

# Trunk and Lower Extremity Kinematics in Individuals With and Without Patellofemoral Pain Syndrome

Brandi Gordon Schwane

A thesis submitted to the faculty of the University of North Carolina at Chapel Hill in partial fulfillment of the requirements for the degree of Master of Arts in the Department of Exercise and Sport Science in the College of Arts and Sciences (Athletic Training).

Chapel Hill  
2011

Approved by:

Advisor: Darin Padua, PhD, ATC

Reader: Troy Blackburn, PhD, ATC

Reader: Benjamin Goerger, MS, ATC

Reader: Shiho Goto, MS, ATC

Reader: Alain Aguilar, MA, AT

© 2011  
Brandi Gordon Schwane  
ALL RIGHTS RESERVED

## ABSTRACT

BRANDI SCHWANE: Trunk and Lower Extremity Kinematics in Individuals With and Without Patellofemoral Pain Syndrome  
(Under the direction of Darin Padua, PhD, ATC)

**Objective:** To compare trunk and lower extremity kinematics between subjects with PFPS and healthy controls and evaluate the influence of trunk kinematics on lower extremity kinematics for each group during a stair descent task. **Design:** Cross-sectional. **Setting:** Research laboratory. **Participants:** Twenty females with PFPS and 20 healthy females. **Data Collection:** Trunk, hip, and knee joint displacement in the sagittal, frontal, and transverse planes. **Results:** PFPS subjects displayed approximately 4° more knee internal rotation displacement than the control group ( $p=0.044$ ). Trunk lateral flexion displacement was more predictive of knee internal rotation displacement for PFPS subjects whereas trunk rotation displacement was more predictive of knee internal rotation displacement for control subjects. **Conclusion:** Knee internal rotation may be a compensatory mechanism of those with PFPS to decrease pain during activity. Furthermore, assessment of the trunk should be considered in females with PFPS. **Key Words:** PFPS, knee internal rotation, trunk kinematics, stair descent

## ACKNOWLEDGEMENTS

Thank you to my advisor, Dr. Darin Padua, for all of your guidance and confidence in me throughout the entire process. You were always willing to meet with me, respond to my countless emails, and provide encouragement. To Ben Goerger, thank you for the invaluable time you invested in my project to ensure that it was successful. You spent innumerable hours meeting with me and guiding me through data reduction, troubleshooting, and statistics. Thank you to Shiho Goto for your assistance with data collection and research guidance. Your knowledge pertaining to the subject matter was extensive and important for the success of my thesis. Thank you to Troy Blackburn and Alain Aguilar for your time in reading my thesis documents and the indispensable editorial remarks that you provided. To my entire committee, thank you for your commitment to research and your dedication to improving the athletic training profession.

I have a tremendous amount of respect for the scientific investigation process and feel that I am a better consumer of the literature after having completed this research project. To my husband, thank you for your patience, support, and encouragement throughout this process. You have made this journey worth the while. Finally, to the National Athletic Trainers' Association Research and Education Foundation, a special thank you for the financial support of this research project.

## TABLE OF CONTENTS

<b>LIST OF FIGURES .....</b>	<b>IX</b>
<b>LIST OF TABLES .....</b>	<b>X</b>
<b>LIST OF APPENDICES .....</b>	<b>XI</b>
<b>CHAPTER I .....</b>	<b>1</b>
STATEMENT OF PURPOSE .....	7
INDEPENDENT VARIABLES .....	7
DEPENDENT VARIABLES .....	7
RESEARCH QUESTIONS .....	8
NULL HYPOTHESES .....	9
RESEARCH HYPOTHESES .....	11
OPERATIONAL DEFINITIONS.....	14
ASSUMPTIONS .....	18
LIMITATIONS.....	19
DELIMITATIONS .....	19
SIGNIFICANCE OF THE STUDY .....	19
<b>CHAPTER II.....</b>	<b>21</b>
INTRODUCTION .....	21
EPIDEMIOLOGY .....	22

PATELLOFEMORAL PAIN SYNDROME .....	25
<i>Contact Area and Pressure</i> .....	26
FUNCTIONAL ANATOMY OF THE KNEE.....	27
<i>Passive Stability</i> .....	29
<i>Dynamic Stability</i> .....	30
RISK FACTORS FOR PATELLOFEMORAL PAIN SYNDROME .....	31
<i>Structural Factors</i> .....	32
<i>Strength Factors</i> .....	35
<i>Biomechanical Factors</i> .....	36
TRUNK STABILITY AND KINEMATICS .....	37
LACK OF EVIDENCE .....	38
<b>CHAPTER III .....</b>	<b>39</b>
SUBJECTS .....	39
INSTRUMENTATION .....	42
<i>Three-Dimensional Motion Capture System</i> .....	42
<i>Force Plates</i> .....	43
<i>Stairs</i> .....	43
PROCEDURES .....	44
<i>Three Dimensional (3-D) Motion Analysis</i> .....	44
<i>Stair Stepping Task</i> .....	45
DATA PROCESSING AND REDUCTION .....	46
STATISTICAL ANALYSIS .....	47
<b>CHAPTER IV .....</b>	<b>49</b>
TRUNK KINEMATICS .....	49

HIP KINEMATICS .....	50
KNEE KINEMATICS.....	50
CORRELATION ANALYSIS.....	50
MULTIPLE REGRESSION .....	51
VAS SCORES .....	51
<b>CHAPTER V .....</b>	<b>53</b>
TRUNK KINEMATICS .....	55
HIP KINEMATICS .....	57
KNEE KINEMATICS.....	59
LIMITATIONS.....	63
CLINICAL SIGNIFICANCE .....	65
SUMMARY .....	65
<b>FIGURES.....</b>	<b>67</b>
FIGURE 1: FORCE PLATE SET UP .....	67
FIGURE 2: STAIR STEPPING TASK.....	68
FIGURE 3: THE EFFECT OF STAIR STEPPING ON KNEE INTERNAL ROTATION.....	69
<b>TABLES.....</b>	<b>70</b>
TABLE 1: SUBJECT DEMOGRAPHICS .....	70
TABLE 2: COMPARISON OF TRUNK AND LOWER EXTREMITY KINEMATICS BETWEEN GROUPS .....	71
TABLE 3: TRUNK AND HIP KINEMATICS VARIABLES CORRELATED TO KNEE INTERNAL ROTATION .....	72
TABLE 4: PEARSON CORRELATION COEFFICIENTS FOR THE MULTIPLE REGRESSION ANALYSES .....	73

TABLE 5: PRE AND POST VAS SCORES .....	74
<b>APPENDICES .....</b>	<b>75</b>
APPENDIX 1: PATELLOFEMORAL PAIN SYNDROME SCREENING SHEET .....	75
APPENDIX 2: CONTROL GROUP SCREENING SHEET .....	77
APPENDIX 3: 10-CM VAS PAIN SCALE.....	78
APPENDIX 4: MANUSCRIPT .....	79
<b>REFERENCES.....</b>	<b>118</b>



## LIST OF FIGURES

Figure 1: Force Plate Set-Up.....	67
Figure 2: Stair Stepping Task .....	68
Figure 3: The Effect of Stair Stepping on Knee Internal Rotation .....	69

## LIST OF TABLES

Table 1: Subject Demographics .....	70
Table 2: Comparison of Trunk and Lower Extremity Kinematics Between Groups .....	71
Table 3: Trunk and Hip Kinematic Variables Correlated to Knee Internal Rotation .....	72
Table 4: Pearson Correlation Coefficients for the Multiple Regression Analyses .....	73
Table 5: Pre and Post VAS Scores.....	74

## LIST OF APPENDICES

Appendix 1: Patellofemoral Pain Syndrome Screening Sheet.....	75
Appendix 2: Control Group Screening Sheet .....	77
Appendix 3: 10-cm VAS Pain Scale.....	78
Appendix 4: Manuscript .....	79

## **CHAPTER I**

### **INTRODUCTION**

Patellofemoral pain syndrome (PFPS) is one of the most common chronic injuries among adolescents and young adults (DeHaven & Lintner, 1986; Ireland, Willson, Ballantyne, & Davis, 2003; 2002). Patellofemoral pain syndrome within the athletic population has a reported incidence rate greater than 25% (Ireland, et al., 2003) and overall the incidence of PFPS is greater in the physically active population compared to the general population (Clement, 1981; Devereaux & Lachmann, 1984; Powers, 2003; Taunton, et al., 2002). Furthermore, females are more likely to experience PFPS in comparison to males (M. Boling, et al., 2009; DeHaven & Lintner, 1986; Ireland, et al., 2003; Taunton, et al., 2002). Due to the high prevalence of PFPS in females there is a need to understand the underlying factors associated with this disorder.

The causes of PFPS are multifactorial with patellofemoral malalignment commonly accepted as a major contributor to PFPS (Ireland, et al., 2003; Powers, 2003). Patellofemoral malalignment increases contact pressure within the patellofemoral joint, leading to abnormal cartilage wear and ultimately degenerative changes if left untreated or if conservative treatment options fail (Insall, 1982; Utting, Davies, & Newman, 2005). Therefore, factors that influence patellofemoral contact pressure are believed to contribute to the development of PFPS. The quadriceps angle (Q-angle) is one of the most commonly assessed measures of postural alignment reported in the literature

(Aglietti, Insall, & Cerulli, 1983; M. C. Boling, et al., 2009; Heiderscheit, Hamill, & Caldwell, 2000; Huberti & Hayes, 1984; Mizuno, et al., 2001; Powers, 2003). The Q-angle represents the alignment between the pelvis, leg, and foot measured in a static stance position. A larger Q-angle causes lateral patellar tracking, thus decreasing patellofemoral contact area and increasing patellofemoral contact pressure (Hirokawa, 1991; Huberti & Hayes, 1984; Mizuno, et al., 2001). However, research studies have yielded conflicting results as to whether an increased static Q-angle is greater in participants with PFPS compared to healthy subjects (Aglietti, et al., 1983; Duffey, Martin, Cannon, Craven, & Messier, 2000; Messier, Davis, Curl, Lowery, & Pack, 1991; Thomee, Renstrom, Karlsson, & Grimby, 1995; Witvrouw, Lysens, Bellemans, Cambier, & Vanderstraeten, 2000); thus, calling into question the role of static Q-angle as a risk factor for PFPS. Other factors that influence patellofemoral contact pressure during dynamic tasks may be more important for understanding one's risk for developing PFPS.

Lower extremity kinematics may directly influence patellofemoral contact pressure during dynamic tasks. Specifically, the motions of femoral internal rotation, femoral adduction, and knee valgus mediate patellofemoral contact pressure (Bolgia, Malone, Umberger, & Uhl, 2008; T. Q. Lee, Anzel, Bennett, Pang, & Kim, 1994; Mascal, Landel, & Powers, 2003; Powers, 2003). Femoral internal rotation has been proposed to increase lateral patellar facet contact pressure due to the unequal distribution of patellar contact within the femoral groove (T. Q. Lee, et al., 1994; Powers, 2003; Salsich & Perman, 2007). Lee et al. (1994) examined the relationship between patellofemoral contact pressure and femoral rotation in seven cadaveric specimens. This study reported higher peak patellofemoral contact pressure on the lateral patellar facet with femoral

internal rotation and higher peak contact pressure on the medial patellar facet with femoral external rotation compared to neutral position (T. Q. Lee, et al., 1994). Femoral adduction increases the angle of the femur in the frontal plane, resulting in a greater dynamic Q-angle; therefore, increasing lateral patellofemoral contact pressure (Powers, 2003). Also, femoral adduction often results in dynamic knee valgus, which is associated with an increase in Q-angle (Claiborne, Armstrong, Gandhi, & Pincivero, 2006; Hollman, et al., 2009; Powers, 2003; Zeller, McCrory, Kibler, & Uhl, 2003). Therefore, lack of control of femoral rotation, femoral adduction, and knee valgus is thought to play an important role in the risk of developing PFPS by directly influencing patellofemoral contact pressure.

Hip external rotator and abductor strength would seemingly play an important role in limiting excessive femoral internal rotation, adduction, and knee valgus during dynamic tasks, thus influencing PFPS. However, it is unclear how hip external rotator and abductor strength are each related to PFPS. Isometric weakness of the hip external rotators and abductors has been associated with PFPS in females (Bolgia, et al., 2008; Cichanowski, Schmitt, Johnson, & Niemuth, 2007; Ireland, et al., 2003; Mascal, et al., 2003; Robinson & Nee, 2007; Souza & Powers, 2009; Willson & Davis, 2009). In contrast, Cowan et al. (2009) and Piva et al. (2005) did not find differences in hip isometric external rotation and abduction strength between PFPS subjects and a control group. This discrepancy in research findings may be attributed to the use of a mixed gender cohort.

Although lesser isometric hip strength has been found in individuals with PFPS, few studies have examined hip strength and lower extremity kinematics simultaneously.

Bolgla et al. (2008) have simultaneously examined isometric hip strength of the external rotators and abductors and kinematics of the hip and knee joints and found that subjects with PFPS had less isometric hip external rotation and abduction strength but did not find significant differences in hip internal rotation and adduction angles during a stair stepping task between the PFPS group and a control group (Bolgla, et al., 2008). In contrast, two case studies by Mascall et al. (2003) found a relationship between decreased hip external rotator and abductor strength and altered lower extremity kinematics. After a 14-week intervention program targeting hip strength and neuromuscular control, subjects exhibited increased hip external rotator and abductor strength and decreased hip internal rotation and adduction angles during a functional step-down task (Mascall, et al., 2003). The difference between these two studies can be attributed to the fact that Bolgla et al. (2008) compared PFPS and control groups while Mascall et al. (2003) did repeated testing on two subjects with PFPS. Mascall et al. (2003) also incorporated trunk strengthening exercises into their rehab program, which may have influenced trunk motion control during activity and ultimately altered lower extremity kinematics.

Previous research examining hip strength has observed altered trunk motion during dynamic activities that may greatly influence lower extremity kinematics (Blackburn & Padua, 2008; Souza & Powers, 2009; Willson & Davis, 2009). Although Souza et al. (2009) did not find that decreased hip abduction strength translated into increased hip adduction angle, the authors suggested that subjects may have employed a lateral trunk lean toward the stance leg and attributed this trunk movement as a compensation for hip abductor weakness (Souza & Powers, 2009). Dierks et al. (2008) also observed a lateral trunk lean in subjects with PFPS in the presence of hip abductor

weakness during running. Although hip strength plays an important role in influencing hip and knee kinematics, strength alone does not explain a significant amount of variability in altered lower extremity kinematics associated with PFPS (Bolgia, et al., 2008; Mascal, et al., 2003; Souza & Powers, 2009). Given the previous research demonstrating a relationship between trunk and lower extremity kinematics, it is plausible that individuals with PFPS may have altered trunk kinematics compared to healthy individuals.

Trunk kinematics may indirectly influence patellofemoral contact pressure by influencing frontal and transverse plane motion of the hip and knee during dynamic tasks. Previous research has shown an association between trunk and lower extremity kinematics during drop landing, walking, and side cutting tasks in a healthy population (Blackburn & Padua, 2008; Houck, Duncan, & De Haven, 2006). Based on these findings it is plausible that uncontrolled trunk motion may facilitate increased femoral rotation, adduction, and knee valgus. However, trunk kinematics have not been studied in those with PFPS.

Trunk biomechanics, such as strength, endurance, proprioception, and displacement, have also been linked to lower extremity injury. Decreases in trunk strength, endurance, and neuromuscular control have shown to increase lower extremity injury risk among females (Leetun, Ireland, Willson, Ballantyne, & Davis, 2004; Willson, Dougherty, Ireland, & Davis, 2005; B. T. Zazulak, Hewett, Reeves, Goldberg, & Cholewicki, 2007a, 2007b). Research in this area has specifically examined ligamentous and meniscal injuries and has not examined the correlation between altered trunk kinematics, strength, endurance, or neuromuscular control and incidence of PFPS. The



only study to specifically focus on hip and trunk muscle function in individuals with PFPS noted that the PFPS subjects had significantly less trunk lateral flexion strength compared to healthy controls (Cowan, et al., 2009). Differences in trunk kinematics between PFPS and healthy individuals may help explain previous research demonstrating differences in lower extremity kinematics associated with increased patellofemoral contact pressure. Unfortunately, research has not investigated whether or not trunk motion differs between PFPS and healthy individuals.

Many studies examining kinematics in those with PFPS have used single-leg squat, jump-landing tasks, or drop-landing tasks to assess lower extremity biomechanics. Other studies have used more functional tasks such as stair ascent or descent to assess lower extremity kinematics (Bolgla, et al., 2008; Brechter & Powers, 2002; Crossley, Cowan, Bennell, & McConnell, 2004; Mascal, et al., 2003; Powers, 2003; Souza & Powers, 2009). Individuals diagnosed with PFPS often complain of pain with stair descent due to the eccentric quadriceps loading and single leg position that occurs during the task. Therefore, assessment of lower extremity biomechanics during stair stepping is believed to be important to understanding mechanisms associated with increased patellofemoral contact pressure. (Bolgla, et al., 2008; Brechter & Powers, 2002; Crossley, et al., 2004; Mascal, et al., 2003; Powers, 2003; Souza & Powers, 2009). Krebs et al. (1992) examined trunk kinematics during a stair stepping task and reported greater overall trunk motion during stair ascent and descent compared to gait. This study also demonstrated that the trunk and pelvis moved in greater synchrony during stair descent (Krebs, et al., 1992). These findings suggest that stair stepping places greater demands on trunk motion control compared to other tasks, such as gait. Also, there appears to be a

coupled movement pattern between trunk motion and lower extremity kinematics. A limitation of this previous research is that it was performed exclusively in a healthy population. Thus, it is not clear how trunk kinematics are affected during stair stepping in those with PFPS. This study will use a stair descent task to examine trunk and lower extremity kinematics.

### **Statement of Purpose**

The primary purpose of this study was to compare trunk and lower extremity kinematics during stair descent between females with PFPS and a healthy control group. A secondary purpose was to evaluate the relationship between trunk and hip kinematics with knee kinematics during stair descent. We hypothesized that females with PFPS would have greater trunk rotation and lateral flexion toward the stance leg, as well as greater overall trunk flexion, during stair descent compared to the control group. Additionally, we believed that females with PFPS would have greater sagittal, frontal, and transverse plane hip and knee motion compared to the control group. We also hypothesized that there would be a positive correlation between trunk and knee kinematics, as well as hip and knee kinematics, during stair descent, such that motion of the trunk and hip would have a significant relationship with knee motion.

### **Independent Variables**

1. Group – patellofemoral pain syndrome group, control group

### **Dependent Variables**

1. Joint Displacement
  - a. Trunk sagittal plane

- b. Trunk frontal plane
- c. Trunk transverse plane
- d. Hip sagittal plane
- e. Hip frontal plane
- f. Hip transverse plane
- g. Knee sagittal plane
- h. Knee frontal plane
- i. Knee transverse plane

### **Research Questions**

1. Is there a significant difference in sagittal, frontal, and transverse plane trunk kinematics during stair descent between subjects with patellofemoral pain syndrome and a control group?
2. Is there a significant difference in sagittal, frontal, and transverse plane hip kinematics during stair descent between subjects with patellofemoral pain syndrome and a control group?
3. Is there a significant difference in sagittal, frontal, and transverse plane knee kinematics during stair descent between subjects with patellofemoral pain syndrome and a control group?

4. Is there a significant difference in pre and post VAS scores in subjects with and without patellofemoral pain syndrome?
5. Are trunk and hip kinematics related to those knee kinematic variables that are found to be significantly different during stair descent between subjects with patellofemoral pain syndrome and a control group?

### **Null Hypotheses**

1. RQ1: Is there a significant difference in sagittal, frontal, and transverse plane trunk kinematics during stair descent between subjects with patellofemoral pain syndrome and a control group?
  - a.  $H_0$ : There will be no difference in sagittal plane trunk kinematics between groups during stair descent.
  - b.  $H_0$ : There will be no difference in frontal plane trunk kinematics between groups during stair descent.
  - c.  $H_0$ : There will be no difference in transverse plane trunk kinematics between groups during stair descent.
2. RQ2: Is there a significant difference in sagittal, frontal, and transverse plane hip kinematics during stair descent between subjects with patellofemoral pain syndrome and a control group?
  - a.  $H_0$ : There will be no difference in sagittal plane hip kinematics between groups during stair descent.

- b.  $H_0$ : There will be no difference in frontal plane hip kinematics between groups during stair decent.
  - c.  $H_0$ : There will be no difference in transverse plane hip kinematics between groups during stair decent.
3. RQ3: Is there a significant difference in sagittal, frontal, and transverse plane knee kinematics during stair descent between subjects with patellofemoral pain syndrome and a control group?
- a.  $H_0$ : There will be no difference in sagittal plane knee kinematics between groups during stair decent.
  - b.  $H_0$ : There will be no difference in frontal plane knee kinematics between groups during stair decent.
  - c.  $H_0$ : There will be no difference in transverse plane knee kinematics between groups during stair decent.
4. RQ4: Is there a significant difference between pre and post VAS scores in subjects with and without patellofemoral pain syndrome?
- a.  $H_0$ : There will be no main effect for group.
  - b.  $H_0$ : There will be no main effect for time.
  - c.  $H_0$ : There will be no interaction effect.

5. RQ5: Are trunk and hip kinematics related to those knee kinematic variables that are found to be significantly different during stair descent between subjects with patellofemoral pain syndrome and a control groups?
  - a.  $H_0$ : There is no association between trunk and knee kinematic variables during stair descent for all subjects.
  - b.  $H_0$ : There is no association between trunk and knee kinematic variables during stair descent for the patellofemoral pain syndrome group.
  - c.  $H_0$ : There is no association between trunk and knee kinematic variables during stair descent for the control group.
  - d.  $H_0$ : There is no association between hip and knee kinematic variables during stair descent for all subjects.
  - e.  $H_0$ : There is no association between hip and knee kinematic variables during stair descent for the patellofemoral pain syndrome group.
  - f.  $H_0$ : There is no association between hip and knee kinematic variables during stair descent for the control group.

### **Research Hypotheses**

1. RQ1: Is there a significant difference in sagittal, frontal, and transverse plane trunk kinematics during stair descent between subjects with patellofemoral pain syndrome and a control group?

- a.  $H_A$ : The patellofemoral pain syndrome group will have greater sagittal plane trunk motion during stair descent.
  - b.  $H_A$ : The patellofemoral pain syndrome group will have greater frontal plane trunk motion during stair descent.
  - c.  $H_A$ : The patellofemoral pain syndrome group will have greater transverse plane trunk motion during stair descent.
2. RQ2: Is there a significant difference in sagittal, frontal, and transverse plane hip kinematics during stair descent between subjects with patellofemoral pain syndrome and a control group?
- a.  $H_A$ : The patellofemoral pain syndrome group will have greater sagittal plane hip motion during stair descent.
  - b.  $H_A$ : The patellofemoral pain syndrome group will have greater frontal plane hip motion during stair descent.
  - c.  $H_A$ : The patellofemoral pain syndrome group will have greater transverse plane hip motion during stair descent.
3. RQ3: Is there a significant difference in sagittal, frontal, and transverse plane knee kinematics during stair descent between subjects with patellofemoral pain syndrome and a control group?
- a.  $H_A$ : The patellofemoral pain syndrome group will have greater sagittal plane knee motion during stair descent.

