The Pennsylvania State University

The Graduate School

Department of Kinesiology

MOMENT ANGLE RELATIONSHIP OF HIP MUSCULATURE

A Dissertation in

Kinesiology

by

Curtis Kindel

© 2015 Curtis Kindel

Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Doctor of Philosophy

May 2015
The dissertation of Curtis Kindel was reviewed and approved* by the following:

John H. Challis  
Professor of Kinesiology  
Dissertation Advisor  
Chair of Committee

Jinger S. Gottschall  
Associate Professor of Kinesiology

Sayers John Miller III  
Assistant Professor of Kinesiology

Andris Freivalds  
Professor of Industrial and Manufacturing Engineering

Stephen J Piazza  
Professor of Kinesiology  
Graduate Program Chair

*Signatures are on file in the Graduate School
ABSTRACT

In the rehabilitation field, developing effective and efficient treatments for individuals with knee pathologies, specifically, patellofemoral syndrome, is very important. While the muscles crossing the knee joint have been widely accepted as having a role to play in knee pathology, muscles of the hip joint have also been associated with knee pathologies such as patellofemoral syndrome. However, research is inconclusive as to whether these hip muscles lack strength, neuromuscular control, or both in subjects with patellofemoral syndrome. Additional research is needed regarding the characteristics and properties of hip musculature in order to comprehensively understand this relationship. This dissertation consisted of three studies designed to analyze the isometric moment-angle relationships of the hip abductors and hip extensors in healthy subjects as well as those with patellofemoral syndrome. The moment-angle relationships were then analyzed in multiple facets: the peak joint moment at pre-determined positions throughout an arc of motion, the gradient of the aforementioned peak moments across the arc of motion, and the joint moment fluctuations at each hip position.

In the first study, measurements of peak isometric joint moments at various positions in hip abduction (-15°, 0°, 15°, 30°) and hip extension (-45°, -30°, -15°, 0°) were gathered and then analyzed to determine the moment angle relationship in normal healthy subjects. The position of the knee was either in flexion or extension throughout the hip joint moment assessments. Results showed a descending moment-angle curve for both hip abduction and hip extension. These results demonstrate that joint strength decreases throughout hip abduction and hip extension. These findings have implications for clinicians for prescribing exercises for this musculature.

The second study analyzed the peak hip joint moments of hip abduction and hip extension in individuals with current complaints of patellofemoral syndrome, and compared them with age and size matched control subjects. The results demonstrated that individuals with
patellofemoral syndrome had a decreased joint moment of hip extension with the knee flexed, but not with the knee extended. This suggests a deficit of strength of the uniarticular gluteus maximus, or increased strength of the biarticular hamstring musculature, in subjects with patellofemoral syndrome. Contrary to previous literature, there were no statistically significant differences in hip abductor strength between the two groups.

The third study examined joint moment fluctuations of subjects with patellofemoral syndrome and healthy controls, during maximal isometric moments produced during hip abduction and hip extension. The fluctuations in joint moment data were quantified using statistical techniques (signal coefficient of variation) in addition to methods from statistical physics (e.g., signal complexity and signal fractal properties). Results showed increased coefficient of variation, indicating greater signal noise and therefore poorer muscle control, of the hip extension moment with the knee flexed for the group of subjects with patellofemoral syndrome. This suggests the weakness of the uniarticular musculature in subjects with patellofemoral syndrome is, at least in part, due to different neuromuscular control. No differences were found in signal complexity between subjects with patellofemoral syndrome and healthy controls.

