100%, which may indicate that subjects could not
perform MVIC of hip external rotation, therefore EMG activities during the SEBT
exceeded that of MVIC.
To date, a limited amount of investigation is available for the comparison because most studies assessed the EMG onset or duration during the dynamic activities. Since existing studies have observed only sagittal plane movement, further research is warranted to investigate EMG not only on the sagittal plane, but also on the other planes including frontal and transverse planes. Additionally, different phases of the activities should be investigated to identify the different activation patterns in concentric and eccentric contraction phases.

**Pain on the VAS**

It was hypothesized that PFPS subjects would experience more knee pain presented by the visual analogue scale (VAS) at rest compared to the healthy subjects. In addition, we hypothesized that the VAS score would increase during performance of the anterior reach task on the SEBT compared to pre and post performance in the PFPS subjects. Our study demonstrated that the subjects with PFPS reported more knee pain at pre, during, and post test compared to the healthy subjects. Furthermore, the subjects with PFPS demonstrated increased knee pain during and post tests compared to the pre test. Increased knee pain may indicate that the anterior reach task on the SEBT is appropriate task to induce knee pain in the PFPS subjects and may be associated with shorter reach distance in the subjects with PFPS compared with that of healthy subjects. While exacerbation of pain did not seem to alter the hip muscle activities perhaps the observed alterations of the hip and knee kinematic were influenced by pain. Future analysis of the data will explore these relationships.
Normalized anterior reach distance (%MAXD)

It was hypothesized that the healthy subjects would reach farther than PFPS subjects during the anterior reach task of the SEBT, indicating a poor dynamic postural control in the PFPS subjects. Our results supported this hypothesis, since PFPS subjects demonstrated shorter reach distance on the SEBT compared to the healthy subjects, and is supported by previous investigation. Aminaka and Gribble\textsuperscript{26} reported significantly shorter MAXD in PFPS subjects compared with healthy group in both taped and untaped condition.

Since subjects with PFPS demonstrated increased pain during the SEBT relative to that in the pre test, the reduction in the anterior reach may be affected by the knee pain. Furthermore, increased knee valgus angle in the subjects with PFPS may affect this reach distance reduction. As it is known that the presence of the knee valgus angle accompanies other kinematic abnormalities of the lower extremity such as foot pronation, tibial internal rotation, pelvic rotation, lateral pelvic drop,\textsuperscript{6,17} we could speculate that increased knee valgus angle may have contributed to the decreased anterior reach distance of the SEBT in the subjects with PFPS. With increased knee valgus angle, the opposite side of the pelvis tends to rotate externally, which may result in the reduction of the distance.

Previous studies have reported reduced MVIC of the hip abductor, hip extensor, and hip external rotator groups, assuming that this weakness may result in the increased valgus angle during the dynamic activities.\textsuperscript{11-13} Therefore, we may assume that less normalized average EMG activities would be present with PFPS. However, GMed and GMax normalized average EMG activities during the SEBT remained similar between
PFPS and control groups. Therefore, this reduction in anterior reach distance may not be related with the normalized average EMG activity of those muscles.

**Summary**

Our study intended to examine the difference in frontal plane kinematic and neuromuscular control of the lower extremity during dynamic postural control in subjects with PFPS. We found that the subject with PFPS demonstrated significantly increased knee angle, VM activation, shorter reach distance, and increased knee pain during the SEBT. Increased knee valgus angle may be associated with shorter anterior reach distance in the SEBT. Increased VM normalized average EMG activities may indicate increased eccentric contraction as subjects with PFPS lowered their center of mass during the SEBT, which may be the compensation technique of the PFPS group to avoid producing more knee pain. In addition, the PFPS group demonstrated increased knee pain during the task, which may also be a factor contributing to shorter reach distance. We did not find GMed or GMax normalized average EMG activity differences between the groups. The task that we selected was the anterior reach, which may not be demanding enough for GMed or GMax to control posture because the tibialis anterior and VM are the primary muscle groups for the postural control in the anterior reach of the SEBT. The GMed and the GMax activation should be investigated in the movement requiring more hip motions, such as medial direction reach and posterior direction reach of the SEBT.
Limitation