- b. H<sub>A</sub>: The patellofemoral pain syndrome group will have greater frontal plane knee motion during stair descent.
  - c. H<sub>A</sub>: The patellofemoral pain syndrome group will have greater transverse plane knee motion during stair descent.
4. RQ4: Is there a significant difference between pre and post VAS scores in subjects with and without patellofemoral pain syndrome?
- a. H<sub>A</sub>: There will be a significant main effect for group.
  - b. H<sub>A</sub>: There will be a significant main effect for time.
  - c. H<sub>A</sub>: There will be a significant interaction effect.
5. RQ5: Are trunk and hip kinematics related to those knee kinematic variables that are found to be significantly different during stair descent between subjects with patellofemoral pain syndrome and a control groups?
- a. H<sub>A</sub>: Trunk kinematics are positively associated with knee kinematics during stair descent for all subjects.
  - b. H<sub>A</sub>: Trunk kinematics are positively associated with knee kinematics during stair descent for the patellofemoral pain syndrome group.
  - c. H<sub>A</sub>: Trunk kinematics are positively associated with knee kinematics during stair descent for the control group.
  - d. H<sub>A</sub>: Hip kinematics are positively associated with knee kinematics during stair descent for all subjects.



- e.  $H_A$ : Hip kinematics are positively associated with knee kinematics during stair descent for the patellofemoral pain syndrome group.
- f.  $H_A$ : Hip kinematics are positively associated with knee kinematics during stair descent for the control group.

### **Operational Definitions**

1. Patellofemoral Pain Syndrome Group: The following inclusion and exclusion criteria were used for placement of subjects into this group.

a. Inclusion Criterion:

i. Female

- 1. Only females were included in the study because this population has a higher incidence rate and prevalence of PFPS compared to males (M. Boling, et al., 2009; DeHaven & Lintner, 1986; Taunton, et al., 2002).

ii. Age between 18 and 35

- 1. Females over the age of 35 were not included in the study to reduce the likelihood of osteoarthritic changes within the patellofemoral joint.
- 2. Adolescents were not included in the study because the causes of PFPS within this population are not well

understood and may differ from the causes of PFPS within an adult population.

- iii. Retropatellar knee pain present for at least 2 months during at least 2 of the following activities: ascending/descending stairs, hopping/jogging, prolonged sitting with flexed knees, kneeling, or squatting (Bolgia, et al., 2008; M. Boling, et al., 2009; Brechter & Powers, 2002; Cowan, Bennell, Hodges, Crossley, & McConnell, 2001; Crossley, et al., 2004)
- iv. Pain on palpation of the patellar tendon in addition to the medial or lateral patellar facets AND/OR pain on palpation of the anterior portion of the medial or lateral femoral condyles (M. Boling, et al., 2009; Powers, 2000; Van Tiggelen, Cowan, Coorevits, Duvigneaud, & Witvrouw, 2009; Witvrouw, et al., 2000). Subjects exclusively with patellar tendon pain upon palpation were excluded.
- v. Insidious onset of knee pain not related to trauma (Brechter & Powers, 2002; Cowan, et al., 2001; Cowan, et al., 2009)
- vi. Negative findings on examination of knee ligament, menisci, or bursa (M. Boling, et al., 2009; Brechter & Powers, 2002; Cowan, et al., 2009; Powers, Heino, Rao, & Perry, 1999; Van Tiggelen, et al., 2009)

vii. Subject rated average pain within the week prior to participation as at least 3 cm on the 10-cm visual analog scale (VAS) pain scale (Bolgla, et al., 2008; Cowan, et al., 2001; Souza & Powers, 2009; Van Tiggelen, et al., 2009) OR rated their pain as at least 3 cm with two of the following activities: ascending/descending stairs, hopping/jogging, prolonged sitting with flexed knees, kneeling, or squatting

b. Exclusion Criterion:

- i. History of knee surgery on the involved extremity (Brechtler & Powers, 2002; Cowan, et al., 2001; Gilleard, McConnell, & Parsons, 1998)
- ii. History of low back, hip, or ankle injury within the 6 months prior to participation
- iii. Currently involved in physical therapy or had undergone physical therapy for a lower extremity injury within the 3 months prior to participation (Gilleard, et al., 1998)
- iv. Neurological injury or disease that would influence gait or balance (Brechtler & Powers, 2002; Crossley, et al., 2004; Powers, et al., 1999; Souza & Powers, 2009)

2. Control Group: Subjects in this group were matched to the subjects in the PFPS group based on age, weight, height, and leg dominance. The following inclusion and exclusion criteria were used for placement of subjects into this group.

a. Inclusion Criterion:

- i. Female
- ii. Age between 18 and 35
- iii. No prior history or diagnosis of knee pain or pathology within the 6 months prior to participation (Bolgla, et al., 2008; Brechter & Powers, 2002; Ireland, et al., 2003; Owings & Grabiner, 2002; Powers, 2000; Powers, et al., 1999)

b. Exclusion Criterion:

- i. History of knee surgery
- ii. History of low back, hip, or ankle injury within the 6 months prior to participation that resulted in activity modification more than 2 days
- iii. Neurological injury or disease that would influence gait or balance (Brechter & Powers, 2002; Protopapadaki, Drechsler, Cramp, Coutts, & Scott, 2007; Riener, Rabuffetti, & Frigo, 2002)

3. Test Leg: For the PFPS group, the test leg was determined as the leg in which the subject was currently experiencing PFPS. If the subject experienced pain

- bilaterally, the most affected leg was tested; this was based on a subjective report of pain from the subject. For the control group, the test leg was the same as the corresponding subject with PFPS (ie. If the PFPS subject experienced pain in her right knee, then the corresponding control subject's right knee was tested.)
4. Leg Dominance: The dominant leg was defined as the leg the subject would use to kick a soccer ball for maximal distance.
  5. Stair Stepping: Stair stepping involved descending stairs in a step-over-step fashion. At no time should both feet have been on the same step.
  6. Stance Phase: The point of initial contact to toe off for the involved limb. Initial contact was determined by vertical ground reaction force exceeding 10 N above baseline. Toe off was determined by vertical ground reaction force dropping below 10 N above baseline.
  7. Joint Displacement: The difference between the maximum or minimum joint angle (dependent upon the direction of interest) and the angle at initial contact.

### **Assumptions**

1. Vicon Nexus and force plates were valid and reliable instruments.
2. Subjects truthfully and accurately responded to the questionnaire regarding inclusion and exclusion criteria for their respective group placement.
3. Subjects in both groups put forth their best effort during the descent task.

4. Stair stepping was a functional task during which subjects with PFPS typically experience pain.

### **Limitations**

1. We could not determine cause and effect based on the data within the PFPS group.
2. We could not generalize findings to other chronic knee conditions.
3. We could not generalize findings to males.
4. We could not generalize findings to adolescents and adults over the age of 35.

### **Delimitations**

1. The subjects were females between the ages of 18 and 35.

### **Significance of the Study**

Despite a growing interest in trunk motion and its effect on lower extremity kinematics, there is limited research on trunk kinematics in subjects with PFPS. It has been theorized that altered trunk kinematics contribute to PFPS but this theory has not been validated by research. This study examined whether there were differences in trunk, hip, and knee kinematics between females with PFPS and a healthy population and whether a relationship existed between the trunk and lower extremity kinematic variables in subjects with PFPS. If there is a relationship between the trunk and lower extremity in females with PFPS, the trunk should be considered in the evaluation and rehabilitation in this population. Furthermore, these findings would facilitate future research regarding

the trunk in those with PFPS. It is the hope of this study that future research can develop enhanced rehab approaches to treating PFPS.

## **CHAPTER II**

### **REVIEW OF THE LITERATURE**

#### **Introduction**

Because patellofemoral pain syndrome (PFPS) is a debilitating condition, it is important to understand the factors contributing to this injury. The literature has indicated that subjects with PFPS have altered lower extremity kinematics. Previous research has proposed that decreased trunk strength, endurance, kinematics, and neuromuscular control affect the dynamic stability of the joints of the lower extremity, leading to increased lower extremity injury, especially in females. However, the role of trunk kinematics has previously been unexamined in subjects with PFPS. Before researchers can examine trunk strength, endurance, and neuromuscular control in subjects with PFPS, we need to understand trunk kinematics in this population. Therefore, the primary purpose of this study is to determine the difference in trunk kinematics during stair ascent and stair descent between subjects with PFPS and a control group. A secondary purpose is to determine the relationship between trunk and lower extremity kinematics during stair ascent and stair descent.

The following literature review will examine the pertinent anatomy related to PFPS, the classification and sequelae of PFPS, the epidemiology of PFPS, and the biomechanics that may contribute to the development of this condition.



## **Epidemiology**

Patellofemoral pain syndrome is one of the most common disorders of the knee (DeHaven & Lintner, 1986; Devereaux & Lachmann, 1984; Taunton, et al., 2002), affecting approximately one in four people (Cleland, 2002; DeHaven & Lintner, 1986; Devereaux & Lachmann, 1984). Patellofemoral pain syndrome is one of the most common problems in individuals from 15 to 30 years of age (DeHaven & Lintner, 1986; Ireland, et al., 2003). Taunton et al. (2002) validated young age as a risk factor for developing PFPS. Sandow and Goodfellow (1985) reported that 60% of patients responding to a questionnaire regarding PFPS initially presented with the condition between the ages of 14 and 16.

Patellofemoral pain syndrome within an athletic population has a reported incidence rate greater than 25% (Ireland, et al., 2003) and overall the incidence of PFPS is greater in a physically active population (Powers, 2003). DeHaven and Linter (1986) found that PFPS was second in occurrence to knee internal derangement for basketball, soccer, baseball, and football while 38.5% of all track and running injuries were due to PFPS. Devereaux and Lachmann (1984) found that running contributed to 32% of all cases of PFPS in athletes. In a study examining running injuries from a sample of 2,002 subjects, 42.1% of the injuries occurred at the knee with 46% of these injuries resulting from PFPS (Taunton, et al., 2002). Clement et al. (1981) reported similar findings, indicating that 42% of running injuries affected the knee, with 60% of these injuries being due to PFPS.

When assessing gender differences, females are more likely to experience PFPS in comparison to their male counterparts (Taunton, et al., 2002). In a study examining

gender differences in incidence and prevalence of PFPS within United States Naval Academy cadets, Boling et al. (2009) found that females were 2.33 times more likely to develop PFPS than their male counterparts. DeHaven and Lintner (1986) found that PFPS accounted for 7.4% of all injuries in males and 19.6% of all injuries in females; furthermore, PFPS and condromalacia accounted for 8.1% of all knee injuries in males and 33.2% of all knee injuries in females. Previous epidemiological studies have reported the prevalence of PFPS in females to be as high as two times that of males (DeHaven & Lintner, 1986; Taunton, et al., 2002). More recent prospective epidemiological studies have shown that gender is not a significant predictor of prevalence of PFPS but was a significant predictor of incidence of PFPS. Boling et al. (2009) found that the prevalence of PFPS was higher in females (15.3%) than males (12.3%). Although prevalence of PFPS was not significantly different for gender, females were 25% more likely to develop PFPS. The study noted that prevalence was most likely underestimated due to the fact that subjects were only asked about a history of PFPS within the 6 months before entering the United States Naval Academy (M. Boling, et al., 2009).

Patellofemoral pain syndrome can have long-term effects on an individual's quality of life. Individuals that have been treated for PFPS continue to have pain later in life. Devereaux and Lachmann (1984) noted that only 28.6% of subjects that had been treated for PFPS were symptom-free within thirteen months. Sandow and Goodfellow (1985) found that 94% of subjects with PFPS continued to experience pain. In a retrospective case-control analysis of patients previously diagnosed with PFPS, 91% of the 22 subjects still had knee pain. Patellofemoral pain syndrome had restricted physical

activity in 8 of the 22 patients (36%) and 45% noted that their daily lives had been affected (Stathopulu & Baildam, 2003). Individuals with PFPS have also noted decreased participation in sporting activities. Witvrouw et al. (2000) specifically noted that 67% of subjects with PFPS participated in competitive sports in comparison to 84% of subjects without PFPS.

Osteoarthritic changes later in life can result from PFPS. In a retrospective investigation of subjects with patellofemoral pain osteoarthritis, 22% of subjects reported anterior knee pain as an adolescent (Christoforakis & Strachan, 2005). Christoforakis and Strachan (2005) noted that severe patella maltracking is associated with isolated patellofemoral joint degeneration leading to patellofemoral arthritis. They reported that the incidence of patellofemoral joint arthritis is 8.1% and that patellofemoral joint degeneration occurs at a relatively young age (33.7 years) (Christoforakis & Strachan, 2005). Utting et al. (2005) reported that 22% of 118 patients with patellofemoral arthritis had anterior knee pain as an adolescent or during early adulthood. Many of these subjects report having symptoms for approximately twenty years (Utting, et al., 2005). Maetzel et al. (2004) estimated that the total cost for an individual with osteoarthritis could be as high as \$5700 annually. In Canada alone, the total health care cost of osteoarthritis is \$3.26 billion (Maetzel, et al., 2004). In addition, Gabriel et al. (1995) reported that individuals with osteoarthritis living in Minnesota incurred 28% higher medical costs compared to non-arthritic controls. Patellofemoral pain syndrome has long-term consequences for individuals in terms of degenerative bone changes, diminished quality of life, and high medical expenses.

## **Patellofemoral Pain Syndrome**

Patellofemoral pain syndrome is a condition characterized by abnormal patellar tracking that commonly results in anterior knee pain (Bolgia, et al., 2008; Connolly, Ronsky, Westover, Kupper, & Frayne, 2009; Crossley, et al., 2004; Ireland, et al., 2003; Mascal, et al., 2003; Owings & Grabiner, 2002; Powers, 2003). In the past there has been no clear consensus in the literature as to the specific definition of PFPS because patients experience a variety of symptoms with dissimilar levels of pain and disability (Thomee, Augustsson, & Karlsson, 1999). Patellofemoral pain syndrome is a comprehensive term that is often used synonymously with chondromalacia patella, patellofemoral arthralgia, patellar pain, and PFPS (Thomee, et al., 1999). Because patients experience symptoms other than anterior knee pain, the term “syndrome” is appropriately used to define signs and symptoms that occur collectively (Thomee, et al., 1999). Recently, the 2010 Consensus Statement on PFPS suggested defining PFPS in the context of inclusion and exclusion criteria. The consensus statement recommended that subjects with a traumatic mechanism of injury not be included in studies of PFPS. Duration of PFPS, aggravating symptoms, level of pain, and gender are general criteria that should be addressed when developing a study pertaining to PFPS (Davis & Powers, 2010).

Many diagnostic criteria are based on the subjective history and objective physical exam of the patient. Subjectively the patient may report anterior knee pain with ascending or descending stairs, hopping, jogging, prolonged sitting with knees flexed, kneeling, and squatting (Bolgia, et al., 2008; M. C. Boling, et al., 2009; Brechter & Powers, 2002; Cowan, et al., 2009; Crossley, et al., 2004; Ireland, et al., 2003; Powers, 2000; Powers, Chen, Reischl, & Perry, 2002; Van Tiggelen, et al., 2009; Witvrouw, et al.,

2000). Patients report duration of symptoms anywhere from six weeks (Witvrouw, et al., 2000) to three months (Ireland, et al., 2003). On physical examination, patients had retropatellar and/or peripatellar knee pain. Often patients complained of pain upon palpation of either the medial or lateral patellar facets or anterior portion of the medial or lateral femoral condyles (Bolgia, et al., 2008; M. C. Boling, et al., 2009; Cowan, et al., 2009; Crossley, et al., 2004; Earl & Vetter, 2007; Powers, 2000; Powers, et al., 2002; Van Tiggelen, et al., 2009; Witvrouw, et al., 2000). Other objective findings, infrequently used as inclusion criteria in studies on PFPS, included pain with compression of the patella into the femoral condyles, pain upon palpation of the posterior surface of the patella, and pain with resisted knee extension (Ireland, et al., 2003; Witvrouw, et al., 2000).

#### *Contact Area and Pressure*

Patellofemoral pain syndrome is primarily the result of increased contact pressure leading to cartilage wear and ultimately degenerative changes if left untreated or if conservative treatment options fail (Insall, 1982; Utting, et al., 2005). Before discussing the causes of PFPS, it is important to understand the concept of contact area and contact pressure. Pressure is mathematically defined as  $P = F/A$  where F is force and A is area. An inverse relationship exists between contact area and pressure. As contact area increases, contact pressure decreases. With greater contact area, forces are distributed over larger areas, decreasing pressure.

Several studies of cadavers and living humans have indicated that as knee flexion angle increases, patellofemoral contact area increases due to improved congruity between the patella and the trochlear groove (Besier, Draper, Gold, Beaupre, & Delp, 2005;

Brechter & Powers, 2002; D'Agata, Pearsall, Reider, & Draganich, 1993; Hsieh, Draganich, Ho, & Reider, 2002; Huberti & Hayes, 1984; Salsich, Ward, Terk, & Powers, 2003). Conversely, Connolly et al. (2009) found that subjects with PFPS demonstrated greater patellofemoral contact area at lower knee flexion angles (0-15°). The researchers postulated that this finding was a potential compensatory mechanism in individuals with PFPS, who attempt to increase contact area between the patella and trochlear groove in order to redistribute load, and therefore decrease patellofemoral joint stress and decrease pain (Connolly, et al., 2009). Brechter et al. (2002) also found that subjects with PFPS compensate kinematically during a stair ascent task. During stair ascent, subjects exhibited lower knee extensor moment and patellofemoral joint reaction force, indicating quadriceps avoidance. They also noticed that subjects with PFPS had a slower cadence when ascending the stairs (Brechter & Powers, 2002). Brechter and Powers (2002) postulated that slower cadence is an attempt of subjects with PFPS to reduce ground reaction forces and loading of the limb during weight acceptance. Powers et al. (2002) also found that subjects with PFPS had a slower cadence when walking. In essence, greater knee flexion angles increase contact area between the patella and trochlear groove.

### **Functional Anatomy of the Knee**

The knee joint is a modified hinge joint consisting of the patella, distal femur, and proximal tibia. The two joints at the knee are the tibiofemoral and patellofemoral joints. The tibiofemoral joint is comprised of the medial and lateral femoral condyles and the proximal tibia, allowing active flexion and extension and internal and external rotation. Passively, valgus and varus occur at the knee but cannot be actively reproduced by an

individual. The two joints at the knee are the tibiofemoral and patellofemoral joints. The femoral condyles are located at the distal end of the femur. They are convex and covered with articular cartilage. The condyles are asymmetrical in shape with the medial femoral condyle being longer and larger than the lateral condyle. However, the lateral condyle projects more anteriorly than the medial condyle. The medial and lateral femoral condyles are separated by the femoral groove, also referred to as the intercondylar fossa (Chhabra, 2001). The medial femoral condyle acts a bony block to the patella when excessively translated medially.

The proximal tibia is a concave surface with a medial and lateral tibial plateau that is separated by an intercondylar eminence. The intercondylar tubercles form the intercondylar eminence. The tubercles fit in the intercondylar fossa during knee extension. The medial tibial plateau is larger than the lateral to accommodate the size of the medial femoral condyle. The medial and lateral menisci help increase conformity between the rounded femoral condyles and flat tibial plateaus (Chhabra, 2001). The tibial tuberosity, the attachment site of the patella tendon, is located at the superior portion of the anterior border of the tibial shaft.

The patellofemoral joint is comprised of the patella and distal femur. The patella, which is classified as a sesamoid bone, is triangular in shape and measures approximately 5cm in diameter. The patella has a medial and lateral facet that is separated by a vertical ridge. The articular surface of the patella is thickest in the body due to its articulation with the femur and the high amount of forces it absorbs. The patella serves as a fulcrum for the quadriceps tendon (Chhabra, 2001). The posterior surface of the patella fits within the patellar groove (located proximally to the intercondylar fossa) in knee

extension and the intercondylar fossa in knee flexion. The femoral condyles articulate with the patellar facets during knee flexion and extension.

### *Passive Stability*

The patella is passively stabilized by the geometry of the trochlear groove, the shape of the patella, and the medial and lateral retinacula (Thomee, et al., 1999). Stability of the patellofemoral joint is influenced by the geometry of the trochlear groove (Amis, 2007). Both the depth and steepness of the slope of the groove affect the placement of the patella. The lateral aspect of the trochlear groove is deepest on the anterior aspect of the femur and decreases in height as the patella moves distally and posteriorly during knee flexion (Amis, 2007). In some individuals there is an incongruity between patellar shape and the trochlear groove, allowing for an unequal distribution of contact between the femur and patella. Contact area shifts across the posterior aspect of the patella as the knee flexes and extends. The patella disengages from the trochlear groove at full extension; therefore, the patella is dependent upon soft tissue structures to maintain stability. As the knee moves through flexion, there is increased contact between the patella and trochlear groove (Amis, 2007).

A MRI study demonstrated that subjects with PFPS had a shallower trochlear groove compared to subjects without PFPS (Powers, 2000). Trochlear groove depth was also a predictor of lateral patellar tilt; as depth decreased, there was an increase in lateral tilt (Powers, 2000). In an individual with a shallow trochlear groove, the patella is prone to lateral displacement (Amis, 2007; Powers, 2000). Lateral patellar displacement decreases overall contact area and increases contact pressure within the patellofemoral



joint. Over time, continued lateral displacement of the patella causes cartilage degeneration.

Patellar shape has been correlated to patellar tracking and contact area at low flexion angles (Connolly, et al., 2009). A sagittal plane morphology ratio ( $a/b = \text{patellar length/articular surface length}$ ), as described by Wiberg, has been used to classify patella shape as Type I ( $1.2 \leq a/b \leq 1.5$ ), Type II ( $a/b > 1.5$ ), and Type III ( $a/b < 1.2$ ). Connolly et al. (2009) and Fucentese et al. (2006) demonstrated that subjects with PFPS had increased Type II and III patella shape compared to healthy subjects. Subjects with PFPS had increased contact area at low flexion angles ( $0-15^\circ$ ) compared to healthy subjects (Connolly, et al., 2009).

Finally, the medial and lateral retinacula contribute to passive stability of the patella. The lateral retinaculum binds the patellar tendon, vastus lateralis, and ITB together (Waryasz & McDermott, 2008). The medial retinaculum consists of three ligaments: medial patellofemoral ligament (MPFL), medial patellomeniscal ligament (MPML), and medial patellotibial ligament (MPTL). Of the three, the MPFL is thought to contribute the most stability to the medial aspect of the patellofemoral joint. The MPFL unites with the VMO and, together, they counteract excessive lateral patellar deviation (Waryasz & McDermott, 2008).

### *Dynamic Stability*

Dynamically, the patella is stabilized by the quadriceps, biceps femoris, and iliotibial band (Thomee, et al., 1999). The patella sits within the patellar tendon and increases the strength of the extensor mechanism by increasing the quadriceps moment arm (Chhabra, 2001). The quadriceps are located on the anterior aspect of the thigh and

consist of four muscles: rectus femoris, vastus lateralis, vastus medialis, and vastus intermedius. Collectively the quadriceps is a biarticular muscle responsible for hip flexion and knee extension. These muscles attach to the patella via the patellar tendon (Chhabra, 2001). The vastus lateralis and medialis also attach independently to the patella and form an aponeuroses which are often referred to in the literature as the medial and lateral patellar retinacula. The retinacula add to passive stability of the knee, keeping the patella aligned over the articular surface of the femur. The muscle fibers of the vastus medialis contain an oblique orientation referred to as the vastus medialis oblique (VMO). The VMO is the only muscle on the medial aspect of the patella that counteracts the lateral muscular forces (Amis, 2007).