These studies demonstrated that subjects with patellofemoral syndrome were found to be deficient in strength and neuromuscular control for hip extension joint moment, especially when the knee was flexed. Therefore, the hip extensor musculature should be strengthened when rehabilitating individuals with patellofemoral syndrome. The hip extensor muscle group should also be trained to facilitate neuromuscular control, such as controlled eccentric exercise and static isometric holds, at various joint angles of hip extension.
## TABLE OF CONTENTS

List of Figures .................................................................................................................. ix
List of Tables ...................................................................................................................... xii
Acknowledgements .......................................................................................................... xv

Chapter 1 Introduction ..................................................................................................... 1

1.1 General Introduction ................................................................................................. 1
1.2 Purpose of the Study ................................................................................................. 2
1.3 Specific Aims ........................................................................................................... 3
1.4 Study Overview ....................................................................................................... 4
1.5 Thesis Structure ..................................................................................................... 4
1.6 References ............................................................................................................. 5

Chapter 2 Literature Review ......................................................................................... 7

2.1 Introduction ............................................................................................................. 7
2.2 Muscles of the Hip ................................................................................................. 7
   2.2.1 Uniarticular Muscles ....................................................................................... 7
   2.2.2 Biarticular Muscles ....................................................................................... 8
2.3 Muscle Architecture ............................................................................................... 9
   2.3.1 Fiber Lengths ................................................................................................ 9
   2.3.2 Physiological Cross-Sectional Area ............................................................ 11
   2.3.3 Muscle Moment Arms ................................................................................. 13
   2.3.4 Estimation of Muscle Forces ....................................................................... 14
2.4 Joint Moment-Angle Relationship ........................................................................ 15
   2.4.1 Healthy Population ...................................................................................... 17
   2.4.2 Influence of Aging ....................................................................................... 18
   2.4.3 Populations with Pathologies ..................................................................... 18
2.5 Hip Musculature and Joint Pathologies .................................................................. 18
   2.5.1 Knee Joint Function .................................................................................... 19
   2.5.2 Ankle Joint Function ................................................................................... 21
   2.5.3 Contrary Findings ....................................................................................... 22
Appendix C Male-Female Subject Data .................................................................109
Appendix D Clamshell Exercise ........................................................................111
Appendix E Approximate Entropy- ApEn ............................................................112
Appendix F Detrended Fluctuation Analysis- DFA .............................................114
Appendix G Tables of p-values for ApEn, DFA, CV, and signal power .............116
LIST OF FIGURES

Figure 2.1. Map of Gluteus Maximus. (Obtained from http://muscle.ucsd.edu/projects/architecture/LE/glut_max.shtml, Ward et al., 2009)…8

Figure 2.2. Force-length relationship demonstrating force on the y-axis (vertical) and sarcomere length on the x-axis (horizontal)……………………………………………………10

Figure 2.3. Human strength curves (moment-angle relationship) of hip abduction between -20° (adduction) to 60° (abduction) (Kulig, Andrews, and Hay, 1984)…………………..16

Figure 3.1. Subject is right side-lying performing isometric left hip abduction with the knee flexed to 90°. Left hip is in 15° of abduction………………………………………36

Figure 3.2. Subject is prone-lying and performing left isometric hip extension with the knee extended. Left hip is in 0° (neutral) position……………………………………….37

Figure 3.3. Linear regression of the moment-angle relationship of hip abduction. Solid line represents hip abduction with the knee extended. Dashed line represents hip abduction with the knee flexed 90°……………………………………………………………………….40

Figure 3.4. Linear regression of the moment-angle relationship of hip extension. Solid line represents hip extension with the knee extended. Dashed line represents hip extension with the knee flexed 90°……………………………………………………………………….42

Figure 3.5. Plot of tension relative to change in length of a green Theraband®. (Based on data from Page et al., 2000.)………………………………………………………………….45

Figure 3.6. Calculated moment–angle relationship of sidelying hip abduction based on average segment weight (N) and center of mass (m) location. Anthropometric data were calculated utilizing the data of Winter (1990). This resistance moment-angle gradient (strength curve) more closely resembles the one found in this study……………………………………………46
Figure 4.1. Subject is left side-lying performing isometric right hip abduction with the knee flexed to 90°. The hip is in 15° of abduction………………………………………………56

Figure 4.2. Subject is prone-lying and performing left isometric hip extension with the knee flexed to 90°. Left hip is in -15° (flexion) position……………………………………57

Figure 4.3. The moment-angle relationship of hip abduction comparing patellofemoral subjects to control subjects with the knee extended…………………………61