Subjects were asked to perform MVIC with their maximal effort; however, they might not have achieved their maximal effort, which may have affected the normalized normalized average EMG value. The method that we selected for measuring MVIC may not be appropriate for normalizing the EMG activities. MVIC was performed in the OKC while the selected task was performed in the CKC. Few data exceeded 100% after normalization in hip extension in subjects with and without PFPS, indicating maximal efforts may not have accompanied the MVIC, or the difficulty to produce maximal effort in the selected task. Subjects with PFPS reported increased pain during MVIC which may inhibit the maximal contraction. This inhibition would elevate average EMG.

Since knee valgus occurs within the lower extremity kinetic chain, future study should investigate all lower extremity segments such as the pelvis, hip, knee, lower leg and foot, to understand the relationship between each segment. In addition, frontal and transverse plane movement should be involved to assess the hip and knee EMG activities and lower extremity kinematics.

Clinical implication

PFPS patients may demonstrate increased knee valgus angle during the single leg squat which may cause more pain. Therefore, during rehabilitation, clinicians should observe patients’ lower extremity kinematics to avoid the knee from passing into an increased valgus angle. Moreover, clinicians should control the degree of the knee flexion angle during the single leg squat to avoid induce pain to the PFPS patients. It would be beneficial for the patients with PFPS to learn correct movement patterns of the
lower extremity during single leg squat tasks.

**Conclusion**

The results derived from our study indicate that PFPS subjects demonstrate increased knee valgus angle in the anterior reach task on the SEBT. In addition, the PFPS group demonstrated shorter reach distance on the SEBT, along with increased pain on the VAS. On the contrary to our hypothesis, subjects with PFPS demonstrated greater VM activities than healthy subjects. In the sagittal plane movement, VM may play an important role to maintain the balance, while GMed and GMax may not be the primary muscle for the postural control during the task.
References


Appendix A

Informed Consent Form
ADULT RESEARCH SUBJECT INFORMATION AND CONSENT FORM

THE EFFECT OF PATELLOFEMORAL PAIN SYNDROME ON HIP NEUROMUSCULAR CONTROL ON HIP AND KNEE KINEMATICS DURING DYNAMIC POSTURAL CONTROL

Principal Investigator: Phillip Gribble, Ph.D., ATC
Other Staff (identified by role): Naoko Aminaka, MS., ATC, Co-investigator
Shiho Goto, ATC, Co-investigator

Contact Phone number(s): Dr. Phillip Gribble: (419) 530-2691
Naoko Aminaka: (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 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 effect of a knee condition called patellofemoral pain syndrome (PFPS) on muscle activity and movement at the hip and knee during single leg balance. You will be examined for muscle activity as well as joint angle at the hip and knee during single leg squat. We believe that the individuals with PFPS have certain altered characteristics of the knee and hip joint movement and muscle activity that have led to the development of the symptoms of PFPS. The result of this study will provide an understanding about neuromuscular and pain contributions to PFPS during dynamic activity, and will provide more information of the role of lower extremity mechanics in the development of PFPS. The result will help to establish the rehabilitation guidelines for individuals suffering from PFPS and to prevent future development of PFPS.

You were selected as someone who may want to take part in this study because you have met the following criteria:

- Volunteer participant
- Diagnosed by a physician or evaluated by the investigator as having PFPS and the associated symptoms about your knee.
- Physically active individual (participating in at least 30 minutes of moderate or high intensity physical activities, such as walking and jogging, more than twice a week).
- Between the ages of 18 and 30 years.
- No current or previous history of lower extremity injuries, concussions or any other neurological conditions that may affect maintaining balance.
- No previous history of surgical procedures that have caused major structural change in the lower extremities.
- No physical therapy within thirty days prior to the study.

You are enrolling as one of 30 participants (15 subjects with PFPS and 15 subjects with no lower extremity injury). This research study will be conducted in the Athletic Training Research Laboratory in the Health Science and Human Services building at The University of Toledo.