The biceps femoris attaches to the fibular head and lateral tibia via the long head and to the lateral tibial condyle via the short head (Chhabra, 2001). The iliotibial band (ITB) is a continuation of the tensor fascia latae (TFL) and gluteus maximus, inserting at the lateral epicondyle of the femur and Gerdy's tubercle on the tibia (Amis, 2007; Chhabra, 2001; Waryasz & McDermott, 2008). Fibers of the ITB attach to the patellar tendon and the vastus lateralis (Amis, 2007). The ITB is positioned anteriorly to the knee when it is in extension. The ITB moves posteriorly to the knee at 30° of knee flexion (Chhabra, 2001).

### **Risk Factors for Patellofemoral Pain Syndrome**

Altered patellar tracking is the fundamental source of PFPS. The causes of abnormal patellar tracking are multifactorial. In this section, patellofemoral contact area and pressure and stair stepping will be discussed in relation to structural, strength, and biomechanical risk factors.

### *Structural Factors*

Trochlear groove depth has been associated with PFPS (Ali, Helmer, & Terk, 2010; Amis, 2007; Powers, 2000). MRI studies examining the patellofemoral joint have shown that individuals with PFPS have a shallow trochlear groove, as measured by the sulcus angle (Ali, et al., 2010; Carrillon, et al., 2000; Davies, Costa, Shepstone, Glasgow, & Donell, 2000; Pfirrmann, Zanetti, Romero, & Hodler, 2000; Powers, 2000).

Individuals with a shallow trochlear groove have an increased risk of lateral patellar displacement (Amis, 2007; Powers, 2000; Senavongse & Amis, 2005), increasing the contact pressure of the lateral patellar facet and femoral condyle. When the knee is fully extended, the patella sits above the trochlear groove, allowing for minimal contact area (Amis, 2007; Salsich, et al., 2003). Although not statistically significant, Powers (2000) observed that subjects with PFPS had a shallower groove as the knee extended beyond 27°; this find was similar to the work of Kujala et al. (1989) and Schutzer et al. (1986). Ali et al. (2010) found that trochlear depth was significantly different between subjects with normal-appearing-cartilage and subjects with severe cartilage defects under the age of 40. Subjects with severe cartilage defects had a shallower trochlear groove (Ali, et al., 2010).

Patella alta is considered a predisposing factor for PFPS (Insall, Goldberg, & Salvati, 1972; Kujala, Osterman, Kvist, Aalto, & Friberg, 1986). It is characterized by a patella that moves superiorly to the femoral trochlear during knee flexion and extension (Insall & Salvati, 1971). Patella alta is thought to increase patellofemoral joint stress due to the lack of contact between the patella and the trochlear groove (Kannus, 1992).

Overtime, cartilage degeneration occurs and leads to patellofemoral joint pain (Heino

Brechtler & Powers, 2002; Moller, Moller-Larsen, & Frich, 1989). In a study comparing fast walking and normal walking speeds, Ward et al. (2004) found that subjects with patella alta had decreased contact area within the patellofemoral joint at the point of peak stress.

A common clinical assessment of static alignment is the quadriceps angle (Q-angle). The Q-angle has been defined as the angle formed by the intersection of two imaginary lines, one connecting the anterior superior iliac spine (ASIS) to the center of the patella and the other connecting the center of the patella to the tibial tuberosity (Earl & Vetter, 2007). A larger Q-angle has been proposed to lead to increased lateral patellar tracking by way of femoral internal rotation or tibial external rotation. In femoral internal rotation, the patella is positioned medially with respect to the ASIS and tibial tuberosity (Powers, 2003), increasing the Q-angle. Femoral anteversion is an anatomical abnormality that can contribute to femoral internal rotation (Reikeras, 1992). Due to the angle of inclination, the femur must internally rotate to increase contact between the head of the femur and the acetabulum (Earl & Vetter, 2007). Increased femoral internal rotation increases contact pressure between the patella and the lateral trochlear groove (T. Q. Lee, et al., 1994). Tibial external rotation “relocates” the tibial tuberosity more lateral than normal and, therefore, increases the Q-angle (Earl & Vetter, 2007). Mizuno et al. (2001) examined the relationship between the Q-angle, hip and knee kinematics, and patellar kinematic. The researchers found that tibial internal rotation decreased the Q-angle, resulting in a medial patellar shift, while tibial external rotation increased the Q-angle, resulting in a lateral patellar shift (Mizuno, et al., 2001). Therefore, a larger Q-angle increases patellofemoral contact area on the lateral patellar facet. The subtalar joint

is thought to influence tibial rotation. Pronation has been associated with tibial internal rotation and supination with tibial external rotation (Powers, et al., 2002).

Although the subtalar joint influences tibial rotation, there is mixed research as to the relationship between the subtalar joint and PFPS. Excessive foot pronation has been theorized to cause PFPS. Powers et al. (2002) found no significant relationship between excessive pronation and PFPS nor between tibial internal rotation and PFPS. As discussed earlier, tibial external rotation is more likely to cause PFPS due to its effect on the Q-angle. These findings differ from the work of Boling et al (2009). The researchers demonstrated that excessive pronation as measured by navicular drop was a risk factor for developing PFPS (M. C. Boling, et al., 2009). The different finding between the two studies is attributable to the way pronation was measured. Powers et al. (2002) measured pronation dynamically during ambulation and Boling et al. (2009) measured pronation statically with the navicular drop test.

Tiberio (1987) explained a mechanism by which excessive pronation and tibial internal rotation could contribute to PFPS. When pronation occurs the tibia internally rotates. In order for the knee to extend when the tibia is internally rotated, the femur must compensate and internally rotate. This internal rotation of the femur increases contact pressure at the lateral patellar facet (Tiberio, 1987). Powers et al. (2002) found that subjects with PFPS had increased femoral external rotation, suggesting this may have been a compensatory strategy to minimize pain. The work of Reischl et al. (1999) contradicts the explanation of Tiberio (1987) that femoral internal rotation follows tibial internal rotation, finding an inconsistent pattern of femoral rotation. The researchers also showed that tibial internal rotation and pronation do not occur simultaneously (Reischl, et

al., 1999). Due to the conflicting data, a specific lower extremity kinematic pattern cannot be inferred from excessive pronation.

### *Strength Factors*

Quadriceps dysfunction is often the result of an imbalance between the medial and lateral structures of the knee. The vastus lateralis, biceps femoris, ITB, and lateral retinaculum produce forces that result in lateral displacement of the patella. The vastus medialis oblique and medial retinaculum are the only structures that produce medially directed forces. An imbalance in muscle strength or altered firing patterns can alter the equilibrium of the patella (Witvrouw, et al., 2000). Usually, the VMO is weak or has delayed firing pattern and cannot counteract the laterally directed forces. Patients with PFPS have shown decreased EMG activity of the VMO (Waryasz & McDermott, 2008). The ITB is also problematic in creating lateral displacement of the patella and increasing lateral contact pressure if tightness is present within this structure (Waryasz & McDermott, 2008).

Hip muscle strength is thought to influence the position of the patella within the trochlear groove. Researchers have demonstrated a relationship between hip muscle strength and lower extremity alignment. It has been found that subjects with PFPS have decreased isometric hip abduction and external rotation strength when compared to healthy subjects (Ireland, et al., 2003; Leetun, et al., 2004; Mascal, et al., 2003). Decreased hip abduction and external rotation strength are thought to contribute to increased femoral adduction and internal rotation, respectively (Powers, 2003). This alignment promotes lateral patellar tracking and increases lateral contact pressure. Other studies have demonstrated gender differences in hip muscle strength. Females

consistently had decreased hip abduction and external rotation strength when compared to males (Leetun, 2003).

### *Biomechanical Factors*

Femoral and tibial internal and external rotation affect patellofemoral contact pressure. Lee et al. (1994) demonstrated that femoral external rotation increased contact on the medial aspect of the patellar facet and internal rotation increased contact on the lateral aspect of the patellar facet. The authors specifically noted that contact pressure significantly increases with femoral internal or external rotation greater than 20 degrees. The authors also found that the effect of tibial internal and external rotation increased contact pressure on the ipsilateral facets of the patella; tibial internal rotation increased contact on the medial aspect of the patellar facet and external rotation increased contact of the lateral aspect of the patellar facet (Hefzy, Jackson, Saddemi, & Hsieh, 1992; T. Q. Lee, et al., 1994). Lee et al. (1994) and Csintalan et al. (2002) have shown that 15 degrees of external tibial rotation increases the Q-angle, as well as the contact pressure on the lateral patellar facet.

Hip adduction has been proposed as a cause of PFPS. Hip adduction has been associated with an increased Q-angle (Powers, 2003). Individuals with larger Q-angles have increased lateral patellofemoral contact pressure. Few studies have exclusively examined hip adduction in subjects with PFPS. In a prospective study by Boling et al. (2009), the authors examined biomechanical risk factors for predicting PFPS. Boling and colleagues found that hip adduction was not a significant predictor of developing PFPS although subjects who later developed PFPS were weaker on measures of hip abduction. Bolgla et al. (2008) found no statistically significant difference in hip adduction during a

stair descent task between PFPS subjects and a control group. The authors postulated that the stair descent task may not have been challenging enough to elicit kinematic differences between groups. They also postulated that the PFPS subjects may have developed a compensatory movement pattern to avoid pain when descending stairs. The authors did not assess pain during the stair descent task and, therefore, cannot validate their theory (Bolgla, et al., 2008). In contrast, Mascal et al. (2003) have found that subjects with PFPS have increased hip adduction. After a 14-week strengthening program, hip adduction decreased from  $8.7^{\circ}$  to  $2.3^{\circ}$  (Mascal, et al., 2003).

Knee valgus has been purported to increase patellofemoral contact pressure. Often, knee valgus is a result of hip adduction and increases the Q-angle. As previously indicated, structural abnormalities at the hip, can result in greater knee valgus and increase the Q-angle (T. Q. Lee, Morris, & Csintalan, 2003). Boling et al. (2009) found that knee valgus was not a significant predictor of developing PFPS. Bolgla et al. (2008) found that subjects with PFPS maintained their knee in greater varus than controls during a stair descent task. In contrast, Mascal et al. (2003) demonstrated that subjects with PFPS had decreased knee valgus after a 14-week strengthening program.

### **Trunk Stability and Kinematics**

The body is considered a multisegmental system. Forces or motion occurring at one joint or segment influences the other segments (B. Zazulak, Cholewicki, & Reeves, 2008). Poor neuromuscular control of the trunk has been theorized to affect the dynamic stability of joints in the lower extremity; this theory has only been proved in females. Deficits in core proprioception have been considered a risk factor for developing knee, ligament, and meniscal injuries for females but not males. Core proprioception predicted



knee injury status with 90% sensitivity (B. T. Zazulak, et al., 2007b). Studies assessing the relationship between knee injury and trunk neuromuscular control have not focused specifically on PFPS. Other studies have shown that poor neuromuscular control may contribute to valgus positioning of the knee through increased hip adduction and internal rotation (B. T. Zazulak, et al., 2007a). Zazulak et al. (2007a) also found that greater trunk displacement was a risk factor for knee, ligament, and meniscal injury in females.

Trunk strength and range of motion have been shown to alter lower extremity kinematics. Krebs et al. (1992) demonstrated that trunk flexion and lateral flexion were greater during a stair stepping task than during normal gait in a healthy population. Specifically subjects had decreased trunk flexion during stair descent, decreased trunk rotation during stair stepping, and increased trunk lateral flexion toward the stance leg during stair ascent (Krebs, et al., 1992). Cowan et al. (2009) demonstrated that subjects with PFPS had significantly less trunk lateral flexion strength. Souza et al. (2009) found that subjects with PFPS laterally flexed toward the stance leg during a stair-stepping task.

### **Lack of Evidence**

There is a lack of evidence specifically linking PFPS to altered trunk kinematics. This study will examine the difference between trunk kinematics between subjects with PFPS and a control group, as well as examine the relationship between trunk and lower extremity kinematics associated with PFPS. The relationship between trunk movement and lower extremity kinematics has been assessed by many researchers but few have examined this relationship in subjects with PFPS.

## **CHAPTER III**

### **METHODOLOGY**

#### **Subjects**

This study utilized a cross-sectional research design. Forty females were recruited (age range 18-35), twenty of which constituted the patellofemoral pain syndrome (PFPS) group and twenty of which served as the control group. The control group was matched to the PFPS group based on age, height, weight, and leg dominance (Bolgla, et al., 2008; Brechter & Powers, 2002; Grenholm, 2009; Powers, 2000). Subjects were recruited from the student body at The University of North Carolina at Chapel Hill with the use of flyers and a recruitment letter sent out to the UNC listserv. The principal investigator evaluated subjects from the student body prior to testing to determine compliance with the inclusion and exclusion criteria and determine group assignment (Appendix I & II). Part of the evaluation for the PFPS subjects included a knee evaluation by the principal investigator, who was also a certified athletic trainer, in order to rule out meniscal, ligamentous, or bursa involvement. The knee evaluation included the following special tests: Valgus and Varus at 0 and 30 degrees, Sag Test, Posterior and Anterior Drawer, Lachman's, McMurray's Test, Bounce Home, and Apley's Compression and Distraction.

An *a priori* statistical power analysis was performed based on previously published data comparing lower extremity kinematics between subjects with PFPS and controls (McKenzie, Galea, Wessel, & Pierrynowski, 2010). The study revealed that a 66% change in hip adduction between the PFPS and control groups was approaching significance ( $p = 0.052$ ) with a total sample size of 20, 10 subjects per group. The study also revealed that a 34% change in hip internal rotation between the PFPS and control groups was significant. Using pilot data measuring trunk kinematics during a stair stepping task in healthy individuals, we calculated that a sample size of 20 subjects per group would provide a power of 0.80 for each trunk kinematic variable to detect a 34-66% change in trunk kinematics between groups.

Subjects in the PFPS group were included in the study if they met the following criteria: (1) female; (2) age between 18 and 35 years; (3) retropatellar knee pain present for at least two months during at least two of the following activities: ascending/descending stairs, hopping/jogging, prolonged sitting with flexed knees, kneeling, or squatting; (4) pain on palpation of the medial or lateral patellar facets and/or pain on palpation of the anterior portion of the medial or lateral femoral condyles (Bolgla, et al., 2008; M. C. Boling, et al., 2009; Brechter & Powers, 2002; Cowan, et al., 2001; Ireland, et al., 2003; Powers, 2000; Powers, et al., 2002; Van Tiggelen, et al., 2009; Witvrouw, et al., 2000); (5) average pain within the week prior to testing rated as at least 3 cm on the 10-cm VAS pain scale (Bolgla, et al., 2008; Cowan, et al., 2001; Souza & Powers, 2009; Van Tiggelen, et al., 2009); (6) negative findings on examination of ligament, menisci, or bursa (M. Boling, et al., 2009; Brechter & Powers, 2002; Cowan, et al., 2009; Powers, et al., 1999; Van Tiggelen, et al., 2009); and (7) insidious onset of knee

pain not related to trauma (Brechtler & Powers, 2002; Cowan, et al., 2001). Due to subject recruitment difficulty, the inclusion criteria were modified to include subjects that had pain upon palpation of the patellar tendon in addition to pain along the medial or lateral patellar facets or femoral condyles. Subjects exclusively with patellar tendon pain upon palpation were still excluded. In addition, the inclusion criterion regarding the VAS scale was modified to include subjects who were able to rate their pain as at least 3 cm with specific activities, such as ascending/descending stairs, hopping/jogging, prolonged sitting with flexed knees, kneeling, or squatting. Subjects only rated their pain for the activities they indicated they had pain during for at least two months at the beginning of the screening.

Subjects were excluded from the PFPS group if any of the following were present: (1) history of knee surgery on the involved extremity (Brechtler & Powers, 2002; Cowan, et al., 2001; Gilleard, et al., 1998); (2) history of low back, hip, or ankle injury within the six months prior to participation; (3) currently involved in physical therapy or had undergone physical therapy for a lower extremity injury within the three months prior to participation (Gilleard, et al., 1998); and (4) any neurological injury or disease that would influence gait or balance (Brechtler & Powers, 2002; Crossley, et al., 2004; Powers, et al., 1999; Souza & Powers, 2009).

Subjects in the control group were included in the study if they met the following criteria: (1) female; (2) age between 18 and 35 years and (3) no prior history or diagnosis of knee pain or pathology within the six months prior to participation (Bolgia, et al., 2008; Brechtler & Powers, 2002; Ireland, et al., 2003; Owings & Grabiner, 2002; Powers, 2000; Powers, et al., 1999). Control subjects were excluded from the study if any of the

following were present: (1) history of knee surgery; (2) history of low back, hip, or ankle injury within the six months prior to participation that resulted in activity modification for more than two days; and (3) any neurological injury or disease that would influence gait or balance (Brechtler & Powers, 2002; Protopapadaki, et al., 2007; Riener, et al., 2002).

Only females were included in the study because this population has a higher incidence and prevalence of PFPS compared to males (M. Boling, et al., 2009; DeHaven & Lintner, 1986; Taunton, et al., 2002). Females over the age of 35 were not included in the study to reduce the likelihood of osteoarthritic changes within the patellofemoral joint. Furthermore, adolescents were not included in the study because the causes of PFPS within this population are not well understood and may differ from the causes of PFPS within an adult population.

Prior to data collection each subject read and signed the informed consent form approved by the institutional review board. Data were sampled from the affected leg for the PFPS group. If PFPS subjects experienced pain bilaterally, the most affected leg was tested (Bolgia, et al., 2008; Grenholm, 2009). For the control group, the test leg was the same as the corresponding subject with PFPS. For example, if the PFPS subject experienced pain in her right knee, then the corresponding control subject's right knee was tested.

## **Instrumentation**

### *Three-Dimensional Motion Capture System*

A seven camera infrared optical motion capture system (Vicon MX Camera (7), Vicon Motion Systems, Los Angeles, California, USA) was used to collect trunk and

lower extremity kinematic data during a stair stepping task at a sampling frequency of 120 Hz. The outcome measurements were joint displacement for trunk flexion, trunk lateral flexion toward/away from the stance leg, trunk rotation toward/away from the stance leg, hip flexion, hip adduction/abduction, hip internal/external rotation, knee flexion, knee varus/valgus, and knee internal/external rotation.

### *Force Plates*

Two conductive force plates (model FP4060-10, Bertec Corporation, Columbus, Ohio, USA) were used to collect ground reaction forces to determine the stance phase of stair descent. Force plate data was collected synchronously with the kinematic data at a sampling frequency of 1200 Hz. The force plates were located under the second and third steps (Figure 1).

### *Stairs*

The stair task consisted of a total of four steps. The first step was 68.5x66x60.5 cm (width, height, and depth) and did not make contact with the first force plate. The second step was 58.5x45.5x30.5 cm and sat directly on the first force plate. The third step was 58.5x25.5x30.5 cm and sat directly on the second force plate. The fourth step was 68.5x5x40.5 cm and did not make contact with the second force plate (**Figure 1**) (Bolgla, et al., 2008; Costigan, Deluzio, & Wyss, 2002; Protopapadaki, et al., 2007; Riener, et al., 2002). The stairs were held together by a cloth strap to prevent them from moving during the task.

## **Procedures**

Potential subjects met with the principal investigator at the Sports Medicine Research Laboratory in Fetzer Gymnasium for approximately 5-10 minutes to determine if they satisfied the inclusion and exclusion criteria for their respective groups. At a later date subjects who satisfied the inclusion and exclusion criteria returned to the laboratory for a single testing session lasting approximately one hour. The researchers recorded demographic information that included age, height, weight, test leg, and leg dominance. Subjects then performed a stair descent task.

### *Three Dimensional (3-D) Motion Analysis*

Subjects wore a non-reflective black spandex outfit and running shoes during testing. Each subject was asked to wear running shoes that they wore on a regular basis. Subjects were outfitted with a standard retroreflective marker set (25 static, 21 dynamic) placed bilaterally on the acromion process, anterior superior iliac spine, greater trochanter, anterior thigh, medial and lateral epicondyles, anterior shank, medial and lateral malleoli, calcaneus, 1<sup>st</sup> and 5<sup>th</sup> metatarsal heads, and the sacrum using double-sided tape.

Subjects completed a static trial facing the positive x-direction with arms abducted 90 degrees. Trunk, hip, knee, and ankle joint centers were defined using the described marker set. The trunk was defined as the intersection of the midpoint between the right and left acromion and the longitudinal axis bisecting L4-L5. The hip joint center was defined using the Bell Method (Bell, Pedersen, & Brand, 1990). The knee joint center was estimated as the midpoint between the medial and lateral epicondyle markers. The ankle joint center was defined as the midpoint between the medial and

lateral malleoli markers. After completion of the static trial, the medial markers were removed for data collection during the stair stepping task. 3-D videographic data were collected using Vicon Motion System with a sampling rate of 120 Hz.

### *Stair Stepping Task*

Each subject was instructed to descend four steps in a step-over-step fashion (Protopapadaki, et al., 2007) (**Figure 2**). The subject led with the non-test leg. Each subject was instructed to take a minimum of two strides immediately following stair stepping to maintain a continuous movement pattern (Bolgia, et al., 2008). The stair stepping task was performed using a metronome set at 96 beats per minute to control for gait velocity (Bolgia, et al., 2008; Crossley, et al., 2004; Gilleard, et al., 1998). Each subject was allowed five practice trials and performed five test trials of stair descent with thirty seconds of rest between each trial. Five trials were collected in order to ensure that three adequate trials would be available for each subject to guard against the loss of subject data due to marker occlusion or measurement error during data collection.

Prior to and immediately following the task, subjects were administered the 10-cm VAS pain scale to determine if testing increased symptoms (Cowan, et al., 2001; Crossley, et al., 2004). The far left side of the VAS scale indicated “no pain” while the far right side indicated “worst pain imaginable” (Appendix III). Subjects were asked to draw a perpendicular line on the scale at the position that best described the pain they experienced before and after the test (Bolgia, et al., 2008). Subjects rated their pre and post test pain on separate sheets of paper. The purpose of these data were to assist with the interpretation of trunk motion. If subjects reported a higher level of pain with the stair descent task and had greater trunk motion then it was possible that altered trunk



kinematics were a cause of PFPS. Alternatively, if subjects reported no change in pain with the task and had greater trunk motion, then it is possible that altered trunk kinematics were a compensatory mechanism to cope with knee pain during stair descent.

Acceptable stair stepping trials included those during which the subject (1) walked with the specified cadence, (2) took a minimum of two strides following the stair stepping task, (3) made contact with the second step with the appropriate foot, and (4) completed the task in a step-over-step fashion.

### **Data Processing and Reduction**

Global and segment axis systems were established using the right-hand rule, in which the x-axis was positive in the anterior direction, the y-axis was positive to the left of the subject, and the z-axis was positive in the superior direction. Motion about the trunk was defined as the trunk segment relative to the global axis system. Trunk joint angles were calculated using an Euler sequence of X, Y, Z. Motion was defined about the hip as the thigh relative to the sacrum, and about the knee as the shank relative to the thigh. Hip and knee joint angles were calculated using an Euler sequence of Y, X, Z. The Euler sequences of the trunk, hip, and knee all correspond with a first rotation to define sagittal plane motion, a second rotation to define frontal plane motion, and third rotation to define transverse plane motion. The difference in Euler sequences between trunk and lower extremity kinematics was a result of trunk motion being referenced to the global axis system. During stair descent, each subject was facing and moved in the direction of the positive y-axis of the global axis system. Therefore, sagittal plane motion of the trunk occurred about the x-axis of the global axis system, frontal plane motion of the trunk occurred about the x-axis of the global axis system, and transverse plane motion

of the trunk occurred about the z-axis of the global axis system. The x-axis corresponded to knee valgus(-)/varus(+), hip abduction(-)/adduction(+), and trunk flexion(+)/extension(-). The y-axis corresponded to hip flexion(-)/extension(+), knee flexion(+)/extension(-), and trunk lateral flexion toward the stance leg(+)/trunk lateral flexion away from the stance leg(-). The z-axis corresponded to knee internal rotation(+)/external rotation(-), hip internal rotation(+)/external rotation(-), and trunk rotation toward the stance leg(-)/trunk rotation away from the stance leg(+).