Figure 4.4. The moment-angle relationship of hip abduction comparing patellofemoral subjects to control subjects with the knee flexed 90°………………………………………62

Figure 4.5. Moment-angle relationship of hip extension of patellofemoral subjects vs. control subjects with the knee extended…………………………………………………64

Figure 4.6. Moment-angle relationship of hip extension of patellofemoral subjects vs. control subjects with the knee flexed…………………………………………………..65

Figure 5.1 Chart of ApEn values for patellofemoral subjects and control subjects for hip abduction…………………………………………………………………………………80

Figure 5.2 Chart of ApEn values for patellofemoral subjects and control subjects for hip extension…………………………………………………………………………………81

Figure 5.3 Chart of DFA values for patellofemoral subjects and control subjects for hip abduction…………………………………………………………………………………82

Figure 5.4 Chart of DFA values for patellofemoral subjects and control subjects for hip extension…………………………………………………………………………………83

Figure 5.5 Chart of CV values for patellofemoral subjects and control subjects for hip abduction…………………………………………………………………………………84
Figure 5.6 Chart of CV values for patellofemoral subjects and control subjects for hip extension………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………
LIST OF TABLES

Table 2-1. The physiological cross-sectional area of specific lower extremity musculature (Data collected from Ward et al., 2009)……………………..12

Table 3-1. Table of measured joint motions with a standard goniometer (Norkin and White, 2009)……………………………………………………………………35

Table 3-2. The means (± standard deviation) of the joint ranges of motion for the whole subject group, and the male and female sub-groups…………………………………………………………………………38

Table 3-3. The means (± standard deviation) of the peak hip abduction moment and the angle at which it occurred for the whole subject group. In addition the gradient of the line of the joint angle-moment relationship is reported………………………………………………………………39

Table 3-4. The means (± standard deviation) of the peak hip extension moment and the angle at which it occurred for the whole subject group. In addition the gradient of the line of the joint angle-moment relationship is reported……………………………………………………41

Table 4.1. Descriptive statistics comparing control group subjects and patellofemoral group subjects. A t-test indicated no significant differences between the groups for age, mass, or height (p < 0.05)………………………………………………………………………………54

Table 4.2. Table of measured joint motions with a standard goniometer (Norkin and White, 2009)……………………………………………………………………………55

Table 4.3. The means (± standard deviation) of the joint ranges of motion for the control subject group and the patellofemoral subject group………………………………………59
Table 4.4. The means (± standard deviation) of the peak hip abduction joint moment and the angle at which it occurred for the subject groups. In addition the the gradient of the line of the joint angle-moment relationship is reported. No significant difference was found between the patellofemoral group and control group for hip abduction……………………………………...60

Table 4.5. The means (± standard deviation) of the peak hip extension moment and the angle at which it occurred for the subject groups. In addition the gradient of the line of the joint angle-moment relationship is reported. Significant differences are indicated by (*)…………………..63

Table 5.1 Descriptive statistics comparing control group subjects and patellofemoral group subjects. No statistical significant differences were found between groups (p < 0.05)……………………………………………………………………………………………………77

Table 5.2 The means (± standard deviation) of the peak hip abduction and extension moments for the subject groups. Significant differences are indicated by (*)………………………………………..79

Table G.1 Approximate Entropy- Analysis of variance of knee position, presence of pathology, and interaction of both across each angle of hip abduction and hip extension examined. No statistically significant differences were found…………………………………………………………126

Table G.2 Detrended Fluctuation Analysis- Analysis of variance of knee position, presence of pathology, and interaction of both across each angle of hip abduction and hip extension examined. (asterisk denotes statistical significance)…………………………………………………………127
Table G.3 Coefficient of Variation- Coefficient of variation of knee position, presence of pathology, and interaction of both across each angle of hip abduction and hip extension examined. (asterisk denotes statistical significance)…………………………………………128

Table G.4 Signal Power- Signal power of knee position, presence of pathology, and interaction of both across each angle of hip abduction and hip extension examined…………………………129
ACKNOWLEDGEMENTS

I would like to thank the individuals who donated their time to be my subjects. I would also like to thank the DiSepio Institute for Rural Health and Wellness and director Mark Boland at Saint Francis University for the use of the Biodex Systems 4 isokinetic dynamometer.