**DESCRIPTION OF THE RESEARCH PROCEDURES AND DURATION OF YOUR INVOLVEMENT**
If you decide to take part in this study, you will be asked to fill out a 10-cm visual analogue scale (VAS) for the level of pre-test knee pain. Body weight, height, and leg length will be measured. Skin will be cleaned with an alcohol swab, lightly rubbed with sandpaper (to remove dead skin cells), and shaved if necessary to eliminate any object which may cause the electrodes to come off.

First, disposable electromyography (EMG) electrodes will be placed on your skin of the hips and thighs in order to record your muscle activity. These electrodes are used for recording purposes of the electrical activity produced during a muscle contraction. You will not feel any sensations from these electrodes any differently than wearing a band-aid.

Maximum voluntary isometric contraction (MVC) of the gluteus medius, gluteus maximus, hip adductor, and quadriceps will be measured during resistive hip abduction, hip adduction, hip extension, hip external rotation, and knee extension. You will be asked to perform the MVC against the examiner's hand resistance. Hip abduction MVC will be measured in the sidelying position on the carpeted floor. You will be asked to bring the top leg up to about 30° with the toes slightly facing up, and hold it in place against the investigator's hand resistance just below the knee. Hip adduction MVC will be performed in the same sidelying position, however with the bottom leg brought up about 6 inches off the floor and toes facing straight forward, while the top leg is crossed in front of the body. Hand resistance will be applied just below the inside of the knee. Hip extension is performed while you are lying on your stomach with the knee flexed to 90°. You will then be asked to bring the whole leg up against the examiner's hand resistance applied at the mid-thigh. The MVC for hip external rotation is performed while you are sitting on a treatment table with the hip and knee flexed to 90°. The examiner applies resistance at your lower leg, and you are asked to bring the foot toward the midline of your body. Knee extension MVC will be performed in a sitting position similar to the hip external rotation MVC. You will be asked to bring your knee into a slightly flexed position, and hold the position against the examiner's hand resistance. The MVCs will be performed three times for six seconds for each activity. You will be given at least one-minute rest between each trial, to avoid muscle fatigue or tiredness.

After completing performance of MVC, you will be asked to perform the MVC of hip abductor, hip extensor and hip external rotator using biodex isokinetic system. The MVC of the hip abduction and extension will be evaluated in standing position, and hip external rotation will be evaluated in sitting position. You will be asked to perform three times for six seconds for each activity with at least one minute rest between each trial.

Following the five minutes of rest after completing the MVC collection, electromagnetic sensors will be attached at the lower back, outer thigh, and outer lower leg with loop straps. These sensors will allow us to measure the position and movement patterns of your joints. You will not feel any sensations from the sensors. The sensors
and the cords will be secured to your skin with a non-adhesive elastic tape or a strap to keep the sensors in place and prevent the cords from interfering with your movement.

You will then be asked to perform single leg squat with bare feet with your hands at the hip. This is also known as the Star Excursion Balance Test (SEBT). You will be instructed to reach into forward direction along the tape measure, using the toes of the non-standing leg to make a touch as lightly as possible, and then return to the starting point with double-leg stance. The reaching distance will be marked and measured in centimeters. All measures will be recorded by the same investigator. You will be allowed to complete four practice trials to eliminate the learning effect. Following a five-minute rest, you will perform five forward direction reaches. Each trial will be separated by 15 seconds of rest. You will be asked to repeat the trial if the stance foot is lifted while reaching, let your non-standing foot touch the mat, or if you lose balance during the trials.

You will be asked to report the maximum pain which will be perceived during the test on the VAS upon completion of all the SEBT tests, and also to report the pain five minutes after completing the test. The whole data collection session will last approximately two hours.

**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 performing a single leg squat, there is a slight chance of falling during the SEBT. However, you will be given instruction on how to perform the task and 4 practice trials as you become comfortable with the task.
2. You may experience increase in pain during the SEBT which involves repetitive knee flexion and extension. You will be closely monitored during the test and able to stop testing any time. Having the rest periods between the tasks should help to minimize this risk. Furthermore, you will be asked to withdraw from the study if the investigators see the risk of further injury if the study continues.
3. Adhesive tapes are used to secure electrodes. You may have skin reaction if your skin is sensitive and had a reaction before. If you know of any existing skin sensitivities, it is important that you inform the investigator.