Raw three-dimensional kinematic data were imported into The Motion Monitor software (Innovative Sports Training Inc., Chicago, IL) for analysis. Kinematic data were filtered using a 4<sup>th</sup> order Butterworth filter with an estimated cut-off frequency of 12 Hz. Joint displacement for each dependent variable was calculated during the stance phase of stair descent. The stance phase was defined as the point of initial contact to toe off for the involved limb. Initial contact was defined as the first time point at which vertical ground reaction force exceeded 10 N. Toe off was defined as the first time point at which vertical ground reaction force dropped below 10 N. Joint displacement was defined as the difference between the maximum or minimum joint angle (dependent upon the direction of interest) and the angle at initial contact.

### **Statistical Analysis**

Mean joint displacement for each dependent variable was calculated across three trials. Although we collected five trials of data, we selected the three middle trials of the five trial sequence for each subject and only used the first and last trials if one of the three middle trials were not acceptable. Comparison of trunk, hip, and knee joint kinematics between the PFPS and control groups were performed using independent t-tests for each

dependent variable (15 total). Based on the 15 independent t-tests, variables that were found to be significantly different were placed into a correlation analysis to determine if there was a significant relationship between those variables and other kinematic variables. Finally, multiple regression analyses were performed to determine significant predictors of knee kinematics, and consisted of those trunk and hip kinematics that were significantly related to knee kinematics during stair descent. Three separate correlation and multiple regression analyses were performed with the group factor collapsed and separately for the PFPS and control groups. To determine if VAS scores differed between groups before and after the stair descent task we performed a mixed-model repeated measures ANOVA with group as the between subjects factor and time (pre-stair descent and post-stair descent) as the within subjects factor. Post-hoc analyses were calculated using two independent samples t-tests (group) and two paired t-tests (time) with a Bonferroni correction, adjusting the level of significance to 0.0125. Statistical analyses were conducted using SPSS 18.0 (SPSS, Inc., Chicago, IL). Statistical significance was established *a priori* as  $\alpha \leq 0.05$ .

## CHAPTER IV

### RESULTS

All 40 subjects were retained throughout the study. After reducing and analyzing the data for quality, no data were excluded from the analyses. Take-off during the stair stepping task for one patellofemoral pain syndrome (PFPS) and one control subject had to be visually estimated within the motion capture system due to an error with data collection in which one of the moveable steps was in contact with both force plates. This resulted in an inability to determine when the test leg first came into contact with the step. One PFPS subject only had two usable trials of stair descent due to the loss of marker visualization and tracking for more than ten consecutive frames; therefore, the mean joint displacement for all trunk and lower extremity kinematic variables were calculated using two trials for this subject. Subject demographics are presented in **Table 1**. There were no significant differences in age, height, and weight between the PFPS and control groups. Means, standard deviations, 95% confidence intervals, and effect sizes for the trunk, hip, and knee kinematic variables are presented in **Table 2**.

#### **Trunk Kinematics**

Trunk flexion ( $t_{38} = -0.120$ ,  $p = 0.905$ ), trunk lateral flexion toward the stance leg ( $t_{26.885} = 0.281$ ,  $p = 0.781$  with equal variances not assumed), trunk lateral flexion away from the stance leg ( $t_{38} = -0.156$ ,  $p = 0.877$ ), trunk rotation toward the stance leg ( $t_{38} = -$

0.567,  $p = 0.574$ ), and trunk rotation away from the stance leg ( $t_{38} = -0.498$ ,  $p = 0.622$ ) did not differ between the PFPS and control groups.

### **Hip Kinematics**

There were no significant differences between groups for the following variables: hip flexion ( $t_{38} = 0.042$ ,  $p = 0.967$ ), hip adduction ( $t_{38} = -0.281$ ,  $p = 0.780$ ), hip abduction ( $t_{38} = -0.562$ ,  $p = 0.578$ ), hip internal rotation ( $t_{38} = 0.399$ ,  $p = 0.692$ ), or hip external rotation ( $t_{38} = 0.526$ ,  $p = 0.602$ ).

### **Knee Kinematics**

There was a significant difference for knee internal rotation ( $t_{38} = 2.082$ ,  $p = 0.044$ ) as the PFPS group demonstrated significantly greater knee (tibia relative to femur) internal rotation displacement compared to the control group (**Figure 3**). The PFPS group displayed approximately  $4^\circ$  more knee internal rotation compared to the control group, which represents a 30% greater amount of knee internal rotation and is associated with a moderate to large effect size ( $ES = 0.68$ ). There was no significant difference in knee flexion ( $t_{38} = 0.227$ ,  $p = 0.821$ ), knee valgus ( $t_{38} = 0.074$ ,  $p = 0.942$ ), knee varus ( $t_{38} = 1.816$ ,  $p = 0.077$ ), or knee external rotation ( $t_{26.799} = -0.992$ ,  $p = 0.330$  with equal variances not assumed) between groups.

### **Correlation Analysis**

Because knee internal rotation was the only kinematic variable found to be significantly different between groups, a correlation analysis was calculated to examine the relationship between the trunk and hip kinematic variables with knee internal rotation displacement for all subjects. Probability statistics and pearson product moment

correlation coefficients are presented in **Table 3**. A significant relationship was found between knee internal rotation displacement and the following variables: trunk lateral flexion away from the stance leg ( $r_{(38)} = 0.292$ ,  $p = 0.034$ ), trunk rotation toward the stance leg ( $r_{(38)} = -0.354$ ,  $p = 0.013$ ), and hip adduction ( $r_{(38)} = 0.301$ ,  $p = 0.030$ ).

### **Multiple Regression**

Based on the correlation analysis, a forward stepwise multiple regression was performed with knee internal rotation displacement as the criterion variable and the predictor variables included trunk lateral flexion away from the stance leg, trunk rotation toward the stance leg, and hip adduction. Separate analyses were performed for all subjects, PFPS subjects, and control subjects. Pearson product moment correlation coefficients are presented in **Table 4**. Analyses utilizing all subjects demonstrated that only trunk rotation displacement toward the stance leg significantly predicted knee internal rotation displacement ( $R^2 = 0.125$ ,  $F_{(1,38)} = 5.442$ ,  $p = 0.025$ ). Analyses for the PFPS subjects revealed that only trunk lateral flexion displacement away from the stance leg was significantly predictive of knee internal rotation displacement ( $R^2 = 0.253$ ,  $F_{(1,18)} = 6.082$ ,  $p = 0.024$ ). The control subject analysis demonstrated that trunk rotation displacement toward the stance leg was the only predictor of knee internal rotation displacement ( $R^2 = 0.273$ ,  $F_{(1,38)} = 6.750$ ,  $p = 0.018$ ).

### **VAS Scores**

Means and standard deviations for VAS scores are presented in **Table 5**. There was a significant group x time interaction ( $F_{(1,38)} = 12.453$ ,  $p = 0.001$ ). In addition, the main effects for time ( $F_{(1,38)} = 13.932$ ,  $p = 0.001$ ) and group were significant ( $F_{(1,38)} = 38.211$ ,  $p < 0.001$ ). Post hoc analyses revealed that VAS score was significantly greater

in the PFPS group at pre-stair descent ( $t_{19} = 5.419$ ,  $p < 0.001$  with equal variances not assumed) and post-stair descent ( $t_{19.074} = 6.601$ ,  $p < 0.001$  with equal variances not assumed) time points. There was no change in VAS scores between pre-stair descent and post-stair descent time points for the control group ( $t_{19} = -1.000$ ,  $p = 0.330$ ). However, there was a significant increase in VAS scores between pre- and post-stair descent for the PFPS group ( $t_{19} = -3.650$ ,  $p = 0.002$ ).

## **CHAPTER V**

### **DISCUSSION**

The most important finding of our study is that females with patellofemoral pain syndrome (PFPS) had greater knee internal rotation ( $4^{\circ}$ ) compared to healthy controls. We also found a significant relationship between knee internal rotation and trunk kinematics. Based on the regression model findings, it appears that trunk lateral flexion and rotation are important predictors of knee internal rotation displacement during stair descent. However, the importance of these variables differed between the PFPS and control subjects. Trunk lateral flexion displacement away from the stance leg was more predictive of knee internal rotation displacement in the PFPS subjects whereas trunk rotation displacement toward the stance leg was more predictive in the control subjects.

To our knowledge, this is the first study to assess the relationship between trunk motion and lower extremity kinematics in females with PFPS. Our findings revealed that trunk and hip sagittal, frontal, and transverse plane motion did not differ between the PFPS and control groups. Additionally, knee sagittal and frontal plane motion did not differ between groups. These findings were not what we expected. We expected to find that females with PFPS would have greater trunk rotation and lateral flexion toward the stance leg, as well as overall trunk flexion. We also expected to find that subjects with PFPS would have greater hip adduction and internal rotation, as well as knee valgus,



based on previous research (M. C. Boling, et al., 2009; Dierks, et al., 2008; McKenzie, et al., 2010; Salsich & Long-Rossi, 2010; Souza & Powers, 2009; Willson & Davis, 2009). Although trunk motion was not different between groups, it did influence knee internal rotation displacement differently between groups. This finding indicates that trunk motion may be an important characteristic related to PFPS.

We also found a significant difference in VAS scores between groups at pre-stair descent and post-stair descent time points with the PFPS group experiencing greater pain than the control group pre and post testing. Additionally, we found that the PFPS subjects had a significant increase in VAS scores from pre-stair descent to post-stair descent. Although statistically significant, the change in VAS scores from pre-test to post-test for the PFPS group was 5.4 mm. Research studies assessing pain (Bodian, Freedman, Hossain, Eisenkraft, & Beilin, 2001; Gallagher, Liebman, & Bijur, 2001; Kelly, 1998; Nordby, Staalesen Strumse, Frosli, & Stanghelle, 2007; Todd, 1996; Todd, Funk, Funk, & Bonacci, 1996), patient satisfaction (Singer & Thode, 1998), and sleep quality (Zisapel & Nir, 2003) have found that a minimal clinically significant difference (MCSD) in VAS scores is between 9-13 mm, with the lowest reported MCSD of 7 mm (Singer & Thode, 1998) and the highest of 30 mm (J. S. Lee, Hobden, Stiell, & Wells, 2003). Therefore, although the change in VAS scores for the PFPS group was statistically significant, it was not clinically meaningful. The relatively small change in VAS scores coupled with the lack of difference in trunk motion between groups did not allow us to determine if trunk motion was a cause or a compensation of PFPS. It is possible that subjects with PFPS may already know how to avoid or minimize pain

during stair descent, attributing to the small change in VAS scores. Furthermore, stair walking may not be a demanding enough task to elicit differences in trunk kinematics.

### **Trunk Kinematics**

Although we expected to find that females with PFPS would display greater trunk lateral flexion and rotation toward the stance leg and greater trunk flexion, our results did not support these hypotheses, as trunk kinematics did not differ between groups. Currently, there is no research that has examined 3D trunk kinematics in subjects with PFPS.

Of those studies that have observed altered trunk kinematics in subjects with PFPS, they have found that PFPS subjects have increased trunk flexion and lateral flexion toward the stance leg compared to healthy controls. Salsich et al. (2001) did not examine 3D trunk kinematics but did observe an increase in trunk flexion during stair descent in a subjects with PFPS compared to controls. This finding differs from our study and may be the result of a mixed gender cohort utilized by the authors. It is also plausible that the author's observation may not be accurate or significant and can only be determined with the use of 3D kinematic analysis. Both Souza et al. (2009) and Dierks et al. (Dierks, et al., 2008) observed trunk lateral flexion toward the stance leg in females and a mixed gender cohort, respectively, with PFPS and attributed this movement pattern as a compensatory strategy for hip abductor weakness. Although this movement was observed, trunk kinematics were not quantified as part of each study; therefore, we cannot compare the results of these studies to the results of our study.

Because prolonged or chronic PFPS often develops into knee osteoarthritis, studies assessing trunk kinematics in this population should be considered (Christoforakis

& Strachan, 2005; Utting, et al., 2005). Studies examining trunk kinematics in subjects with knee osteoarthritis have found that males and females display greater trunk lateral flexion toward the symptomatic limb during gait (Hunt, Wrigley, Hinman, & Bennell, 2010) and greater trunk flexion during the stance phase of stair ascent as the disease severity increased (Asay, Mundermann, & Andriacchi, 2009). These findings differ from our study and could be the result of a mixed gender cohort, choice of inclusion criteria, or the duration of the disease. Hunt et al. (2010) only included subjects that were over 50 years of age whereas we excluded subjects over the age of 35. Both Hunt et al. (2010) and Asay et al. (2009) found alterations in trunk kinematics as disease severity increased. However Asay et al. (2009) found that trunk flexion angles in those with less severe OA were similar to those reported for the control group in the study. Additionally, Hunt et al. (2010) found that subjects with less severe OA displayed trunk lateral flexion away from the stance leg. We also suspect that subjects in our study did not have knee OA at the time of the study. It may be that as OA develops trunk kinematics may become more exaggerated. Unfortunately we cannot assume the findings of our study are similar to these studies as information on the duration of pain for the OA groups was not included. Based on the data we collected from our screening process, PFPS subjects in our study had experienced knee pain anywhere from eight to twelve years.

Although no other studies have examined 3D trunk kinematics in subjects with PFPS, the literature indicates that trunk kinematics influence lower extremity kinematics in healthy individuals (Blackburn & Padua, 2008; Blackburn, Riemann, Myers, & Lephart, 2003; Houck, et al., 2006). Blackburn et al. (2003) demonstrated that a double leg balance task results in trunk lateral flexion opposite hip adduction in both males and

females whereas Houck et al. (2006) found that trunk lateral flexion contributed to knee valgus during straight and side step cutting tasks. Blackburn and Padua (2008) also found that increased trunk flexion during a drop landing task increased hip and knee flexion angles.

Furthermore, the literature indicates that the trunk is associated with lower extremity injury in females. Although not statistically significant, Leetun et al. (2004) found that male and female athletes who experienced an injury over the course of a season generally demonstrated lower core stability than those that did not sustain an injury. Zazulak et al. (2007a) have demonstrated that lateral trunk displacement is the sole predictor of traumatic knee injury in females. Although these are measures of trunk stability, it supports the theory that factors related to the trunk are associated with lower extremity injury. At this time we do not know what that association is in females with PFPS. This study has explored this theory in those with PFPS and has demonstrated that the trunk may influence PFPS by affecting knee kinematics.

### **Hip Kinematics**

Although we expected to find that females with PFPS would display greater hip adduction and internal rotation, our results did not support these hypotheses, as hip kinematics did not differ between groups. Our finding that there was no difference in hip adduction and internal rotation between groups agrees with previous research (Bolgla, et al., 2008; M. C. Boling, et al., 2009; Grenholm, 2009; Souza & Powers, 2009). Bolgla et al. (2008) did not find significant differences in hip adduction or internal rotation between females with and without PFPS. This study utilized a stair descent task similar to the task in this study. Grenholm et al. (2009) did not measure hip internal rotation but

found that hip adduction did not differ between females with and without PFPS during stair descent. The authors (Grenholm, 2009) suggested that because limited research has shown that lower extremity kinematics differ between PFPS and control groups, a global analysis of kinematics may be useful. We believe that the reason for the lack of difference in hip adduction and internal rotation can be attributed to the task; stair descent may not be challenging enough to elicit differences between groups. Although Boling et al. (2009) did not find differences in hip adduction and internal rotation between subjects with and without PFPS during a more challenging task (jump landing task), the authors utilized a mixed gender cohort and may have found significant differences if kinematic analysis had been stratified by gender. The work of Souza et al. (2009) demonstrates this point. The authors found that females with PFPS had greater peak hip internal rotation across progressively demanding tasks compared to controls. The tasks consisted of running, a step-down maneuver, and a drop jump. Although the authors did not find a significant difference for hip adduction during these tasks, the authors noted that the PFPS subjects displayed a lateral trunk lean toward the stance leg and attributed this to a compensatory strategy to reduce hip adduction in the presence of hip abductor weakness.

Our findings disagree with the work of other authors (Mascal, et al., 2003; McKenzie, et al., 2010; Souza & Powers, 2009; Willson & Davis, 2008). Although Mascal et al. (2003) found that one subject with PFPS exhibited a considerable decrease in hip adduction after a 14 week intervention program, the authors utilized a step-down maneuver and did not have a control group with which to compare hip kinematics. No statistical analyses were calculated for the 3D kinematic analysis; therefore, we do not know whether the change in hip adduction from pre to post intervention was statistically

significant. The authors acknowledged this limitation and suggested that although the change in hip adduction was only 6.4°, it was clinically meaningful since the subject reported an improvement in pain on the 10-cm VAS pain scale. Furthermore, Mascal et al. (2003) reported that both subjects utilized in the study showed a decrease in hip internal rotation during the step-down maneuver; however, hip internal rotation kinematics were not sampled and may explain the difference in finding between our study and this study. McKenzie et al. (2010) observed hip adduction and internal rotation during ascent and descent at both self-selected and taxing speeds and found that females with PFPS had greater hip adduction and internal rotation during stair descent collapsed across task. The authors (McKenzie, et al., 2010) defined the taxing speed as 20% faster than the self-selected comfortable pace; therefore, all subjects may not have descended the stairs at the same speed. In contrast, our study controlled for stair descent speed by using a metronome and may account for the difference in findings between the two studies.

### **Knee Kinematics**

Few studies have examined knee internal rotation in subjects with PFPS. Of those that have (Barton, Levinger, Webster, & Menz, 2011; M. C. Boling, et al., 2009; Willson & Davis, 2008), the findings disagree with the results of our study. Boling et al. (2009) found that knee internal rotation was not different between a mixed cohort of subjects with PFPS and a control group during a jump landing task, but that the difference approached significance ( $p = 0.07$ ). This finding differs from our study because we only examined females during a stair descent task whereas Boling et al. (2009) examined kinematics in both males and females during a jump landing task. Willson and Davis

(2008) found that females with PFPS actually demonstrated 4.3° greater knee external rotation than controls across tasks (running, single leg squat, and single leg jump); although this finding was not statistically significant ( $p = 0.06$ ), the difference approached significance. This study differs from our study in methodology and statistical analysis. Willson and Davis (2008) used a more dynamic task than stair descent. The authors also quantified joint angles at discrete points such as peak knee extensor moment and 45° of knee flexion whereas we determined joint displacement during the stance phase. Furthermore, Barton et al. (2011) did not find differences in knee internal rotation in a mixed gender cohort with PFPS during walking. Walking may be a less challenging task than stair descent and may account for the differences between studies.

Studies assessing knee internal rotation in healthy females have found that females display increased knee internal rotation across various tasks. Golden et al. (2009) found that knee internal rotation in female basketball players increased progressively from running to lateral stepping with a width of 20% of the subject's height to lateral stepping with a width of 35% of the subject's height. Imwalle et al. (2009) found that knee internal rotation in female soccer players increased progressively from a 45° cut to a 90° cut. In contrast, Earl et al. (2007) did not find differences in knee internal rotation in healthy females when comparing a drop-vertical jump and single-leg step down task. It is possible that Earl et al. (2007) did not find differences across tasks because the chosen tasks occurred primarily in the sagittal plane whereas Golden et al. (2009) and Imwalle et al. (2009) utilized tasks that occurred more in the frontal and transverse planes, placing greater demands on the knee.

Knee internal rotation is not typically associated with PFPS. Research conducted using cadaver specimens has shown that knee external rotation increases lateral patellar contact pressure whereas knee internal rotation has little to no effect on medial or lateral patellar contact pressure (Csintalan, et al., 2002; T. Q. Lee, Yang, Sandusky, & McMahon, 2001; Li, DeFrate, Zayontz, Park, & Gill, 2004). During tibial internal rotation, the tibial tuberosity moves medially, decreasing the Q-angle. A large Q-angle has been associated with PFPS. The presence of increased knee internal rotation for the PFPS subjects in our study may be a compensatory mechanism to unload the lateral facet of the patellofemoral joint, decreasing their pain. After reviewing the data collected for the PFPS subjects during the screening session, we noted that PFPS subjects had experienced knee pain for approximately eight to twelve years. It is possible that over time these subjects began compensating to decrease their knee pain.

Another plausible cause of greater knee internal rotation in subjects with PFPS is excessive pronation. Previous research has examined pronation in subjects with PFPS and has shown that these individuals do not consistently demonstrate excessive pronation (M. C. Boling, et al., 2009; Cornwall & McPoil, 1995; McClay & Manal, 1998; Powers, et al., 2002; Reischl, et al., 1999).

Although the subtalar joint influences tibial rotation, there is mixed research as to the relationship between the subtalar joint and PFPS. Excessive foot pronation has been theorized to cause PFPS. Tiberio (1987) explained how arthrokinematics such as excessive pronation and tibial internal rotation could contribute to PFPS. During pronation the talus adducts, resulting in an obligatory tibial internal rotation that is accompanied by an increase in femoral internal rotation. In order for the knee to extend



when the tibia is internally rotated, the femur must compensate and internally rotate. The work of Reischl et al. (1999) found that although all subjects demonstrated foot pronation during early stance and tibial internal rotation after initial contact, foot pronation was not a significant predictor of tibial internal rotation. Furthermore, their research contradicts the explanation of Tiberio (1987) that femoral internal rotation follows tibial internal rotation, as they observed an inconsistent pattern of femoral rotation (Reischl, et al., 1999). Additionally, Powers et al. (2002) found no significant relationship between excessive pronation and PFPS nor between tibial internal rotation and PFPS. These findings differ from the work of Boling et al. (2009) who demonstrated that excessive pronation as measured by navicular drop was a risk factor for developing PFPS (M. C. Boling, et al., 2009). The different findings between studies are attributable to the way pronation was measured. Powers et al. (2002) and Reischl et al. (1999) measured pronation dynamically during ambulation and Boling et al. (2009) measured pronation statically with the navicular drop test. We believe that a static measure of pronation is best to examine the relationship between pronation and PFPS. Moreover, McClay and Manal (1998) found that subjects that excessively pronated had greater knee internal rotation compared to those with normal feet; although not statistically significant, the authors believe that significance may have been obtained if a larger sample size had been utilized.

Additional research has focused on the effects of orthotics on pronation and tibial internal rotation. The work of Cornwall and McPoil (1995) showed that tibial internal rotation was concurrent with pronation and that shoes acting as a natural orthotic device decreased transverse plane knee motion compared to barefoot walking. Nawoczenski et

al. (1995) and McPoil and Cornwall (2000) have demonstrated that orthotics limit the magnitude of tibial internal rotation.

We did not assess pronation in our study and, therefore, cannot draw a direct correlation between excessive foot pronation and increased knee internal rotation. We are merely suggesting that excessive pronation could be a cause of the greater knee internal rotation displacement that we saw in females with PFPS.