My committee was very helpful in their comments and feedback.

My colleagues in the Department of Physical Therapy at Saint Francis University were all very supportive and encouraging throughout these years of work.

I thank John for his guidance and mentoring in developing my efforts as a researcher. I learned an extreme amount through this process. I look forward to continuing to produce research together.

Thank you to my family, for instilling in me a priority for education.

Finally, to Heather, Jessa, and Maura; I know that I have been quite busy and sometimes discouraged through this educational experience. Thank you for your patience, love, and support.

To Heather, my wife; I love you dearly and could not have completed this without your assistance, editing, and, most of all, encouragement.
Chapter 1

Introduction

1.1 General Introduction

The knee joint complex is formed by the articulation of two long bones, the femur and the tibia. It is typically the victim of forces applied both proximally and distally. Patellofemoral syndrome is a clinical condition that is characterized by retropatellar and/or peripatellar pain associated with activities involving lower limb loading (e.g., walking, running, jumping, stair climbing, and prolonged sitting and kneeling) (Davis and Powers, 2010). Patellofemoral syndrome has been reported as the most frequently diagnosed condition in adolescents and adults with knee complaints (Lankhorst et al., 2013). For example, in a group of adolescent female athletes, 26.6% reported incidence of patellofemoral syndrome (Barber Foss et al., 2012).

Research has shown the hip musculature to be deficient in individuals exhibiting signs and symptoms of patellofemoral syndrome (Powers, 2010; Souza and Powers, 2009; Brindle et al. 2003; Cowan et al. 2009). However, the cause of this hip muscle weakness is yet to be determined. Researchers are unsure whether this weakness is a cause of knee pathologies, or if it is a result of changes in lower extremity kinetics. More information regarding the biomechanical properties of the hip musculature may provide insight into the etiology of the patellofemoral pain and therefore contribute to the prevention and more efficient rehabilitation of individuals exhibiting knee pathologies.

One of these properties is the moment-angle relationship, or strength curve. The muscles crossing a particular joint are capable of producing a net moment about that joint. Kulig et al. (1984) reported moment-angle relationships for many human joints, including the hip. The joint motions of hip abduction and hip extension have been examined. However, no research has been performed by manipulating the position of the knee, and therefore altering the lengths of the bi-articular muscles of the hip when assessing these moment-angle relationships.
Enoka et al. (2003) stated that muscle forces always fluctuate about an average value when performing isometric contractions, when the task is to maintain a constant force. In vivo, these fluctuations are manifested by a fluctuation in the moment produced at the relevant joint. This is termed moment fluctuation. Approximate entropy (ApEn) is a regularity statistic designed for the analysis of medical data (Pincus, 1991). It has been used to quantify the moment fluctuations exhibited by muscles about a joint (e.g. ankle, wrist, etc.), but has not been used for the hip complex.

1.2 Purpose of the Study

The purpose of this study was to examine the moment-angle relationship of the hip musculature. The moment-angle relationship can have various meanings. For example, the peak moment of the specified joint at various angles was analyzed. In addition, the gradient (slope) of the curve when comparing joint moment to joint angle was studied. Finally, the fluctuation of moment at various joint angles was analyzed. The moment-angle relationships of the motions of hip abduction and extension were assessed in this study. Chapter 3 examined the peak moment of hip abduction and hip extension of a normal population at two differing knee positions (0° and 90°). Additionally, the slopes of the moment-angle curves were compared between the two knee positions. Chapter 4 examined similar data except in a pathological population, and then compared the data of the normal population to those with a knee pathology. Chapter 5 then analyzed the change in moment production over time (fluctuation) throughout the hip motions of the normal population compared to the population with pathology.