**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 and postural control.
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
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.

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 of Toledo 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 Phillip Gribble, PhD, ATC (419) 530-2691, or Naoko Aminaka, MS, ATC (419) 530-2764.

VOLUNTARY PARTICIPATION
Taking part in this study is voluntary. You may refuse to participate or discontinue participation at any time without penalty or a loss of benefits to which you are otherwise entitled. If you decide not to participate or to discontinue participation, your decision will not affect your future relations with the University of Toledo or The University of Toledo Medical Center.
CONFIDENTIALITY

The researchers will make every effort to prevent anyone who is not on the research team from knowing that you provided this information, or what that information is. The consent forms with signatures will be kept separate from responses, which will not include names and which will be presented to others only when combined with other responses. Although we will make every effort to protect your confidentiality, there is a low risk that this might be breached.

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.
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. If you have questions regarding the research at any time before, during or after the study, you may contact Phillip Gribble, PhD, ATC (419) 530-2691.

If you have questions beyond those answered by the research team or your rights as a research subject or research-related injuries, please feel free to contact the Chairperson of the University of Toledo Biomedical Institutional Review Board at 419-383-6796.

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 PROTECTED 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).

Name of Subject (please print) __________________________ Signature of Subject or Person Authorized to Consent __________________________ Date __________________________

Relationship to the Subject (Healthcare Power of Attorney authority or Legal Guardian) __________________________ Time p.m.________________________

Name of Subject (please print) __________________________ Signature of Subject or Person Authorized to Consent __________________________ Date __________________________

Relationship to the Subject (Healthcare Power of Attorney authority or Legal Guardian) __________________________ Time p.m.________________________
<table>
<thead>
<tr>
<th>Name of Person Obtaining Consent (please print)</th>
<th>Signature of Person Obtaining Consent</th>
<th>Date</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Name of Witness to Consent Process (when required by ICH Guidelines)</th>
<th>Signature of Witness to Consent Process (when required by ICH Guidelines)</th>
<th>Date</th>
</tr>
</thead>
</table>

(please print)

YOU WILL BE GIVEN A **SIGNED** COPY OF THIS FORM TO KEEP.
Appendix B

Visual Analogue Scale
Place an x on the line below to indicate your current level of pain, prior to testing.

Visual Analog Scale (VAS)

No Pain  Pain as bad as it could possibly be
Place an x on the line below to indicate your current level of pain, during test.

**Visual Analog Scale (VAS)**

No Pain

Pain as bad as it could possibly be
Place an x on the line below to indicate your current level of pain, 5 minutes post test.

Visual Analog Scale (VAS)

No Pain

Pain as bad as it could possibly be
Appendix C

Star Excursion Balance Test Reach Directions
Star Excursion Balance Test Reach Directions

Left-leg stance

Right-leg stance
Appendix D

Picture of Anterior Reach of the Star Excursion Balance Test
Anterior Reach of the SEBT
Appendix E

Data Collection Sheet
Subject # _____________

Height: __________cm  Weight: __________kg

Stance Leg Length  L: __________cm  R: __________cm

MVIC (average EMG)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

SEBT

<table>
<thead>
<tr>
<th></th>
<th>Reach distance (cm)</th>
<th>Normalized distance (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### iEMG

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Valgus knee angle at touchdown

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td></td>
</tr>
</tbody>
</table>
Appendix E

Pictures of Maximal Voluntary Isometric Contraction
MVIC: Hip abduction
MVIC: Hip Extension
MVIC: Hip External Rotation
MVIC: Knee Extension
Appendix F

Pictures of Motion Monitor
The right half of the picture presents kinematic data (top), EMG data (middle), and event markers (bottom) that were placed during the SEBT. A dashed line (left) indicates the initiation of the SEBT while the other dashed line (right) indicates the end of the SEBT. Bold line indicates the point of touch-down. EMG data was measured between two dashed lines. The knee valgus angle was measured at the touch-down point.