Research assessing knee internal rotation within both healthy and unhealthy populations is limited. Furthermore, research examining knee internal rotation in subjects with PFPS is even more limited. Future research should examine transverse plane knee kinematics during different tasks to better understand the causes of PFPS. Future research should also examine the relationship between excessive pronation and knee internal rotation in females with PFPS.

### **Limitations**

The first limitation noted in this study was the task that subjects were asked to complete. We chose this task because subjects with PFPS most often complain of pain with stair descent. However, the task may not have been challenging enough to reveal altered trunk or lower extremity kinematics. Subjects were only asked to descend four steps. During the screening, many subjects reported that their knee pain would be greater if they had to descend several flights of stairs as opposed to three to four steps. Because additional steps cannot be added to the task due to limited lab space, future research could use a fatigue protocol to elicit knee pain prior to analyzing 3D kinematics during a stair descent task that consisted of descending a limited number of steps. Future research could also replicate this study using different tasks to assess trunk and lower extremity

kinematics. Furthermore, EMG analysis could be included to assess muscle activation patterns during stair descent. EMG may help explain why females with PFPS have lesser hip abductor and external rotator strength compared to healthy individuals but tend not to have greater femoral adduction and internal rotation during dynamic tasks such as stair descent or running.

A second limitation of the study was the 10-cm VAS pain scale inclusion criteria. It was difficult to find PFPS subjects that rated their average pain as at least 3cm within the past week. We modified the criteria and included individuals that were able to rate their pain as at least 3cm with at least two of the following activities: ascending/descending stairs, hopping/jogging, prolonged sitting with flexed knees, kneeling, or squatting. Because many of the PFPS had experienced knee pain for several years, it is possible that they had become accustomed to their pain, which they often expressed during the screening, and rated their pain low. The relatively low amount of pain experienced by PFPS subjects could also be a result of mild lower extremity dysfunction. It is plausible that the PFPS subjects did not exhibit a severe enough alteration in lower extremity kinematics to elicit pain and could explain why we did not see differences in other kinematic variables, except for knee internal rotation.

Finally, we cannot truly determine cause and effect because this study used a cross-sectional research design. Whereas trunk lateral flexion displacement was predictive of knee internal rotation displacement in PFPS subjects, trunk rotation was more predictive in the control subjects. We cannot determine if PFPS is a cause or effect of this relationship. However, we attempted to control for this by using the 10-cm VAS pain scale. Our theory was that if trunk motion was different between groups and

subjects' pain increased from pre-stair descent to post-stair descent that altered trunk kinematics were a cause of PFPS. However, if trunk motion was different between groups and the PFPS group had no change in pain from pre-stair descent to post-stair descent, then altered trunk kinematics were a compensatory mechanism to cope with knee pain during the task. Because PFPS subjects did not have a clinically meaningful change in VAS scores and did not display altered trunk kinematics compared to the control group, we cannot determine if trunk mechanics were a cause or a compensation of PFPS. In order to determine cause a prospective cohort study would need to be conducted.

### **Clinical Significance**

This study is important in that it is the first to examine trunk kinematics and its relationship to lower extremity kinematics in females with PFPS. It is important for clinicians to recognize that while knee internal rotation is not a cause of PFPS, it may be a compensatory mechanism for females with PFPS to unload the patellofemoral joint. Because trunk lateral flexion away from the stance leg was predictive of knee internal rotation in subjects with PFPS, it is important for clinicians to understand that the trunk may be a causative factor in the development of PFPS in females. The trunk should be considered in the examination and rehabilitation of females with PFPS.

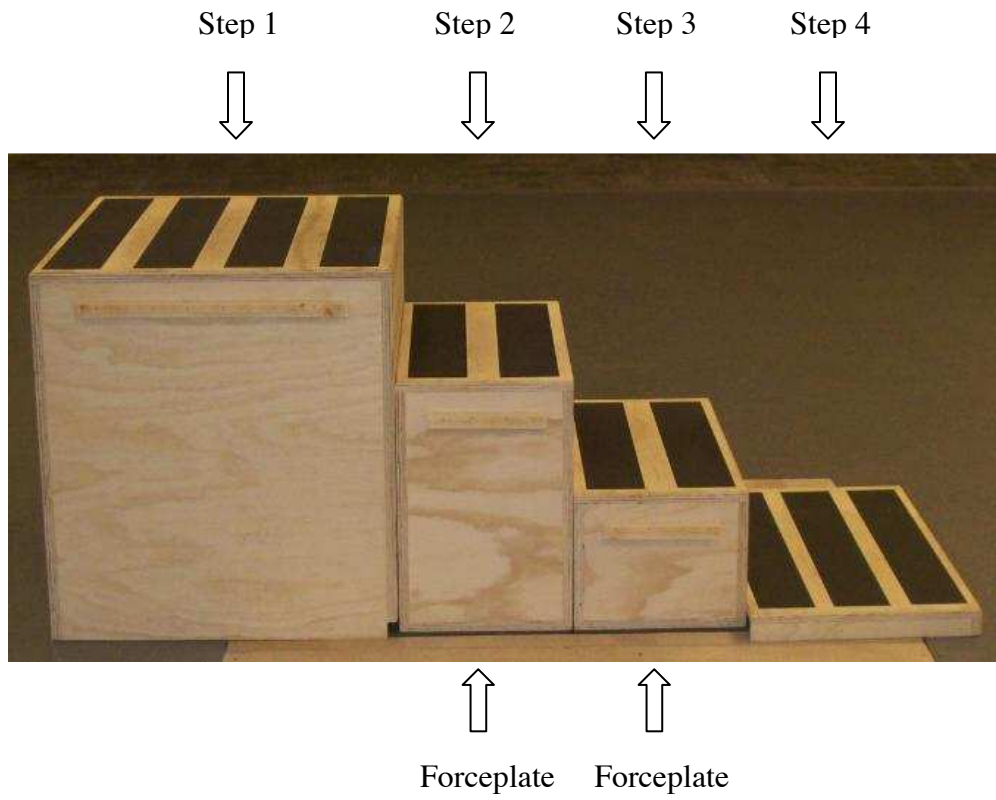
### **Summary**

Our research is the first to examine 3D trunk kinematics in females with PFPS. Although we did not find differences in trunk kinematics between groups, we did find that trunk kinematics influenced knee internal rotation differently between groups. Furthermore, we found that knee internal rotation was significantly greater in females

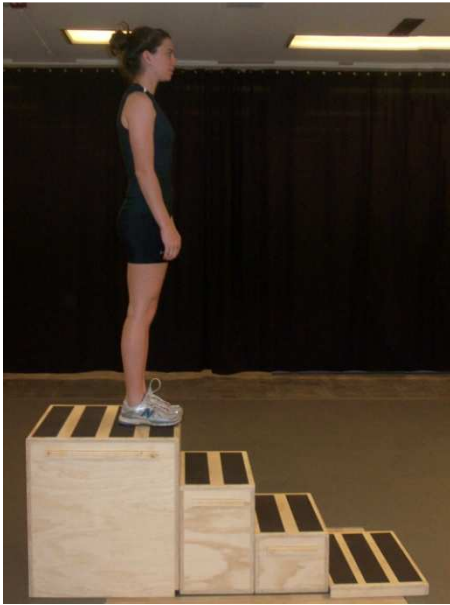
with PFPS. Our findings differ from other studies that have examined knee internal rotation in subjects with PFPS. Although our findings were different, we believe they are valid since our study could not be compared to the other studies based on gender and task selection. Further research needs to be done in this area using the same population and task to better understand the relationship between knee internal rotation and PFPS. Additionally, more research should focus on trunk kinematics in subjects with PFPS.

## FIGURES

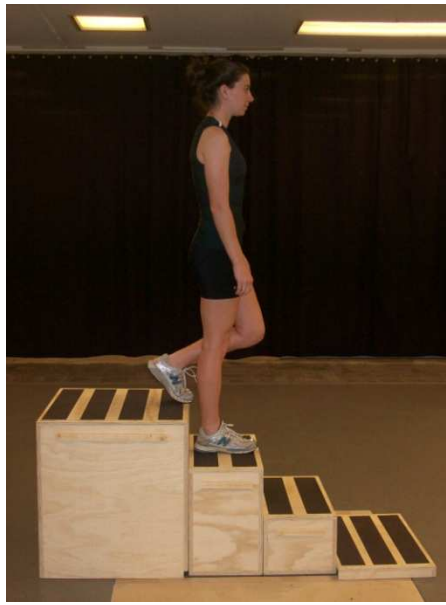
**Figure 1: Force Plate Set Up**



**Figure 2: Stair Stepping Task**



A.



B.

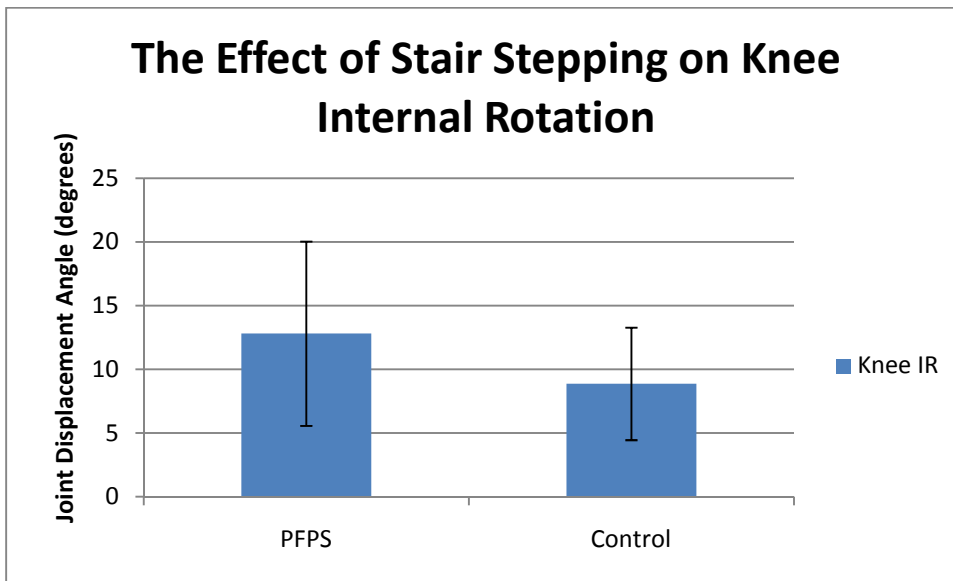


C.



D.

**Figure 3: The Effect of Stair Stepping on Knee Internal Rotation**





## TABLES

**Table 1: Subject Demographics**

	PFPS		Control	
	Mean	SD	Mean	SD
Age	22.2	3.1	21.0	2.6
Height (cm)	164.5	9.2	164.5	7.1
Weight (kg)	63.5	13.6	63.8	12.7

**Table 2: Comparison of Trunk and Lower Extremity Kinematics Between Groups**

Kinematics Variables	PFPS		Control		p-value	ES	
	Mean	SD	Mean	SD			95% CI
Trunk flexion	1.7	1.1	1.7	0.9	1.3, 2.1	0.905	0.04
Trunk lateral flexion <sup>†</sup>	1.7	1.7	1.6	0.8	1.2, 1.9	0.781	0.09
Trunk lateral flexion <sup>‡</sup>	-1.5	1.1	-1.4	1.1	-1.9, -0.9	0.877	0.05
Trunk rotation <sup>†</sup>	-5.5	4.6	-4.7	4.3	-6.7, -2.7	0.574	0.18
Trunk rotation <sup>‡</sup>	3.0	3.2	3.6	4.3	1.6, 5.6	0.622	0.16
Hip flexion	-4.6	3.4	-4.6	3.9	-6.4, -2.8	0.967	0.01
Hip adduction	10.5	4.1	10.9	4.2	9.0, 12.9	0.780	0.09
Hip abduction	-0.7	1.2	-0.5	0.9	-0.9, -0.1	0.587	0.18
Hip internal rotation	4.4	3.3	4.0	3.3	2.5, 5.6	0.692	0.13
Hip external rotation	-3.9	2.4	-4.3	2.3	-5.4, -3.2	0.602	0.17
Knee flexion	79.7	5.9	79.3	5.8	76.6, 82.0	0.821	0.07
Knee valgus	-2.6	5.1	-2.7	3.0	-4.2, -1.3	0.942	0.02
Knee varus	5.3	3.4	3.5	2.6	2.3, 4.7	0.077	0.58
Knee internal rotation	12.8	7.2	8.9	4.4	6.8, 10.9	0.044*	0.68
Knee external rotation	-1.5	2.2	-0.9	1.0	-1.4, -0.4	0.327	0.33

Means and standard deviations measured in degrees.

\* indicates significance at the 0.05 level (2-tailed)

<sup>†</sup> indicates toward the stance leg

<sup>‡</sup> indicates away from the stance leg

**Table 3: Trunk and Hip Kinematics Variables Correlated to Knee Internal Rotation**

Kinematic Variables	r-value	p-value
Trunk flexion	0.019	0.454
Trunk lateral flexion <sup>†</sup>	0.140	0.194
Trunk lateral flexion <sup>‡</sup>	0.292	0.034*
Trunk rotation <sup>†</sup>	-0.354	0.013*
Trunk rotation <sup>‡</sup>	-0.171	0.146
Hip flexion	-0.103	0.263
Hip adduction	0.301	0.030*
Hip abduction	0.151	0.177
Hip internal rotation	0.067	0.341
Hip external rotation	0.030	0.426

\* indicates significance at the 0.05 level (1-tailed)

† indicates toward the stance leg

‡ indicates away from the stance leg

**Table 4: Pearson Correlation Coefficients for the Multiple Regression Analyses**

Kinematic Variables	<i>All Subjects</i>	<i>PFPS Subjects</i>	<i>Control Subjects</i>
Trunk lateral flexion‡	0.292	0.503	0.017
Trunk rotation†	-0.354	-0.254	-0.522
Hip adduction	0.301	0.341	0.346

† indicates toward the stance leg

‡ indicates away from the stance leg

**Table 5: Pre and Post VAS Scores**

	PFPS		Control	
	Mean	SD	Mean	SD
Pre-VAS	17.3	14.3	0.0	0.0
Post-VAS	22.7	15.2	0.2	0.7

## APPENDICES

### Appendix 1: Patellofemoral Pain Syndrome Screening Sheet

All of the following criterion must be met to be included in the patellofemoral pain syndrome group:

1. age between 18-35
2. retropatellar knee pain during at least 2 of the following activities:
  - a. ascending/descending stairs
  - b. hopping/jogging
  - c. prolonged sitting with flexed knees
  - d. kneeling
  - e. squatting
3. knee pain present for at least 2 months
  - a. duration of symptoms: \_\_\_\_\_ months
4. insidious onset of knee pain not related to trauma
5. pain upon palpation with at least one of the following:
  - a. pain upon palpation of the medial or lateral patellar facets
  - b. pain upon palpation of the anterior portion of the medial or lateral femoral condyles
6. negative findings on examination of knee ligament, menisci, or bursa
7. average pain within the past week of at least 3 cm on the 10-cm visual analog scale (VAS) pain scale either at rest or during activity
  - a. VAS rating: \_\_\_\_\_

PFPS subjects will be excluded from the study if they answer “yes” to any of the following questions:

1. Does the subject have a history of knee surgery on the involved extremity?
2. Does the subject have a history of low back, hip, or ankle injury within the past 6 months?
3. Is the subject currently involved in physical therapy or has undergone physical therapy within the past 3 months?
4. Does the subject have any neurological injury or disease that affects their gait or balance?

## **Appendix 2: Control Group Screening Sheet**

All of the following criterion must be met to be included in the control group:

1. age between 18-35
2. no prior history or diagnosis of knee pain or pathology within the past 6 months

Control subjects will be excluded from the study if they answer “yes” to any of the following questions:

1. Does the subject have a history of knee surgery?
2. Does the subject have a history of low back, hip, or ankle injury within the past 6 months that resulted in activity modification for more than 2 days?
3. Does the subject have any neurological injury or disease that affects their gait or balance?



### Appendix 3: 10-cm VAS Pain Scale

Visual Analog Scale (VAS)



## **Appendix 4: Manuscript**

### **Trunk and Lower Extremity Kinematics in Individuals With and Without Patellofemoral Pain Syndrome**

Brandi G. Schwane\*; Darin A. Padua\*; J. Troy Blackburn\*; Benjamin M. Georger\*;  
Shiho Goto\*; Alain J. Aguilar\*

\* University of North Carolina, Chapel Hill, NC

*Contributions here*

Address correspondence to Darin A. Padua, PhD, ATC, University of North Carolina,  
Chapel Hill, Department of Exercise and Sport Science, CB #8700, Chapel Hill, NC

27713-8700.

Address email to [dpadua@email.unc.edu](mailto:dpadua@email.unc.edu)

## **Trunk and Lower Extremity Kinematics in Individuals With and Without Patellofemoral Pain Syndrome**

The primary purpose of this study was to determine if subjects with PFPS have different trunk and lower extremity kinematics during stair descent when compared to a healthy control group. The relationship between knee internal rotation and other joint kinematic variables was also examined. A cross-sectional research design was used to compare trunk, hip, and knee joint displacement for the sagittal, frontal, and transverse planes between groups during a stair descent task. Twenty females diagnosed with PFPS and 20 matched controls participated. Fifteen independent t-tests were used to determine differences in trunk and lower extremity kinematics. Three separate correlation and multiple regression analyses were performed with group factor collapsed and separately for the PFPS and control groups to determine the association between knee internal rotation displacement and other kinematic variables. Knee internal rotation was significantly different between groups ( $p = 0.044$ ) as the PFPS group displayed approximately  $4^\circ$  more knee internal rotation than the control group. Furthermore, the multiple regression analyses for each group revealed that trunk lateral flexion was more predictive of knee internal rotation for PFPS subjects whereas trunk rotation was more predictive in control subjects. Assessment and treatment of the trunk should be considered in the rehabilitation of females with PFPS.

## **ACKNOWLEDGEMENTS**

To the National Athletic Trainers' Association Research and Education Foundation, a special thank you for the financial support of this research project.

## **INTRODUCTION**

Patellofemoral pain syndrome (PFPS) is one of the most common chronic injuries among females. The causes of PFPS are multifactorial with patellofemoral malalignment commonly accepted as a major contributor to PFPS (Ireland, et al., 2003; Powers, 2003). Patellofemoral malalignment increases contact pressure within the patellofemoral joint, leading to abnormal cartilage wear and ultimately degenerative changes if left untreated or if conservative treatment options fail (Insall, 1982; Utting, et al., 2005). Therefore, factors that influence patellofemoral contact pressure are believed to contribute to the development of PFPS.

Lower extremity kinematics may directly influence patellofemoral contact pressure during dynamic tasks. Specifically, the motions of femoral internal rotation, femoral adduction, and knee valgus mediate patellofemoral contact pressure (Bolgia, et al., 2008; T. Q. Lee, et al., 1994; Mascal, et al., 2003; Powers, 2003). Lack of control of these motions is thought to play an important role in the risk of developing PFPS. Hip external rotator and abductor strength would seemingly play an important role in limiting excessive femoral internal rotation, adduction, and knee valgus during dynamic tasks, thus influencing PFPS. However, it is unclear how hip external rotator and abductor strength are each related to PFPS. Isometric weakness of the hip external rotators and abductors has been associated with PFPS in females (Bolgia, et al., 2008; Cichanowski, et al., 2007; Ireland, et al., 2003; Mascal, et al., 2003; Robinson & Nee, 2007; Souza & Powers, 2009; Willson & Davis, 2009). Although lesser isometric hip strength has been found in individuals with PFPS, few studies have examined hip strength and lower

extremity kinematics simultaneously. Of those that have, the results are inconclusive (Bolgia, et al., 2008; Mascal, et al., 2003; Souza & Powers, 2009).

Previous research examining hip strength has observed altered trunk motion during dynamic activities that may greatly influence lower extremity kinematics (Blackburn & Padua, 2008; Souza & Powers, 2009; Willson & Davis, 2009). Souza et al. (2009) suggested that PFPS subjects employed a lateral trunk lean toward the stance leg to compensate for hip abductor weakness; therefore, decreasing the hip adduction angle during running and a step-down maneuver (Souza & Powers, 2009). Dierks et al. (2008) also observed a lateral trunk lean in subjects with PFPS in the presence of hip abductor weakness during running. Although hip strength plays an important role in influencing hip and knee kinematics, strength alone does not explain a significant amount of variability in altered lower extremity kinematics associated with PFPS (Bolgia, et al., 2008; Mascal, et al., 2003; Souza & Powers, 2009). Given the previous research demonstrating a relationship between trunk and lower extremity kinematics, it is plausible that individuals with PFPS may have altered trunk kinematics compared to healthy individuals.

Trunk kinematics may indirectly influence patellofemoral contact pressure by influencing frontal and transverse plane motion of the hip and knee during dynamic tasks. Previous research has shown an association between trunk and lower extremity kinematics during drop landing, walking, and side cutting tasks in a healthy population (Blackburn & Padua, 2008; Houck, et al., 2006). Based on these findings it is plausible that uncontrolled trunk motion may facilitate increased femoral rotation, adduction, and knee valgus. However, trunk kinematics have not been studied in those with PFPS.

The primary purpose of this study was to compare trunk and lower extremity kinematics during stair descent between females with PFPS and a healthy control group. A secondary purpose was to evaluate the relationship between trunk and hip kinematics with knee kinematics during stair descent. We hypothesized that females with PFPS would have greater trunk rotation and lateral flexion toward the stance leg, as well as greater overall trunk flexion, during stair descent compared to the control group. Additionally, we believed that females with PFPS would have greater sagittal, frontal, and transverse plane hip and knee motion compared to the control group. We also hypothesized that there would be a positive correlation between trunk and knee kinematics, as well as hip and knee kinematics, during stair descent, such that motion of the trunk and hip would have a significant relationship with knee motion.

## **METHODS**

### **Subjects**

This study utilized a cross-sectional research design. Forty females were recruited (age range 18-35), twenty of which constituted the patellofemoral pain syndrome (PFPS) group and twenty of which served as the control group. Using pilot data measuring trunk kinematics during a stair stepping task in healthy individuals, we calculated that a sample size of 20 subjects per group would provide *a priori* power of 0.80 for each trunk kinematic variable to detect a 34-66% change in trunk kinematics between groups. The control group was matched to the PFPS group based on age, height, mass, and leg dominance (Bolgia, et al., 2008; Brechter & Powers, 2002; Grenholm, 2009; Powers, 2000). The principal investigator evaluated subjects prior to testing to

determine compliance with the inclusion and exclusion criteria and determine group assignment. Part of the evaluation for the PFPS subjects included a knee evaluation by the principal investigator, who was also a certified athletic trainer, in order to rule out meniscal, ligamentous, or bursa involvement. The knee evaluation included the following special tests: Valgus and Varus at 0 and 30 degrees, Sag Test, Posterior and Anterior Drawer, Lachman's, McMurray's Test, Bounce Home, and Apley's Compression and Distraction.

Subjects in the PFPS group were included in the study if they met the following criteria: (1) female; (2) age between 18 and 35 years; (3) retropatellar knee pain present for at least two months during at least two of the following activities: ascending/descending stairs, hopping/jogging, prolonged sitting with flexed knees, kneeling, or squatting; (4) pain on palpation of the medial or lateral patellar facets and/or pain on palpation of the anterior portion of the medial or lateral femoral condyles (Bolgla, et al., 2008; M. C. Boling, et al., 2009; Brechter & Powers, 2002; Cowan, et al., 2001; Ireland, et al., 2003; Powers, 2000; Powers, et al., 2002; Van Tiggelen, et al., 2009; Witvrouw, et al., 2000); (5) average pain within the past week rated as at least 3 cm on the 10-cm VAS pain scale (Bolgla, et al., 2008; Cowan, et al., 2001; Souza & Powers, 2009; Van Tiggelen, et al., 2009); (6) negative findings on examination of ligament, menisci, or bursa (M. Boling, et al., 2009; Brechter & Powers, 2002; Cowan, et al., 2009; Powers, et al., 1999; Van Tiggelen, et al., 2009); and (7) insidious onset of knee pain not related to trauma (Brechter & Powers, 2002; Cowan, et al., 2001).