The hip musculature has been correlated to multiple knee pathologies, including patellofemoral syndrome. More research evaluating the cause of this correlation is necessary. Examining the various moment-angle relationships of the hip joint will contribute to explaining the role of hip musculature in lower extremity kinematics. The moment-angle relationships will be compared across genders and to those with the presence of, or history of, patellofemoral syndrome to assist in defining the role of the bi-
articulart muscle in control of lower extremity function. This role can be in the form of strength, measured by peak moment, or muscular control, measured through moment fluctuation, or both.

1.3 Specific Aims

The specific aims of this study are:

**Aim 1.** The aim of the first study (Chapter 3) was to quantify the strength curves of the hip abductors and extensors in a group of healthy subjects.

  **Hypothesis I** - the normalized peak moments of hip abduction and extension will vary significantly with the knee in two different positions (90° and 0°), due to changes in the contributions from the biarticular muscles.

**Aim 2.** The aim of this second study (Chapter 4) was to quantify the strength curves of the hip abductors and extensors in a group of subjects with patellofemoral syndrome, and compare them to age and size matched control subjects.

  **Hypothesis II** – subjects with patellofemoral syndrome will have weaker strength curves, demonstrated by a decrease in magnitude in their normalized peak moments, compared with healthy controls.

  **Hypothesis III** – subjects with patellofemoral syndrome will have a strength curve with a less steep slope (more positive) with the knee in two different positions (90° and 0°) compared with healthy controls.

**Aim 3.** The aim of this third study (Chapter 5) was to quantify the signal properties of the strength curves of the hip abductors and extensors in a group of subjects with patellofemoral syndrome, and in healthy controls. Analysis of signal properties is used here as a measure of neuromuscular control.
Hypothesis IV – subjects with patellofemoral syndrome will have isometric time moment signals of greater signal regularity as indicated by ApEn, with more random properties as indicated by the DFA (Detrended Fluctuation Analysis), and have greater noise as indicated by a larger CV (Coefficient of Variation) during hip abduction and hip extension compared with healthy controls.

Hypothesis V – subjects with patellofemoral syndrome will have isometric time moment signals of greater signal regularity as indicated by ApEn, with more random properties as indicated by the DFA, and have greater noise as indicated by a larger CV during hip abduction and hip extension with the knee flexed compared with the knee extended compared with healthy controls.

1.4 Study Overview

Subjects were asked to perform maximum isometric muscle actions of the hip abductors and extensors at various joint angles. Peak joint moment data were analyzed in a normal population and in a population with the presence of patellofemoral syndrome. In addition, besides examining the joint moment curves, the moment fluctuations over time were also analyzed between control groups and subjects with pathology.

1.5 Thesis Structure

Chapter 2 contains the review of literature. Chapter 3 describes the first study, where subjects with no knee pathology were tested on an isokinetic dynamometer to determine the joint moment-angle curves for hip extension and hip abduction. In addition, the moment angle relationships were gathered with the knee extended and flexed to ninety degrees (90°). This was done to identify differences in muscle contribution to the joint moment by changing the biarticular muscle lengths and therefore their position on their respective force-length curves. Chapter 4 describes the second study, which included subjects who have or have had recent patellofemoral syndrome and examines their resultant joint
moment-angle curves. These data were compared with age and size matched controls. Chapter 5 analyzes the moment fluctuations of the hip extensors and hip abductors of a normal population versus a population with patellofemoral syndrome. The moment fluctuations were quantified using Approximate Entropy (ApEn), Detrended Fluctuation Analysis (DFA), Coefficient of Variation (CV), and signal power. Chapter 6 contains the discussion and conclusions of the dissertation.

1.6 References


Chapter 2

Literature Review

2.1 Introduction

This chapter reviews the literature of hip musculature, hip mechanics, and the hip’s relationship to pathologies of distal joints (i.e. knee and ankle). In addition, the specific biomechanical properties that affect the moment producing capability of a muscle at a joint such as physiological cross sectional area and muscle moment arms will be discussed. Finally, moment fluctuation and its relevance to muscle strength and control are explained.

2.2 Muscles of the Hip

The muscles of the hip complex function to stabilize yet allow triplanar movement of the femur relative to the pelvis (Neumann, 2010). A disruption that affects the strength, control, or extensibility of the hip muscles can disrupt many routine movements involving functional and recreational activities (Neumann, 2010). The hip is composed of both uniarticular and biarticular muscles. The actions of hip musculature occur in each plane: flexors and extensors in the sagittal plane; abductors and adductors in the frontal plan; and external/internal rotators in the transverse plane.

2.2.1 Uniarticular Muscles

Uniarticular muscles produce a moment at only one joint. For hip abduction, the uniarticular muscles are the gluteus medius (GMed) and gluteus minimus (GMin), which originate on the external iliac surface and insert on the greater trochanter of the femur (Flack et al., 2012). The hip abductor group also plays an especially important role in pelvic stabilization in the frontal plane, including during gait (Flack et al., 2012).

One of the primary uniarticular extensors of the hip is the gluteus maximus (GMax)(Dostal et al., 1986). The GMax is the thickest and most powerful muscle unit of the body (Figure 2.1; Jouffroy and
Medina, 2006). It originates from the ilium, sacrum, coccyx, and sacrotuberous ligament, and has a distal attachment on the iliotibial tract in addition to the proximal, posterior femur. Its action is to extend, externally rotate, and, to some degree, abduct the thigh (Jouffroy and Medina, 2006).

Figure 2.1 Map of Gluteus Maximus. (Obtained from http://muscle.ucsd.edu/projects/architecture/LE/glut_max.shtml, Ward et al., 2009.)

2.2.2 Biarticular Muscles

Biarticular muscles not only cross two joints but also have an action on both (Basmajian, 1957). The tensor fascia latae (TFL) originates on the anterior lateral portion of the iliac crest and inserts into the iliotibial band terminating on the tubercle of the tibia (Flack et al., 2012); it contributes to both hip flexion and abduction of the thigh (Neumann, 2010). The TFL contributes about 11% of the total cross-sectional area of the abductors, and therefore does not contribute as a significant moment producer for abduction.

The biarticular muscles which cause extension of the hip complex are the hamstrings-semimembranosus, semitendinosus, and biceps femoris (Ward et al., 2009). These hamstring muscles have relatively small
physiological cross-sectional areas but function to maintain near-constant muscle length for activities of daily living (Ward et al., 2009).

2.3 Muscle Architecture

To determine the possible deficits of the hip musculature in its relationship with the distal joint(s) in the chain, various biomechanical properties need to be examined. Although numerous physical properties of muscle influence contractile properties, collectively these are referred to as muscle architecture (Ward et al., 2009). These properties include fiber length, physiological cross-sectional area (PCSA), and joint moment arms (Wickiewicz et al., 1983; Lieber and Ward, 2011).

2.3.1 Fiber Lengths

Biomechanical properties of the musculature that affect force production include the length-tension (force-length) relationship of contractile tissue. Gordon, Huxley, and Julian (1966) were the first to accurately measure the sarcomere length-tension relationship. They used frog tissue to show that a contractile unit operates by exhibiting a specified force based upon the length of the sarcomere. They identified an ascending limb, plateau region, and descending limb of this relationship (See Figure 2.2).
Figure 2.2 Force-length relationship demonstrating force on the y-axis (vertical) and sarcomere length on the x-axis (horizontal).

This force-length relationship has been analyzed in various muscles, activities, and movements since it was first introduced (e.g., Herzog, 1991; Ward et al., 2010). For joints that have multiple muscles crossing them, it is difficult to determine the individual muscle’s force-length relationships in vivo. Therefore, Herzog et al. (1991) examined the moment-length relationship of the rectus femoris in cyclists and speed skaters. Determining a moment-length relationship can be complicated, especially in bi-
articulate muscles such as the rectus femoris and hamstrings. When muscles cross multiple joints, the variation of joint positions must be controlled not only at the joint being examined but also at each joint in which the muscle crosses. For example, with the rectus femoris, the hip must be maintained in one position as the knee changes its position. In addition, rather than examine only individual muscles at a joint, one can analyze the combined moment of multiple structures produced at each joint angle, termed the moment-angle relationship. Several researchers have done this (e.g., Kulig et al., 1984; Jensen et al., 1971; Murray and Sepic, 1968) and will be discussed later. What was not determined in these assessments was the specific contribution of each muscle around that joint, such as bi-articular muscles compared with uniarticular muscles.