Due to subject recruitment difficulty, the inclusion criteria were modified to include subjects that had pain upon palpation of the patellar tendon in addition to pain



along the medial or lateral patellar facets or femoral condyles. Subjects exclusively with patellar tendon pain upon palpation were still excluded. In addition, the inclusion criteria regarding the VAS scale was modified to include subjects that were able to rate their pain as at least 3cm with specific activities, such as ascending/descending stairs, hopping/jogging, prolonged sitting with flexed knees, kneeling, or squatting. Subjects only rated their pain for the activities they indicated they had pain during for at least two months at the beginning of the screening.

Subjects were excluded from the PFPS group if any of the following were present: (1) history of knee surgery on the involved extremity (Brechtler & Powers, 2002; Cowan, et al., 2001; Gilleard, et al., 1998); (2) history of low back, hip, or ankle injury within the past six months; (3) currently involved in physical therapy or has undergone physical therapy within the past three months (Gilleard, et al., 1998); and (4) any neurological injury or disease that would influence gait or balance (Brechtler & Powers, 2002; Crossley, et al., 2004; Powers, et al., 1999; Souza & Powers, 2009).

Subjects in the control group were included in the study if they met the following criteria: (1) female; (2) age between 18 and 35 years and (3) no prior history or diagnosis of knee pain or pathology within the past six months (Bolgia, et al., 2008; Brechtler & Powers, 2002; Ireland, et al., 2003; Owings & Grabiner, 2002; Powers, 2000; Powers, et al., 1999). Control subjects were excluded from the study if any of the following were present: (1) history of knee surgery; (2) history of low back, hip, or ankle injury within the past 6 months that resulted in activity modification for more than two days; and (3) any neurological injury or disease that would influence gait or balance (Brechtler & Powers, 2002; Protopapadaki, et al., 2007; Riener, et al., 2002).

Only females were included in the study because this population has a higher incidence and prevalence of PFPS compared to males (M. Boling, et al., 2009; DeHaven & Lintner, 1986; Taunton, et al., 2002). Females over the age of 35 were not included in the study to reduce the likelihood of osteoarthritic changes within the patellofemoral joint. Furthermore, adolescents were not included in the study because the causes of PFPS within this population are not well understood and may differ from the causes of PFPS within an adult population.

Prior to data collection each subject read and signed the informed consent form approved by the institutional review board. Data were sampled from the affected leg for the PFPS group. If PFPS subjects experienced pain bilaterally, the most affected leg was tested (Bolgia, et al., 2008; Grenholm, 2009). For the control group, the test leg was the same as the corresponding subject with PFPS. For example, if the PFPS subject experienced pain in her right knee, then the corresponding control subject's right knee was tested.

## **Instrumentation**

### *Three-Dimensional Motion Capture System*

A seven camera infrared optical motion capture system (Vicon MX Camera (7), Vicon Motion Systems, Los Angeles, California, USA) was used to collect trunk and lower extremity kinematic data during a stair stepping task at a sampling frequency of 120 Hz.

### *Force Plates*

Two conductive force plates (model FP4060-10, Bertec Corporation, Columbus, Ohio, USA) were used to collect ground reaction forces to determine the stance phase of

stair descent. Force plate data was collected synchronously with the kinematic data at a sampling frequency of 1200 Hz. The force plates were located under the second and third steps (Figure 1).

### *Stairs*

The stair task consisted of a total of four steps. The steps were constructed based on standard codes for step height and tread. The second step sat directly on the first force plate and the third step sat directly on the second force plate in order to determine the stance phase of stair descent (**Figure 1**) (Bolgia, et al., 2008; Costigan, et al., 2002; Protopapadaki, et al., 2007; Riener, et al., 2002). The stairs were held together by a cloth strap to prevent them from moving during the task.

### **Procedures**

Potential subjects met with the principal investigator at the Sports Medicine Research Laboratory for approximately 5-10 minutes to determine if they satisfied the inclusion and exclusion criteria for their respective groups. At a later date subjects who satisfied the inclusion and exclusion criteria returned to the laboratory for a single testing session lasting approximately one hour. The researchers recorded demographic information that included age, height, mass, test leg, and leg dominance. Subjects then performed a stair descent task.

### *Three Dimensional (3-D) Motion Analysis*

Subjects wore a non-reflective black spandex outfit and running shoes during testing. Each subject was asked to wear running shoes that they wore on a regular basis. Subjects were outfitted with a standard retroreflective marker set (25 static, 21 dynamic) placed bilaterally on the acromion process, anterior superior iliac spine, greater

trochanter, anterior thigh, medial and lateral epicondyles, anterior shank, medial and lateral malleoli, calcaneus, 1<sup>st</sup> and 5<sup>th</sup> metatarsal heads, and the sacrum using double-sided tape.

Subjects completed a static trial facing the positive x-direction with arms abducted 90 degrees. Trunk, hip, knee, and ankle joint centers were defined using the described marker set. The trunk was defined as the intersection of the midpoint between the right and left acromion and the longitudinal axis bisecting L4-L5. The hip joint center was defined using the Bell Method (Bell, et al., 1990). The knee joint center was estimated as the midpoint between the medial and lateral epicondyle markers. The ankle joint center was defined as the midpoint between the medial and lateral malleoli markers. After completion of the static trial, the medial markers were removed for data collection during the stair stepping task. 3-D videographic data were collected using Vicon Motion System with a sampling rate of 120 Hz.

### *Stair Stepping Task*

Each subject was instructed to descend four steps in a step-over-step fashion (**Figure 2**) (Protopapadaki, et al., 2007). The subject led with the non-test leg. Each subject was instructed to take a minimum of two strides immediately following stair stepping to maintain a continuous movement pattern (Bolgla, et al., 2008). The stair stepping task was performed using a metronome set at 96 beats per minute to control for gait velocity (Bolgla, et al., 2008; Crossley, et al., 2004; Gilleard, et al., 1998). Each subject was allowed five practice trials and performed five test trials of stair descent with thirty seconds of rest between each trial. Five trials were collected in order to ensure that

three adequate trials would be available for each subject to guard against the loss of subject data due to marker occlusion or measurement error during data collection.

Prior to and immediately following the task, subjects were administered the 10-cm VAS pain scale to determine if testing increased symptoms (Cowan, et al., 2001; Crossley, et al., 2004). The far left side of the VAS scale indicated “no pain” while the far right side indicated “worst pain imaginable.” Subjects were asked to draw a perpendicular line on the scale at the position that best described the pain they experienced before and after the test (Bolglia, et al., 2008). Subjects rated their pre and post test pain on separate sheets of paper. The purpose of these data were to assist with the interpretation of trunk motion. If subjects reported a higher level of pain with the stair descent task and had greater trunk motion then it was possible that altered trunk kinematics were a cause of PFPS. Alternatively, if subjects reported no change in pain with the task and had greater trunk motion, then it is possible that altered trunk kinematics were a compensatory mechanism to cope with knee pain during stair descent.

Acceptable stair stepping trials included those during which the subject (1) walked with the specified cadence, (2) took a minimum of two strides following the stair stepping task, (3) made contact with the second step with the appropriate foot, and (4) completed the task in a step-over-step fashion.

### **Data Processing and Reduction**

Global and segment axis systems were established using the right-hand rule, in which the x-axis was positive in the anterior direction, the y-axis was positive to the left of the subject, and the z-axis was positive in the superior direction. Motion about the trunk was defined as the trunk segment relative to the global axis system. Trunk joint

angles were calculated using an Euler sequence of X, Y, Z. Motion was defined about the hip as the thigh relative to the sacrum, and about the knee as the shank relative to the thigh. Hip and knee joint angles were calculated using an Euler sequence of Y, X, Z. The Euler sequences of the trunk, hip, and knee all correspond with a first rotation to define sagittal plane motion, a second rotation to define frontal plane motion, and third rotation to define transverse plane motion. The difference in Euler sequences between trunk and lower extremity kinematics was a result of trunk motion being referenced to the global axis system. During stair descent, each subject was facing and moved in the direction of the positive y-axis of the global axis system. Therefore, sagittal plane motion of the trunk occurred about the x-axis of the global axis system, frontal plane motion of the trunk occurred about the y-axis of the global axis system, and transverse plane motion of the trunk occurred about the z-axis of the global axis system. The x-axis corresponded to knee valgus(-)/varus(+), hip abduction(-)/adduction(+), and trunk flexion(+)/extension(-). The y-axis corresponded to hip flexion(-)/extension(+), knee flexion(+)/extension(-), and trunk lateral flexion toward the stance leg(+)/trunk lateral flexion away from the stance leg(-). The z-axis corresponded to knee internal rotation(+)/external rotation(-), hip internal rotation(+)/external rotation(-), and trunk rotation toward the stance leg(-)/trunk rotation away from the stance leg(+).

Raw three-dimensional kinematic data were imported into The Motion Monitor software (Innovative Sports Training Inc., Chicago, IL) for analysis. Kinematic data were filtered using a 4<sup>th</sup> order Butterworth filter with an estimated cut-off frequency of 12 Hz. The outcome measurements were joint displacement for trunk flexion, lateral flexion, and rotation; hip flexion, adduction/abduction, and internal/external rotation; and

knee flexion, varus/valgus, and internal/external rotation. Joint displacement for each dependent variable was calculated during the stance phase of stair descent. The stance phase was defined as the point of initial contact to toe off for the involved limb. Initial contact was defined as the first time point at which vertical ground reaction force exceeded 10 N. Toe off was defined as the first time point at which vertical ground reaction force dropped below 10 N. Joint displacement was defined as the difference between the initial joint angle and peak joint angle in the direction of interest. The initial joint angle was determined as the angle at initial contact.

### **Statistical Analysis**

Mean joint displacement for each dependent variable was calculated across three trials. Although we collected five trials of data, we selected the three middle trials of the five trial sequence for each subject and used only the first and last trials if one of the three middle trials were not acceptable. Comparison of trunk, hip, and knee joint kinematics between the PFPS and control groups were performed using independent t-tests for each dependent variable (15 total). Based on the 15 independent t-tests, variables that were found to be significantly different were placed into a correlation analysis to determine if there was a significant relationship between those variables and other kinematic variables. Finally, multiple regression analyses were performed to determine significant predictors of knee kinematics, and consisted of those trunk and hip kinematics that were significantly related to knee kinematics during stair descent. Three separate correlation and multiple regression analyses were performed with the group factor collapsed and separately for the PFPS and control groups. To determine if VAS scores differed between groups before and after the stair descent task we performed a mixed-model

repeated measures ANOVA with group as the between subjects factor and time (pre-stair descent and post-stair descent) as the within subjects factor. Post-hoc analyses were calculated using two independent samples t-tests (group) and two paired t-tests (time) with a Bonferroni correction, adjusting the level of significance to 0.0125. Statistical analyses were conducted using SPSS 18.0 (SPSS, Inc., Chicago, IL). Statistical significance was established *a priori* as  $\alpha \leq 0.05$ .

## RESULTS

All 40 subjects were retained throughout the study. After reducing and analyzing the data for quality, no data were excluded from the analyses. Take-off during the stair stepping task for one patellofemoral pain syndrome (PFPS) and one control subject had to be visually estimated within the motion capture system due to an error with data collection in which one of the moveable steps was in contact with both force plates. This resulted in an inability to determine when the test leg first came into contact with the step. One PFPS subject only had two usable trials of stair descent due to the loss of marker visualization and tracking for more than ten consecutive frames; therefore, the mean joint displacement for all trunk and lower extremity kinematic variables were calculated using two trials for this subject. Subject demographics are presented in **Table 1**. There were no significant differences in age, height, and weight between the PFPS and control groups. Means, standard deviations, 95% confidence intervals, and effect sizes for all trunk and lower extremity kinematic variables are presented in **Table 2**.



### **Trunk Kinematics**

Trunk flexion ( $t_{38} = -0.120$ ,  $p = 0.905$ ), trunk lateral flexion toward the stance leg ( $t_{26.885} = 0.281$ ,  $p = 0.781$ ), trunk lateral flexion away from the stance leg ( $t_{38} = -0.156$ ,  $p = 0.877$ ), trunk rotation toward the stance leg ( $t_{38} = -0.567$ ,  $p = 0.574$ ), or trunk rotation away from the stance leg ( $t_{38} = -0.498$ ,  $p = 0.622$ ) did not differ significantly between the PFPS and control groups.

### **Hip Kinematics**

There were no significant differences between groups for the following variables: hip flexion ( $t_{38} = 0.042$ ,  $p = 0.967$ ), hip adduction ( $t_{38} = -0.281$ ,  $p = 0.780$ ), hip abduction ( $t_{38} = -0.562$ ,  $p = 0.578$ ), hip internal rotation ( $t_{38} = 0.399$ ,  $p = 0.692$ ), or hip external rotation ( $t_{38} = 0.526$ ,  $p = 0.602$ ).

### **Knee Kinematics**

There was a significant difference between groups for knee internal rotation ( $t_{38} = 2.082$ ,  $p = 0.044$ ) as the PFPS group demonstrated significantly greater knee (tibia relative to femur) internal rotation displacement compared to the control group (**Figure 3**). The PFPS group displayed approximately  $4^\circ$  more knee internal rotation compared to the control group, which represents a 30% greater amount of knee internal rotation and is associated with a moderate to large effect size ( $ES = 0.68$ ). There was no significant difference in knee flexion ( $t_{38} = 0.227$ ,  $p = 0.821$ ), knee valgus ( $t_{38} = 0.074$ ,  $p = 0.942$ ), knee varus ( $t_{38} = 1.816$ ,  $p = 0.077$ ), or knee external rotation ( $t_{26.799} = -0.992$ ,  $p = 0.330$ ) between groups.

## Correlation Analysis

Because knee internal rotation was the only kinematic variable found to be significantly different between groups, a correlation analysis was calculated to examine the relationship between the trunk and hip kinematic variables with knee internal rotation displacement for all subjects. Probability statistics and Pearson product moment correlation coefficients are presented in **Table 3**. A significant relationship was found between knee internal rotation displacement and the following variables: trunk lateral flexion away from the stance leg ( $r_{(38)} = 0.292$ ,  $p = 0.034$ ), trunk rotation toward the stance leg ( $r_{(38)} = -0.354$ ,  $p = 0.013$ ), and hip adduction ( $r_{(38)} = 0.301$ ,  $p = 0.030$ ).

## Multiple Regression

Based on the correlation analysis, a forward stepwise multiple regression was performed with knee internal rotation displacement as the criterion variable and the predictor variables included trunk lateral flexion away from the stance leg, trunk rotation toward the stance leg, and hip adduction. Separate analyses were performed for all subjects, PFPS subjects, and control subjects. Pearson product moment correlation coefficients are presented in **Table 4**. Analyses utilizing all subjects demonstrated that only trunk rotation displacement toward the stance leg significantly predicted knee internal rotation displacement ( $R^2 = 0.125$ ,  $F_{(1,38)} = 5.442$ ,  $p = 0.025$ ). Analyses for the PFPS subjects revealed that only trunk lateral flexion displacement away from the stance leg was significantly predictive of knee internal rotation displacement ( $R^2 = 0.253$ ,  $F_{(1,18)} = 6.082$ ,  $p = 0.024$ ). The control subject analysis demonstrated that trunk rotation displacement toward the stance leg was the only predictor of knee internal rotation displacement ( $R^2 = 0.273$ ,  $F_{(1,38)} = 6.750$ ,  $p = 0.018$ ).

## VAS Scores

Means and standard deviations for VAS scores are presented in **Table 5**. There was a significant group x time interaction ( $F_{(1,38)} = 12.453, p = 0.001$ ). In addition, the main effects for time ( $F_{(1,38)} = 13.932, p = 0.001$ ) and group ( $F_{(1,38)} = 38.211, p < 0.001$ ) were significant. Post hoc analyses revealed that VAS score was significantly greater in the PFPS at pre-stair descent ( $t_{19} = 5.419, p < 0.001$ ) and post-stair descent ( $t_{19,074} = 6.601, p < 0.001$ ) time points. There was no change in VAS scores between pre-stair descent and post-stair descent time points for the control group ( $t_{19} = -1.000, p = 0.330$ ). However, there was a significant increase in VAS scores between pre- and post-stair descent for the PFPS group ( $t_{19} = -3.650, p = 0.002$ ).

## DISCUSSION

The most important finding of our study is that females with patellofemoral pain syndrome (PFPS) had greater knee internal rotation ( $4^\circ$ ) compared to healthy controls. We also found a significant relationship between knee internal rotation and trunk kinematics. Based on the regression model findings, it appears that trunk lateral flexion and rotation are important predictors of knee internal rotation displacement during stair descent. However, the importance of these variables differed between the PFPS and control subjects. Trunk lateral flexion displacement away from the stance leg was more predictive of knee internal rotation displacement in the PFPS subjects whereas trunk rotation displacement toward the stance leg was more predictive in the control subjects.

To our knowledge, this is the first study to assess the relationship between trunk motion and lower extremity kinematics in females with PFPS. Our findings revealed that

trunk and hip sagittal, frontal, and transverse plane motion did not differ between the PFPS and control groups. Additionally, knee sagittal and frontal plane motion did not differ between groups. These findings were not what we expected. We expected to find that females with PFPS would have greater trunk rotation and lateral flexion toward the stance leg, as well as overall trunk flexion. We also expected to find that subjects with PFPS would have greater hip adduction and internal rotation, as well as knee valgus, based on previous research (M. C. Boling, et al., 2009; Dierks, et al., 2008; McKenzie, et al., 2010; Salsich & Long-Rossi, 2010; Souza & Powers, 2009; Willson & Davis, 2009). Although trunk motion was not different between groups, it did influence knee internal rotation displacement differently between groups. This finding indicates that trunk motion may be an important characteristic related to PFPS.

We also found a significant difference in VAS scores between groups at pre-stair descent and post-stair descent time points with the PFPS group experiencing greater pain than the control group pre and post testing. Additionally, we found that the PFPS subjects had a significant increase in VAS scores from pre-stair descent to post-stair descent. Although statistically significant, the change in VAS scores from pre-test to post-test for the PFPS group was only 5.4 mm. Research studies assessing pain (Bodian, et al., 2001; Gallagher, et al., 2001; Kelly, 1998; Nordby, et al., 2007; Todd, 1996; Todd, et al., 1996), patient satisfaction (Singer & Thode, 1998), and sleep quality (Zisapel & Nir, 2003) have found that a minimal clinically significant difference (MCSD) in VAS scores is between 9-13 mm, with the lowest reported MCSD of 7 mm (Singer & Thode, 1998) and the highest of 30 mm (J. S. Lee, et al., 2003). Therefore, although the change in VAS scores for the PFPS group was statistically significant, it was not clinically

meaningful. The relatively small change in VAS scores coupled with the lack of difference in trunk motion between groups did not allow us to determine if trunk motion was a cause or a compensation of PFPS. It is possible that subjects with PFPS may already know how to avoid or minimize pain during stair descent, attributing to the small change in VAS scores. Furthermore, stair walking may not be a demanding enough task to elicit differences in trunk kinematics.

### **Trunk Kinematics**

Although we expected to find that females with PFPS would display greater trunk lateral flexion and rotation toward the stance leg and greater trunk flexion, our results did not support these hypotheses, as trunk kinematic did not differ between groups.

Currently, there is no research that has examined 3D trunk kinematics in subjects with PFPS.

Of those studies that have observed altered trunk kinematics in subjects with PFPS, they have found that PFPS subjects have increased trunk flexion and lateral flexion toward the stance leg compared to healthy controls. Salsich et al. (2001) did not examine 3D trunk kinematics but did observe an increase in trunk flexion during stair descent in subjects with PFPS compared to healthy controls. This finding differs from our study and may be the result of a mixed gender cohort utilized by the authors. It is also plausible that the author's observation may not be accurate or significant and can only be determined with the use of 3D kinematic analysis. Both Souza et al. (2009) and Dierks et al. (2008) observed trunk lateral flexion toward the stance leg in females and a mixed gender cohort, respectively, with PFPS and attributed this movement pattern as a compensatory strategy for hip abductor weakness. Although this movement was

observed, trunk kinematics were not quantified as part of each study; therefore, we cannot compare the results of these studies to the results of our study.

Because prolonged or chronic PFPS often develops into knee osteoarthritis, studies assessing trunk kinematics in this population should be considered (Christoforakis & Strachan, 2005; Utting, et al., 2005). Studies examining trunk kinematics in subjects with knee osteoarthritis have found that males and females display greater trunk lateral flexion toward the symptomatic limb during gait (Hunt, et al., 2010) and greater trunk flexion during the stance phase of stair ascent as disease severity increased (Asay, et al., 2009). These findings differ from our study and could be the result of a mixed gender cohort, choice of inclusion criteria, or the duration of the disease. Hunt et al. (2010) only included subjects that were over 50 years of age whereas we excluded subjects over the age of 35. Both Hunt et al. (2010) and Asay et al. (2009) found alterations in trunk kinematics as disease severity increased. However Asay et al. (2009) found that trunk flexion angles in those with less severe OA were similar to those reported for the control group in the study. Additionally, Hunt et al. (2010) found that subjects with less severe OA displayed trunk lateral flexion away from the stance leg. We also suspect that subjects in our study did not have knee OA at the time of the study. It may be that as OA develops trunk kinematics may become more exaggerated. Unfortunately we cannot assume the findings of our study are similar to these studies as information on the duration of pain for the OA groups was not included. Based on the data we collected from our screening process, PFPS subjects in our study had experienced knee pain anywhere from eight to twelve years.

Although no other studies have examined 3D trunk kinematics in subjects with PFPS, the literature indicates that trunk kinematics influence lower extremity kinematics in healthy individuals (Blackburn & Padua, 2008; Blackburn, et al., 2003; Houck, et al., 2006). Blackburn et al. (2003) demonstrated that a double leg balance task results in trunk lateral flexion opposite hip adduction in both males and females whereas Houck et al. (2006) found that trunk lateral flexion contributed to knee valgus during straight and side step cutting tasks. Blackburn and Padua (2008) also found that increased trunk flexion during a drop landing task increased hip and knee flexion angles.

Furthermore, the literature indicates that the trunk is associated with lower extremity injury in females. Although not statistically significant, Leetun et al. (2004) found that male and female athletes who experienced an injury over the course of a season generally demonstrated lower core stability than those that did not sustain an injury. Zazulak et al. (2007a) have demonstrated that lateral trunk displacement is the sole predictor of traumatic knee injury in females. Although these are measures of trunk stability, it supports the theory that factors related to the trunk are associated with lower extremity injury. At this time we do not know what that association is in females with PFPS. This study has explored this theory in those with PFPS and has demonstrated that the trunk may influence PFPS by affecting knee kinematics.