2.3.2 Physiological Cross-Sectional Area

Physiological cross-sectional area (PCSA) is an indicator of each muscle’s contribution to the joint moment. Lieber and Ward (2011) also reported that, in approximation, it is possible to estimate the maximum isometric force a muscle can generate by knowing its PCSA. Wickiewicz et al. (1983) were one of the first groups of researchers to examine PCSA. They measured the PCSA of the knee and ankle musculature of three human cadavers. PCSA was determined by multiplying muscle mass by cosine of the average pennation angle, divided by the product of muscle fiber length and muscle density. In essence, this determines the number of sarcomeres in parallel, and therefore relates directly to the amount of tension that can be produced (Wickiewicz et al., 1983). The researchers determined the soleus to have the highest PCSA of the muscles they examined; unfortunately, they did not examine hip musculature. Friederich and Brand (1990) then performed a similar analysis on the lower extremity musculature, including the hips, of two cadavers (37 year old male; 63 year old female). They found reasonable consistency between their PCSA’s and those of Wickiewicz et al. (1983), but did caution against using PCSA’s to predict individual muscle forces. Their reason was that muscle volume can be highly variable, so that estimations on a small sample size of cadavers will prove to be inaccurate. In addition, shrinkage
of muscle fibers occurs after removal, altering one of the main factors required to determine PCSA (Friedrich and Brand, 1990).

Ward et al. (2009) questioned the accuracy of the data from these previous skeletal architecture studies after disassembling 21 human lower extremities. Ward et al. (2009) found that besides the soleus muscle and the vastus lateralis, the GMed and the GMax had the next highest PCSA, respectively, of the lower extremity muscles (Table 2.1). This shows that, accordingly, the GMed and GMax have very high mechanical force producing capability in the lower extremity. The authors stated that the soleus, vastus lateralis, and GMed are likely the most important muscles acting at the ankle, knee, and hip, respectively, based on their high force-generating capacity. Lieber and Ward (2011) also reported that as a whole muscle group, the hip extensors had larger total PCSA’s compared with the flexors, abductors, and adductors. These findings additionally support the importance of hip extensors in their control of the lower extremity during dynamic activities, because there is a physiological purpose for that large amount of muscle tissue. Putting this into perspective, although considered one of the primary hip flexors, the PCSA is rather small for the psoas major and iliacus (7.7 cm$^2$ and 9.9 cm$^2$, respectively) (Ward et al., 2009). However, PCSA is not the only component of moment producing capability. Moment arm length can compensate for a low PCSA.

<table>
<thead>
<tr>
<th>Hip Muscle</th>
<th>PCSA (cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gluteus Medius</td>
<td>33.8 ± 14.4</td>
</tr>
<tr>
<td>Gluteus Maximus</td>
<td>33.4 ± 8.8</td>
</tr>
<tr>
<td>Iliacus</td>
<td>9.9 ± 3.4</td>
</tr>
<tr>
<td>Psoas major</td>
<td>7.7 ± 2.3</td>
</tr>
</tbody>
</table>
2.3.3 Muscle Moment Arms

Whereas PCSA is able to predict a muscle’s force producing capability, strength of a muscle or muscles about a joint is determined by the joint moment. The joint moment is calculated by the individual muscle’s force, determined either directly or indirectly, and multiplied by the muscle’s moment arm. Moment arms are determined by assuming a finite center of joint rotation, estimated from X-ray, computed tomography (CT), or magnetic resonance imaging (MRI), and measuring the perpendicular distance from the joint center to the line of action of the muscle (Pandy, 1999). There also exists a tendon excursion method, in which the change in length of the muscle-tendon unit is measured as a function of the joint angle, and the moment arm is determined by assessing the slope of the muscle length versus joint angle curve. However, these quantities can be difficult to interpret geometrically (Pandy, 1999).