### **Hip Kinematics**

Although we expected to find that females with PFPS would display greater hip adduction and internal rotation, our results did not support these hypotheses, as hip kinematics did not differ between groups. Our finding that there was no difference in hip adduction and internal rotation between groups agrees with previous research (Bolgla, et

al., 2008; M. C. Boling, et al., 2009; Grenholm, 2009; Souza & Powers, 2009). Bolglia et al. (2008) did not find significant differences in hip adduction or internal rotation between females with and without PFPS. This study utilized a stair descent task similar to the task in this study. Grenholm et al. (2009) did not measure hip internal rotation but found that hip adduction did not differ between females with and without PFPS. The authors (Grenholm, 2009) suggested that because limited research has shown that lower extremity kinematics differ between PFPS and control groups, a global analysis of kinematics may be useful. We believe that the reason for the lack of difference in hip adduction and internal rotation can be attributed to the task; stair descent may not be challenging enough to elicit differences between groups. Although Boling et al. (2009) did not find differences in hip adduction and internal rotation between subjects with and without PFPS during a more challenging task (jump landing task), the authors utilized a mixed gender cohort and may have found significant differences if kinematic analysis had been stratified by gender. The work of Souza et al. (2009) demonstrates this point. The authors found that females with PFPS had greater peak hip internal rotation across progressively demanding tasks compared to controls. The tasks consisted of running, a step-down maneuver, and a drop jump. Although the authors did not find a significant difference for hip adduction during these tasks, the authors noted that the PFPS subjects displayed a lateral trunk lean toward the stance leg and attributed this to a compensatory strategy to reduce hip adduction in the presence of hip abductor weakness.

Our findings disagree with the work of other authors (Mascal, et al., 2003; McKenzie, et al., 2010; Souza & Powers, 2009; Willson & Davis, 2008). Although Mascal et al. (2003) found that one subject with PFPS exhibited a considerable decrease



in hip adduction after a 14 week intervention program, the authors utilized a step-down maneuver and did not have a control group with which to compare hip kinematics. No statistical analyses were calculated for the 3D kinematic analysis; therefore, we do not know whether the change in hip adduction from pre to post intervention was statistically significant. The authors acknowledged this limitation and suggested that although the change in hip adduction was only  $6.4^{\circ}$ , it was clinically meaningful since the subject reported an improvement in pain on the 10-cm VAS pain scale. Furthermore, Mascal et al. (2003) reported that both subjects utilized in the study showed a decrease in hip internal rotation during the step-down maneuver; however, hip internal rotation kinematics were not sampled and may explain the difference in finding between our study and this study. McKenzie et al. (2010) observed hip adduction and internal rotation during ascent and descent at both self-selected and taxing speeds and found that females with PFPS had greater hip adduction and internal rotation during stair descent collapsed across task. The authors (McKenzie, et al., 2010) defined the taxing speed as 20% faster than the self-selected comfortable pace; therefore, all subjects may not have descended the stairs at the same speed. In contrast, our study controlled for stair descent speed by using a metronome and may account for the difference in findings between the two studies.

### **Knee Kinematics**

Few studies have examined knee internal rotation in subjects with PFPS. Of those that have (Barton, et al., 2011; M. C. Boling, et al., 2009; Willson & Davis, 2008), the findings disagree with the results of our study. Boling et al. (2009) found that knee internal rotation was not different between a mixed cohort of subjects with PFPS and a

control group during a jump landing task, but that the difference approached significance ( $p = 0.07$ ). This finding differs from our study because we only examined females during a stair descent task whereas Boling et al. (2009) examined kinematics in both males and females during a jump landing task. Willson and Davis (2008) found that females with PFPS actually demonstrated  $4.3^\circ$  greater knee external rotation than controls across tasks (running, single leg squat, and single leg jump); although this finding was not statistically significant ( $p = 0.06$ ), the difference approached significance. This study differs from our study in methodology and statistical analysis. Willson and Davis (2008) used a more dynamic task than stair descent. The authors also quantified joint angles at discrete points such as peak knee extensor moment and  $45^\circ$  of knee flexion whereas we determined joint displacement during the stance phase. Furthermore, Barton et al. (2011) did not find differences in knee internal rotation in a mixed gender cohort with PFPS during walking. Walking may be a less challenging task than stair descent and may account for the differences between studies.

Studies assessing knee internal rotation in healthy females have found that females display increased knee internal rotation across various tasks. Golden et al. (2009) found that knee internal rotation in female basketball players increased progressively from running to lateral stepping with a width of 20% of the subject's height to lateral stepping with a width of 35% of the subject's height. Imwalle et al. (2009) found that knee internal rotation in female soccer players increased progressively from a  $45^\circ$  cut to a  $90^\circ$  cut. In contrast, Earl et al. (2007) did not find differences in knee internal rotation in healthy females when comparing a drop-vertical jump and single-leg step down task. It is possible that Earl et al. (2007) did not find differences across tasks

because the chosen tasks occurred primarily in the sagittal plane whereas Golden et al. (2009) and Imwalle et al. (2009) utilized tasks that occurred more in the frontal and transverse planes, placing greater demands on the knee.

Knee internal rotation is not typically associated with PFPS. Research conducted using cadaver specimens has shown that knee external rotation increases lateral patellar contact pressure whereas knee internal rotation has little to no effect on medial or lateral patellar contact pressure (Csintalan, et al., 2002; T. Q. Lee, et al., 2001; Li, et al., 2004). During tibial internal rotation, the tibial tuberosity moves medially, decreasing the Q-angle. A large Q-angle has been associated with PFPS. The presence of increased knee internal rotation for the PFPS subjects in our study may be a compensatory mechanism to unload the lateral facet of the patellofemoral joint, decreasing their pain. After reviewing the data collected for the PFPS subjects during the screening session, we noted that PFPS subjects had experienced knee pain for approximately eight to twelve years. It is possible that over time these subjects began compensating to decrease their knee pain.

Another plausible cause of greater knee internal rotation in subjects with PFPS is excessive pronation. Previous research has examined pronation in subjects with PFPS and has shown that these individuals do not consistently demonstrate excessive pronation (M. C. Boling, et al., 2009; Cornwall & McPoil, 1995; McClay & Manal, 1998; Powers, et al., 2002; Reischl, et al., 1999).

Although the subtalar joint influences tibial rotation, there is mixed research as to the relationship between the subtalar joint and PFPS. Excessive foot pronation has been theorized to cause PFPS. Tiberio (1987) explained how arthrokinematics such as excessive pronation and tibial internal rotation could contribute to PFPS. During

pronation the talus adducts, resulting in an obligatory tibial internal rotation that is accompanied by an increase in femoral internal rotation. In order for the knee to extend when the tibia is internally rotated, the femur must compensate and internally rotate. The work of Reischl et al. (1999) found that although all subjects demonstrated foot pronation during early stance and tibial internal rotation after initial contact, foot pronation was not a significant predictor of tibial internal rotation. Furthermore, their research contradicts the explanation of Tiberio (1987) that femoral internal rotation follows tibial internal rotation, as they observed an inconsistent pattern of femoral rotation (Reischl, et al., 1999). Additionally, Powers et al. (2002) found no significant relationship between excessive pronation and PFPS nor between tibial internal rotation and PFPS. These findings differ from the work of Boling et al. (2009) who demonstrated that excessive pronation as measured by navicular drop was a risk factor for developing PFPS. The different findings between studies are attributable to the way pronation was measured. Powers et al. (2002) and Reischl et al. (1999) measured pronation dynamically during ambulation and Boling et al. (2009) measured pronation statically with the navicular drop test. We believe that a static measure of pronation is best to examine the relationship between pronation and PFPS. Moreover, McClay and Manal (1998) found that subjects that excessively pronated had greater knee internal rotation compared to those with normal feet; although not statistically significant, the authors believe that significance may have been obtained if a larger sample size had been utilized.

Additional research has focused on the effects of orthotics on pronation and tibial internal rotation. The work of Cornwall and McPoil (1995) showed that tibial internal rotation was concurrent with pronation and that shoes acting as a natural orthotic device

decreased transverse plane knee motion compared to barefoot walking. Nawoczenski et al. (1995) and McPoil and Cornwall (2000) have demonstrated that orthotics limit the magnitude of tibial internal rotation.

We did not assess pronation in our study and, therefore, cannot draw a direct correlation between excessive foot pronation and increased knee internal rotation. We are merely suggesting that excessive pronation could be a cause of the greater knee internal rotation displacement that we saw in females with PFPS.

Research assessing knee internal rotation within both healthy and unhealthy populations is limited. Furthermore, research examining knee internal rotation in subjects with PFPS is even more limited. Future research should examine transverse plane knee kinematics during different tasks to better understand the causes of PFPS. Future research should also examine the relationship between excessive pronation and knee internal rotation in females with PFPS.

### **Limitations**

The first limitation noted in this study was the task that subjects were asked to complete. However, we chose this task because subjects with PFPS most often complain of pain with stair descent. The task may not have been challenging enough to reveal altered trunk or lower extremity kinematics. Subjects were only asked to descend four steps. During the screening, many subjects reported that their knee pain would be greater if they had to descend several flights of stairs as opposed to three to four steps. Because additional steps cannot be added to the task due to limited lab space, future research could use a fatigue protocol to elicit knee pain prior to analyzing 3D kinematics during a stair descent task that consisted of descending a limited number of steps. Future research

could replicate this study using different tasks to assess trunk and lower extremity kinematics. Furthermore, EMG analysis could be included to assess muscle activation patterns during stair descent. EMG may help explain why females with PFPS have lesser hip abductor and external rotator strength compared to healthy individuals but tend not to have greater femoral adduction and internal rotation during dynamic tasks such as stair descent or running.

A second limitation of the study was the 10-cm VAS pain scale inclusion criteria. It was difficult to find PFPS subjects that rated their average pain as at least 3cm within the past week. We modified the criteria and included individuals that were able to rate their pain as at least 3cm with at least two of the following activities:

ascending/descending stairs, hopping/jogging, prolonged sitting with flexed knees, kneeling, or squatting. Because many of the PFPS had experienced knee pain for several years, it is possible that they had become accustomed to their pain, which they often expressed during the screening, and rated their pain low. The relatively low amount of pain experienced by PFPS subjects could also be a result of mild lower extremity dysfunction. It is plausible that the PFPS subjects did not exhibit a severe enough alteration in lower extremity kinematics to elicit pain and could explain why we did not see differences in other kinematic variables, except for knee internal rotation.

Finally, we cannot truly determine cause and effect because this study used a cross-sectional research design. Whereas trunk lateral flexion displacement was predictive of knee internal rotation displacement in PFPS subjects, trunk rotation was more predictive in the control subjects. We cannot determine if PFPS is a cause or effect of this relationship. However, we attempted to control for this by using the 10-cm VAS

pain scale. Our theory was that if trunk motion was different between groups and subjects' pain increased from pre-stair descent to post-stair descent that altered trunk kinematics were a cause of PFPS. However, if trunk motion was different between groups and the PFPS group had no change in pain from pre-stair descent to post-stair descent, then altered trunk kinematics were a compensatory mechanism to cope with knee pain during the task. Because PFPS subjects did not have a clinically meaningful change in VAS scores and did not display altered trunk kinematics compared to the control group, we cannot determine if trunk mechanics were a cause or a compensation of PFPS. In order to determine cause a prospective cohort study would need to be conducted.

### **Clinical Significance**

This study is important in that it is the first to examine trunk kinematics and its relationship to lower extremity kinematics in females with PFPS. It is important for clinicians to recognize that while knee internal rotation is not a cause of PFPS, it may be a compensatory mechanism for females with PFPS to unload the patellofemoral joint. Because trunk lateral flexion away from the stance leg was predictive of knee internal rotation in subjects with PFPS, it is important for clinicians to understand that the trunk may be a causative factor in the development of PFPS in females. The trunk should be considered in the examination and rehabilitation of females with PFPS.

### **Summary**

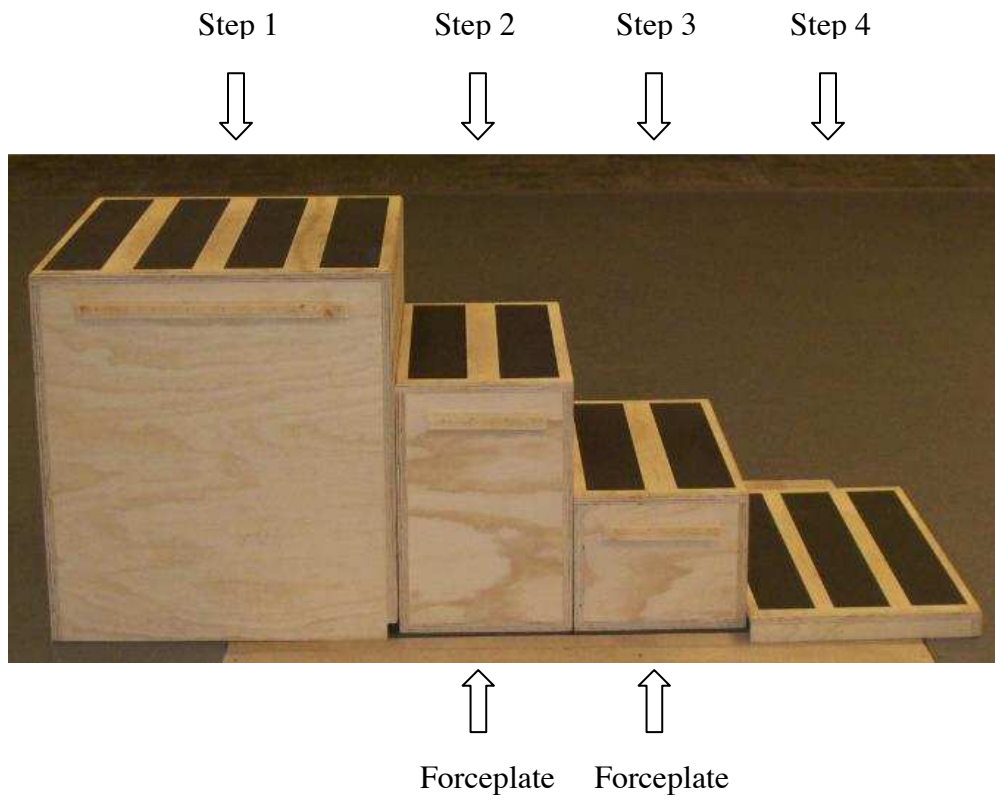
Our research is the first to examine 3D trunk kinematics in females with PFPS. Although we did not find differences in trunk kinematics between groups, we did find that trunk kinematics influence knee internal rotation differently between groups.

Furthermore, we found that knee internal rotation was significantly greater in females with PFPS. Our findings differ from other studies that have examined knee internal rotation in subjects with PFPS. Although our findings were different, we believe they are valid since our study could not be compared to the other studies based on gender and task selection. Further research needs to be done in this area using the same population and task to better understand the relationship between knee internal rotation and PFPS. Additionally, more research should focus on trunk kinematics in subjects with PFPS.



## FIGURES

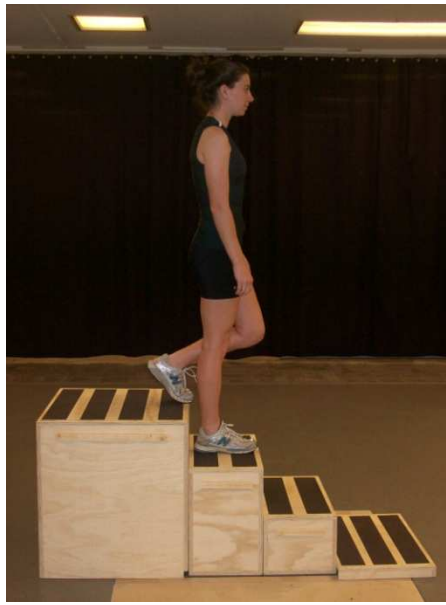
**Figure 1: Force Plate Set Up**



**Figure 2: Stair Stepping Task**



A.



B.

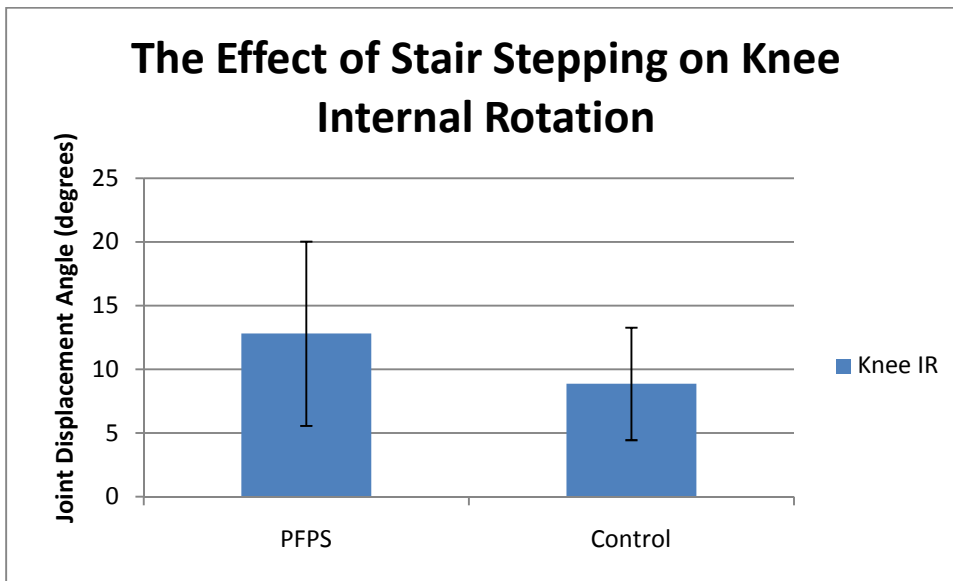


C.



D.

**Figure 3: The Effect of Stair Stepping on Knee Internal Rotation**



## TABLES

**Table 1: Subject Demographics**

	PFPS		Control	
	Mean	SD	Mean	SD
Age	22.2	3.1	21.0	2.6
Height (cm)	164.5	9.2	164.5	7.1
Weight (kg)	63.5	13.6	63.8	12.7

**Table 2: Comparison of Trunk and Lower Extremity Kinematics Between Groups**

Kinematics Variables	PFPS		Control		p-value	ES
	Mean	SD	Mean	SD		
Trunk flexion	1.7	1.1	1.7	0.9	0.905	0.04
Trunk lateral flexion <sup>†</sup>	1.7	1.7	1.6	0.8	0.781	0.09
Trunk lateral flexion <sup>‡</sup>	-1.5	1.1	-1.4	1.1	0.877	0.05
Trunk rotation <sup>†</sup>	-5.5	4.6	-4.7	4.3	0.574	0.18
Trunk rotation <sup>‡</sup>	3.0	3.2	3.6	4.3	0.622	0.16
Hip flexion	-4.6	3.4	-4.6	3.9	0.967	0.01
Hip adduction	10.5	4.1	10.9	4.2	0.780	0.09
Hip abduction	-0.7	1.2	-0.5	0.9	0.587	0.18
Hip internal rotation	4.4	3.3	4.0	3.3	0.692	0.13
Hip external rotation	-3.9	2.4	-4.3	2.3	0.602	0.17
Knee flexion	79.7	5.9	79.3	5.8	0.821	0.07
Knee valgus	-2.6	5.1	-2.7	3.0	0.942	0.02
Knee varus	5.3	3.4	3.5	2.6	0.077	0.58
Knee internal rotation	12.8	7.2	8.9	4.4	0.044*	0.68
Knee external rotation	-1.5	2.2	-0.9	1.0	0.327	0.33

Means and standard deviations measured in degrees.

\* indicates significance at the 0.05 level (2-tailed)

<sup>†</sup> indicates toward the stance leg

<sup>‡</sup> indicates away from the stance leg

**Table 3: Trunk and Hip Kinematics Variables Correlated to Knee Internal Rotation**

Kinematic Variables	r-value	p-value
Trunk flexion	0.019	0.454
Trunk lateral flexion <sup>†</sup>	0.140	0.194
Trunk lateral flexion <sup>‡</sup>	0.292	0.034*
Trunk rotation <sup>†</sup>	-0.354	0.013*
Trunk rotation <sup>‡</sup>	-0.171	0.146
Hip flexion	-0.103	0.263
Hip adduction	0.301	0.030*
Hip abduction	0.151	0.177
Hip internal rotation	0.067	0.341
Hip external rotation	0.030	0.426

\* indicates significance at the 0.05 level (1-tailed)

† indicates toward the stance leg

‡ indicates away from the stance leg

**Table 4: Pearson Correlation Coefficients for the Multiple Regression Analyses**

Kinematic Variables	<i>All Subjects</i>	<i>PFPS Subjects</i>	<i>Control Subjects</i>
Trunk lateral flexion‡	0.292	0.503	0.017
Trunk rotation†	-0.354	-0.254	-0.522
Hip adduction	0.301	0.341	0.346

† indicates toward the stance leg

‡ indicates away from the stance leg

**Table 5: Pre and Post VAS Scores**

	PFPS		Control	
	Mean	SD	Mean	SD
Pre-VAS	17.3	14.3	0.0	0.0
Post-VAS	22.7	15.2	0.2	0.7

\* measured in millimeters



## REFERENCES

- Aglietti, P., Insall, J. N., & Cerulli, G. (1983). Patellar pain and incongruence. I: Measurements of incongruence. *Clin Orthop Relat Res*(176), 217-224.
- Ali, S. A., Helmer, R., & Terk, M. R. (2010). Analysis of the patellofemoral region on MRI: association of abnormal trochlear morphology with severe cartilage defects. *AJR Am J Roentgenol*, 194(3), 721-727.
- Amis, A. A. (2007). Current concepts on anatomy and biomechanics of patellar stability. *Sports Med Arthrosc*, 15(2), 48-56.
- Asay, J. L., Mundermann, A., & Andriacchi, T. P. (2009). Adaptive patterns of movement during stair climbing in patients with knee osteoarthritis. *J Orthop Res*, 27(3), 325-329.
- Barton, C. J., Levinger, P., Webster, K. E., & Menz, H. B. (2011). Walking kinematics in individuals with patellofemoral pain syndrome: a case-control study. *Gait Posture*, 33(2), 286-291.
- Bell, A. L., Pedersen, D. R., & Brand, R. A. (1990). A comparison of the accuracy of several hip center location prediction methods. *J Biomech*, 23(6), 617-621.
- Besier, T. F., Draper, C. E., Gold, G. E., Beaupre, G. S., & Delp, S. L. (2005). Patellofemoral joint contact area increases with knee flexion and weight-bearing. *J Orthop Res*, 23(2), 345-350.
- Blackburn, J. T., & Padua, D. A. (2008). Influence of trunk flexion on hip and knee joint kinematics during a controlled drop landing. *Clin Biomech (Bristol, Avon)*, 23(3), 313-319.
- Blackburn, J. T., Riemann, B. L., Myers, J. B., & Lephart, S. M. (2003). Kinematic analysis of the hip and trunk during bilateral stance on firm, foam, and multiaxial support surfaces. *Clin Biomech (Bristol, Avon)*, 18(7), 655-661.
- Bodian, C. A., Freedman, G., Hossain, S., Eisenkraft, J. B., & Beilin, Y. (2001). The visual analog scale for pain: clinical significance in postoperative patients. *Anesthesiology*, 95(6), 1356-1361.
- Bolgia, L. A., Malone, T. R., Umberger, B. R., & Uhl, T. L. (2008). Hip strength and hip and knee kinematics during stair descent in females with and without patellofemoral pain syndrome. *J Orthop Sports Phys Ther*, 38(1), 12-18.

- Boling, M., Padua, D., Marshall, S., Guskiewicz, K., Pyne, S., & Beutler, A. (2009). Gender differences in the incidence and prevalence of patellofemoral pain syndrome. *Scand J Med Sci Sports*.
- Boling, M. C., Padua, D. A., Marshall, S. W., Guskiewicz, K., Pyne, S., & Beutler, A. (2009). A prospective investigation of biomechanical risk factors for patellofemoral pain syndrome: the Joint Undertaking to Monitor and Prevent ACL Injury (JUMP-ACL) cohort. *Am J Sports Med*, 37(11), 2108-2116.
- Brechter, J. H., & Powers, C. M. (2002). Patellofemoral joint stress during stair ascent and descent in persons with and without patellofemoral pain. *Gait Posture*, 16(2), 115-123.
- Carrillon, Y., Abidi, H., Dejour, D., Fantino, O., Moyen, B., & Tran-Minh, V. A. (2000). Patellar instability: assessment on MR images by measuring the lateral trochlear inclination-initial experience. *Radiology*, 216(2), 582-585.
- Chhabra, A., Elliott, C. C., Miller, M. D. (2001). Normal Anatomy and Biomechanics of the Knee. *Sports Med Arthrosc*, 9(3), 166-177.
- Christoforakis, J. J., & Strachan, R. K. (2005). Internal derangements of the knee associated with patellofemoral joint degeneration. *Knee Surg Sports Traumatol Arthrosc*, 13(7), 581-584.
- Cichanowski, H. R., Schmitt, J. S., Johnson, R. J., & Niemuth, P. E. (2007). Hip strength in collegiate female athletes with patellofemoral pain. *Med Sci Sports Exerc*, 39(8), 1227-1232.
- Claiborne, T. L., Armstrong, C. W., Gandhi, V., & Pincivero, D. M. (2006). Relationship between hip and knee strength and knee valgus during a single leg squat. *J Appl Biomech*, 22(1), 41-50.
- Cleland, J., & McRae, M. (2002). Patellofemoral pain syndrome: a critical analysis of current concepts. *Physical Therapy Reviews*, 7, 153-161.
- Clement, D. B., Taunton, J. E., Smart, G. W., McNicol, K. L. (1981). A Survey of Overuse Injuries. *Phys Sportsmed*, 9, 47-58.
- Connolly, K. D., Ronsky, J. L., Westover, L. M., Kupper, J. C., & Frayne, R. (2009). Differences in patellofemoral contact mechanics associated with patellofemoral pain syndrome. *J Biomech*, 42(16), 2802-2807.
- Cornwall, M. W., & McPoil, T. G. (1995). Footwear and foot orthotic effectiveness research: a new approach. *J Orthop Sports Phys Ther*, 21(6), 337-344.

- Costigan, P. A., Deluzio, K. J., & Wyss, U. P. (2002). Knee and hip kinetics during normal stair climbing. *Gait Posture*, *16*(1), 31-37.
- Cowan, S. M., Bennell, K. L., Hodges, P. W., Crossley, K. M., & McConnell, J. (2001). Delayed onset of electromyographic activity of vastus medialis obliquus relative to vastus lateralis in subjects with patellofemoral pain syndrome. *Arch Phys Med Rehabil*, *82*(2), 183-189.
- Cowan, S. M., Crossley, K. M., & Bennell, K. L. (2009). Altered hip and trunk muscle function in individuals with patellofemoral pain. *Br J Sports Med*, *43*(8), 584-588.
- Crossley, K. M., Cowan, S. M., Bennell, K. L., & McConnell, J. (2004). Knee flexion during stair ambulation is altered in individuals with patellofemoral pain. *J Orthop Res*, *22*(2), 267-274.
- Csintalan, R. P., Schulz, M. M., Woo, J., McMahon, P. J., & Lee, T. Q. (2002). Gender differences in patellofemoral joint biomechanics. *Clin Orthop Relat Res*(402), 260-269.
- D'Agata, S. D., Pearsall, A. W. t., Reider, B., & Draganich, L. F. (1993). An in vitro analysis of patellofemoral contact areas and pressures following procurement of the central one-third patellar tendon. *Am J Sports Med*, *21*(2), 212-219.
- Davies, A. P., Costa, M. L., Shepstone, L., Glasgow, M. M., & Donell, S. (2000). The sulcus angle and malalignment of the extensor mechanism of the knee. *J Bone Joint Surg Br*, *82*(8), 1162-1166.
- Davis, I. S., & Powers, C. M. (2010). Patellofemoral pain syndrome: proximal, distal, and local factors, an international retreat, April 30-May 2, 2009, Fells Point, Baltimore, MD. *J Orthop Sports Phys Ther*, *40*(3), A1-16.
- DeHaven, K. E., & Lintner, D. M. (1986). Athletic injuries: comparison by age, sport, and gender. *Am J Sports Med*, *14*(3), 218-224.
- Devereaux, M. D., & Lachmann, S. M. (1984). Patello-femoral arthralgia in athletes attending a Sports Injury Clinic. *Br J Sports Med*, *18*(1), 18-21.
- Dierks, T. A., Manal, K. T., Hamill, J., & Davis, I. S. (2008). Proximal and distal influences on hip and knee kinematics in runners with patellofemoral pain during a prolonged run. *J Orthop Sports Phys Ther*, *38*(8), 448-456.
- Duffey, M. J., Martin, D. F., Cannon, D. W., Craven, T., & Messier, S. P. (2000). Etiologic factors associated with anterior knee pain in distance runners. *Med Sci Sports Exerc*, *32*(11), 1825-1832.

- Earl, J. E., Monteiro, S. K., & Snyder, K. R. (2007). Differences in lower extremity kinematics between a bilateral drop-vertical jump and a single-leg step-down. *J Orthop Sports Phys Ther*, 37(5), 245-252.
- Earl, J. E., & Vetter, C. S. (2007). Patellofemoral pain. *Phys Med Rehabil Clin N Am*, 18(3), 439-458, viii.
- Fucentese, S. F., von Roll, A., Koch, P. P., Epari, D. R., Fuchs, B., & Schottle, P. B. (2006). The patella morphology in trochlear dysplasia--a comparative MRI study. *Knee*, 13(2), 145-150.
- Gabriel, S. E., Crowson, C. S., & O'Fallon, W. M. (1995). Costs of osteoarthritis: estimates from a geographically defined population. *J Rheumatol Suppl*, 43, 23-25.
- Gallagher, E. J., Liebman, M., & Bijur, P. E. (2001). Prospective validation of clinically important changes in pain severity measured on a visual analog scale. *Ann Emerg Med*, 38(6), 633-638.
- Gilleard, W., McConnell, J., & Parsons, D. (1998). The effect of patellar taping on the onset of vastus medialis obliquus and vastus lateralis muscle activity in persons with patellofemoral pain. *Phys Ther*, 78(1), 25-32.
- Golden, G. M., Pavol, M. J., & Hoffman, M. A. (2009). Knee joint kinematics and kinetics during a lateral false-step maneuver. *J Athl Train*, 44(5), 503-510.
- Grenholm, A., Stensdotter, A., Hager-Ross, C. (2009). Kinematic Analyses During Stair Descent in Young Women With Patellofemoral Pain. *Clin Biomech (Bristol, Avon)*, 24, 88-94.
- Hefzy, M. S., Jackson, W. T., Saddemi, S. R., & Hsieh, Y. F. (1992). Effects of tibial rotations on patellar tracking and patello-femoral contact areas. *J Biomed Eng*, 14(4), 329-343.
- Heiderscheit, B. C., Hamill, J., & Caldwell, G. E. (2000). Influence of Q-angle on lower-extremity running kinematics. *J Orthop Sports Phys Ther*, 30(5), 271-278.
- Heino Brechter, J., & Powers, C. M. (2002). Patellofemoral stress during walking in persons with and without patellofemoral pain. *Med Sci Sports Exerc*, 34(10), 1582-1593.
- Hirokawa, S. (1991). Three-dimensional mathematical model analysis of the patellofemoral joint. *J Biomech*, 24(8), 659-671.
- Hollman, J. H., Ginos, B. E., Kozuchowski, J., Vaughn, A. S., Krause, D. A., & Youdas, J. W. (2009). Relationships between knee valgus, hip-muscle strength, and hip-

- muscle recruitment during a single-limb step-down. *J Sport Rehabil*, 18(1), 104-117.
- Houck, J. R., Duncan, A., & De Haven, K. E. (2006). Comparison of frontal plane trunk kinematics and hip and knee moments during anticipated and unanticipated walking and side step cutting tasks. *Gait Posture*, 24(3), 314-322.
- Hsieh, Y. F., Draganich, L. F., Ho, S. H., & Reider, B. (2002). The effects of removal and reconstruction of the anterior cruciate ligament on the contact characteristics of the patellofemoral joint. *Am J Sports Med*, 30(1), 121-127.
- Huberti, H. H., & Hayes, W. C. (1984). Patellofemoral contact pressures. The influence of q-angle and tendofemoral contact. *J Bone Joint Surg Am*, 66(5), 715-724.
- Hunt, M. A., Wrigley, T. V., Hinman, R. S., & Bennell, K. L. (2010). Individuals with severe knee osteoarthritis (OA) exhibit altered proximal walking mechanics compared with individuals with less severe OA and those without knee pain. *Arthritis Care Res (Hoboken)*, 62(10), 1426-1432.
- Imwalle, L. E., Myer, G. D., Ford, K. R., & Hewett, T. E. (2009). Relationship between hip and knee kinematics in athletic women during cutting maneuvers: a possible link to noncontact anterior cruciate ligament injury and prevention. *J Strength Cond Res*, 23(8), 2223-2230.
- Insall, J. (1982). Current Concepts Review: patellar pain. *J Bone Joint Surg Am*, 64(1), 147-152.
- Insall, J., Goldberg, V., & Salvati, E. (1972). Recurrent dislocation and the high-riding patella. *Clin Orthop Relat Res*, 88, 67-69.
- Insall, J., & Salvati, E. (1971). Patella position in the normal knee joint. *Radiology*, 101(1), 101-104.
- Ireland, M. L., Willson, J. D., Ballantyne, B. T., & Davis, I. M. (2003). Hip strength in females with and without patellofemoral pain. *J Orthop Sports Phys Ther*, 33(11), 671-676.
- Kannus, P. A. (1992). Long patellar tendon: radiographic sign of patellofemoral pain syndrome--a prospective study. *Radiology*, 185(3), 859-863.
- Kelly, A. M. (1998). Does the clinically significant difference in visual analog scale pain scores vary with gender, age, or cause of pain? *Acad Emerg Med*, 5(11), 1086-1090.
- Krebs, D. E., Wong, D., Jevsevar, D., Riley, P. O., & Hodge, W. A. (1992). Trunk kinematics during locomotor activities. *Phys Ther*, 72(7), 505-514.

- Kujala, U. M., Osterman, K., Kormanio, M., Nelimarkka, O., Hurme, M., & Taimela, S. (1989). Patellofemoral relationships in recurrent patellar dislocation. *J Bone Joint Surg Br*, 71(5), 788-792.
- Kujala, U. M., Osterman, K., Kvist, M., Aalto, T., & Friberg, O. (1986). Factors predisposing to patellar chondropathy and patellar apicitis in athletes. *Int Orthop*, 10(3), 195-200.
- Lee, J. S., Hobden, E., Stiell, I. G., & Wells, G. A. (2003). Clinically important change in the visual analog scale after adequate pain control. *Acad Emerg Med*, 10(10), 1128-1130.
- Lee, T. Q., Anzel, S. H., Bennett, K. A., Pang, D., & Kim, W. C. (1994). The influence of fixed rotational deformities of the femur on the patellofemoral contact pressures in human cadaver knees. *Clin Orthop Relat Res*(302), 69-74.
- Lee, T. Q., Morris, G., & Csintalan, R. P. (2003). The influence of tibial and femoral rotation on patellofemoral contact area and pressure. *J Orthop Sports Phys Ther*, 33(11), 686-693.
- Lee, T. Q., Yang, B. Y., Sandusky, M. D., & McMahon, P. J. (2001). The effects of tibial rotation on the patellofemoral joint: assessment of the changes in in situ strain in the peripatellar retinaculum and the patellofemoral contact pressures and areas. *J Rehabil Res Dev*, 38(5), 463-469.
- Leetun, D. T., Ireland, M. L., Willson, J. D., Ballantyne, B. T., & Davis, I. M. (2004). Core stability measures as risk factors for lower extremity injury in athletes. *Med Sci Sports Exerc*, 36(6), 926-934.
- Li, G., DeFrate, L. E., Zayontz, S., Park, S. E., & Gill, T. J. (2004). The effect of tibiofemoral joint kinematics on patellofemoral contact pressures under simulated muscle loads. *J Orthop Res*, 22(4), 801-806.
- Maetzel, A., Li, L. C., Pencharz, J., Tomlinson, G., & Bombardier, C. (2004). The economic burden associated with osteoarthritis, rheumatoid arthritis, and hypertension: a comparative study. *Ann Rheum Dis*, 63(4), 395-401.
- Mascal, C. L., Landel, R., & Powers, C. (2003). Management of patellofemoral pain targeting hip, pelvis, and trunk muscle function: 2 case reports. *J Orthop Sports Phys Ther*, 33(11), 647-660.
- McClay, I., & Manal, K. (1998). A comparison of three-dimensional lower extremity kinematics during running between excessive pronators and normals. *Clin Biomech (Bristol, Avon)*, 13(3), 195-203.

- McKenzie, K., Galea, V., Wessel, J., & Pierrynowski, M. (2010). Lower Extremity Kinematics of Females With Patellofemoral Pain Syndrome While Stair Stepping. *J Orthop Sports Phys Ther*.
- McPoil, T. G., & Cornwall, M. W. (2000). The effect of foot orthoses on transverse tibial rotation during walking. *J Am Podiatr Med Assoc*, 90(1), 2-11.
- Messier, S. P., Davis, S. E., Curl, W. W., Lowery, R. B., & Pack, R. J. (1991). Etiologic factors associated with patellofemoral pain in runners. *Med Sci Sports Exerc*, 23(9), 1008-1015.
- Mizuno, Y., Kumagai, M., Mattessich, S. M., Elias, J. J., Ramrattan, N., Cosgarea, A. J., et al. (2001). Q-angle influences tibiofemoral and patellofemoral kinematics. *J Orthop Res*, 19(5), 834-840.
- Moller, B. N., Moller-Larsen, F., & Frich, L. H. (1989). Chondromalacia induced by patellar subluxation in the rabbit. *Acta Orthop Scand*, 60(2), 188-191.
- Nawoczenski, D. A., Cook, T. M., & Saltzman, C. L. (1995). The effect of foot orthotics on three-dimensional kinematics of the leg and rearfoot during running. *J Orthop Sports Phys Ther*, 21(6), 317-327.
- Nordby, P. A., Staalesen Strumse, Y. A., Frosli, K. F., & Stanghelle, J. K. (2007). Patients with neuromuscular diseases benefit from treatment in a warm climate. *J Rehabil Med*, 39(7), 554-559.
- Owings, T. M., & Grabiner, M. D. (2002). Motor control of the vastus medialis oblique and vastus lateralis muscles is disrupted during eccentric contractions in subjects with patellofemoral pain. *Am J Sports Med*, 30(4), 483-487.
- Pfirschmann, C. W., Zanetti, M., Romero, J., & Hodler, J. (2000). Femoral trochlear dysplasia: MR findings. *Radiology*, 216(3), 858-864.
- Piva, S. R., Goodnite, E. A., & Childs, J. D. (2005). Strength around the hip and flexibility of soft tissues in individuals with and without patellofemoral pain syndrome. *J Orthop Sports Phys Ther*, 35(12), 793-801.
- Powers, C. M. (2000). Patellar Kinematics, Part II: The Influence of the Depth of the Trochlear Groove in Subjects With and Without Patellofemoral Pain. *Phys Ther*, 80(10), 965-978.
- Powers, C. M. (2003). The influence of altered lower-extremity kinematics on patellofemoral joint dysfunction: a theoretical perspective. *J Orthop Sports Phys Ther*, 33(11), 639-646.

- Powers, C. M., Chen, P. Y., Reischl, S. F., & Perry, J. (2002). Comparison of foot pronation and lower extremity rotation in persons with and without patellofemoral pain. *Foot Ankle Int*, *23*(7), 634-640.
- Powers, C. M., Heino, J. G., Rao, S., & Perry, J. (1999). The influence of patellofemoral pain on lower limb loading during gait. *Clin Biomech (Bristol, Avon)*, *14*(10), 722-728.
- Protopapadaki, A., Drechsler, W. I., Cramp, M. C., Coutts, F. J., & Scott, O. M. (2007). Hip, knee, ankle kinematics and kinetics during stair ascent and descent in healthy young individuals. *Clin Biomech (Bristol, Avon)*, *22*(2), 203-210.
- Reikeras, O. (1992). Patellofemoral characteristics in patients with increased femoral anteversion. *Skeletal Radiol*, *21*(5), 311-313.
- Reischl, S. F., Powers, C. M., Rao, S., & Perry, J. (1999). Relationship between foot pronation and rotation of the tibia and femur during walking. *Foot Ankle Int*, *20*(8), 513-520.
- Riener, R., Rabuffetti, M., & Frigo, C. (2002). Stair ascent and descent at different inclinations. *Gait Posture*, *15*(1), 32-44.
- Robinson, R. L., & Nee, R. J. (2007). Analysis of hip strength in females seeking physical therapy treatment for unilateral patellofemoral pain syndrome. *J Orthop Sports Phys Ther*, *37*(5), 232-238.
- Salsich, G. B., Brechter, J. H., & Powers, C. M. (2001). Lower extremity kinetics during stair ambulation in patients with and without patellofemoral pain. *Clin Biomech (Bristol, Avon)*, *16*(10), 906-912.
- Salsich, G. B., & Long-Rossi, F. (2010). Do females with patellofemoral pain have abnormal hip and knee kinematics during gait? *Physiother Theory Pract*, *26*(3), 150-159.
- Salsich, G. B., & Perman, W. H. (2007). Patellofemoral joint contact area is influenced by tibiofemoral rotation alignment in individuals who have patellofemoral pain. *J Orthop Sports Phys Ther*, *37*(9), 521-528.
- Salsich, G. B., Ward, S. R., Terk, M. R., & Powers, C. M. (2003). In vivo assessment of patellofemoral joint contact area in individuals who are pain free. *Clin Orthop Relat Res*(417), 277-284.
- Sandow, M. J., & Goodfellow, J. W. (1985). The natural history of anterior knee pain in adolescents. *J Bone Joint Surg Br*, *67*(1), 36-38.



- Schutzer, S. F., Ramsby, G. R., & Fulkerson, J. P. (1986). The evaluation of patellofemoral pain using computerized tomography. A preliminary study. *Clin Orthop Relat Res*(204), 286-293.
- Senavongse, W., & Amis, A. A. (2005). The effects of articular, retinacular, or muscular deficiencies on patellofemoral joint stability. *J Bone Joint Surg Br*, 87(4), 577-582.
- Singer, A. J., & Thode, H. C., Jr. (1998). Determination of the minimal clinically significant difference on a patient visual analog satisfaction scale. *Acad Emerg Med*, 5(10), 1007-1011.
- Souza, R. B., & Powers, C. M. (2009). Differences in hip kinematics, muscle strength, and muscle activation between subjects with and without patellofemoral pain. *J Orthop Sports Phys Ther*, 39(1), 12-19.
- Stathopulu, E., & Baildam, E. (2003). Anterior knee pain: a long-term follow-up. *Rheumatology (Oxford)*, 42(2), 380-382.
- Taunton, J. E., Ryan, M. B., Clement, D. B., McKenzie, D. C., Lloyd-Smith, D. R., & Zumbo, B. D. (2002). A retrospective case-control analysis of 2002 running injuries. *Br J Sports Med*, 36(2), 95-101.
- Thomee, R., Augustsson, J., & Karlsson, J. (1999). Patellofemoral pain syndrome: a review of current issues. *Sports Med*, 28(4), 245-262.
- Thomee, R., Renstrom, P., Karlsson, J., & Grimby, G. (1995). Patellofemoral pain syndrome in young women. I. A clinical analysis of alignment, pain parameters, common symptoms and functional activity level. *Scand J Med Sci Sports*, 5(4), 237-244.
- Tiberio, D. (1987). The effect of excessive subtalar joint pronation on patellofemoral mechanics: a theoretical model. *J Orthop Sports Phys Ther*, 9(4), 160-165.
- Todd, K. H. (1996). Clinical versus statistical significance in the assessment of pain relief. *Ann Emerg Med*, 27(4), 439-441.
- Todd, K. H., Funk, K. G., Funk, J. P., & Bonacci, R. (1996). Clinical significance of reported changes in pain severity. *Ann Emerg Med*, 27(4), 485-489.
- Utting, M. R., Davies, G., & Newman, J. H. (2005). Is anterior knee pain a predisposing factor to patellofemoral osteoarthritis? *Knee*, 12(5), 362-365.
- Van Tiggelen, D., Cowan, S., Coorevits, P., Duvigneaud, N., & Witvrouw, E. (2009). Delayed vastus medialis obliquus to vastus lateralis onset timing contributes to

- the development of patellofemoral pain in previously healthy men: a prospective study. *Am J Sports Med*, 37(6), 1099-1105.
- Ward, S. R., & Powers, C. M. (2004). The influence of patella alta on patellofemoral joint stress during normal and fast walking. *Clin Biomech (Bristol, Avon)*, 19(10), 1040-1047.
- Waryasz, G. R., & McDermott, A. Y. (2008). Patellofemoral pain syndrome (PFPS): a systematic review of anatomy and potential risk factors. *Dyn Med*, 7, 9.
- Willson, J. D., & Davis, I. S. (2008). Lower extremity mechanics of females with and without patellofemoral pain across activities with progressively greater task demands. *Clin Biomech (Bristol, Avon)*, 23(2), 203-211.
- Willson, J. D., & Davis, I. S. (2009). Lower extremity strength and mechanics during jumping in women with patellofemoral pain. *J Sport Rehabil*, 18(1), 76-90.
- Willson, J. D., Dougherty, C. P., Ireland, M. L., & Davis, I. M. (2005). Core stability and its relationship to lower extremity function and injury. *J Am Acad Orthop Surg*, 13(5), 316-325.
- Witvrouw, E., Lysens, R., Bellemans, J., Cambier, D., & Vanderstraeten, G. (2000). Intrinsic risk factors for the development of anterior knee pain in an athletic population. A two-year prospective study. *Am J Sports Med*, 28(4), 480-489.
- Zazulak, B., Cholewicki, J., & Reeves, N. P. (2008). Neuromuscular control of trunk stability: clinical implications for sports injury prevention. *J Am Acad Orthop Surg*, 16(9), 497-505.
- Zazulak, B. T., Hewett, T. E., Reeves, N. P., Goldberg, B., & Cholewicki, J. (2007a). Deficits in neuromuscular control of the trunk predict knee injury risk: a prospective biomechanical-epidemiologic study. *Am J Sports Med*, 35(7), 1123-1130.
- Zazulak, B. T., Hewett, T. E., Reeves, N. P., Goldberg, B., & Cholewicki, J. (2007b). The effects of core proprioception on knee injury: a prospective biomechanical-epidemiological study. *Am J Sports Med*, 35(3), 368-373.
- Zeller, B. L., McCrory, J. L., Kibler, W. B., & Uhl, T. L. (2003). Differences in kinematics and electromyographic activity between men and women during the single-legged squat. *Am J Sports Med*, 31(3), 449-456.
- Zisapel, N., & Nir, T. (2003). Determination of the minimal clinically significant difference on a patient visual analog sleep quality scale. *J Sleep Res*, 12(4), 291-298.