Dostal and Andrews (1981) used a straight line action model of the hip musculature to determine moment arms of these muscles in three planes. Although muscles are not directly straight lines from origin to insertion, these researchers used a straight line model because of particular problems with broadly attaching muscles and unusual shapes. By determining a straight line, the moment arm vector can be determined in each plane, leading to an understanding of the moment generating capacity of muscles based on moment arms. Coupling this with PCSA, the moment generating capacity of a muscle is more accurately calculated.

Dostal et al. (1986) showed that the GMed had the largest moment arm of all the abductors, and GMax had the fourth largest moment arm for hip extension in the sagittal plane (after two hamstrings and the adductor magnus). This further supports the GMed and, to a slightly lesser degree, the GMax as having extremely high moment generating capability at the hip. Again, compared with the hip flexors, the iliopsoas (the combined insertion of the iliacus and psoas major) had 2.5 times a smaller moment arm than the GMax and almost 3 times a smaller moment arm than the GMed (Dostal et al., 1986).

It is imperative to understand hip musculature moment arms when related to individuals performing hip reconstructions. Delp and Maloney (1993) experimented by modeling variations in hip joint center locations thus altering the moment arms, and resultant joint moments, of surrounding
musculature. In their model, they translated the anatomical hip center in each direction up to 2 cm. The researchers found that displacement of the hip center along the superior-inferior axis had the greatest effect on muscle performance, with inferior displacement increasing the moment generating capacity (Delp and Maloney, 1993). Their data were based on moment arms computed from muscle attachment coordinates described by Brand et al. (1982).

Blazevich et al. (2009) examined 19 subjects and analyzed predictors of moment producing capacity about the knee joint. These researchers found that although moment arm is a significant factor of moment producing capacity, its prediction value was significantly lower than muscle volume. This was explained due to the low magnitude of variability of moment arms across subjects (Blazevich et al., 2009).

2.3.4 Estimation of Muscle Forces

Researchers often desire a quantification of muscular forces during functional movements. This is especially important clinically in the treatment, prevention, or enhancement of function. These muscle forces can be measured sometimes directly, in vivo, or more commonly indirectly, by using models for calculation.

Although techniques exist to measure force in vivo, they all involve invasive techniques (e.g., Gregor et al., 1991; Finni et al., 1998). The optic fiber technique was utilized by Finni et al. (1998) to measure in vivo muscular forces. The optic fiber technique is based on light intensity modulation when the fiber is compressed inside the tendon. In attempts to validate it by Erdemir et al. (2002), it was found to have total root-mean-square error of less than 32%, suggesting a limitation of this method. Finni et al. (1998) examined eight subjects and inserted the optic fiber through the skin and through the Achilles tendon.

Gregor et al. (1991) utilized a buckle-type force transducer that was surgically implanted on the Achilles tendon to accurately measure the force of the triceps surae muscle. The investigators demonstrated that direct force measurement was consistent with calculated force measurement by other
researchers. Although feasible, both Gregor et al. (1991) and Finni et al. (1998) used invasive techniques which can cause possible discomfort for subjects.

Every skeletal muscle has a certain architecture. Rather than expose human subjects to invasive techniques, muscle forces can be estimated using architectural information such as PCSA and moment arm data.

2.4 Joint Moment-Angle Relationship

Similar to the length-tension relationship, the moment-angle relationship can demonstrate all or portions of the parabolic like curve seen for the force-length properties of muscle fibers (Kulig et al., 1984). Kulig et al. (1984) reviewed five articles related to hip abduction, and all demonstrated, to some degree, descending moment-angle curves (Figure 2.3).
Figure 2.3 Human strength curves (moment-angle relationship) of hip abduction between -20° (adduction) to 60° (abduction) (Kulig, Andrews, and Hay, 1984)

-Note- the number on each line refers to:


Fewer articles were available for hip extension, but a descending only curve was found by Clark (1966), and an ascending-descending curve was found by Jensen et al. (1971). However, all of the articles examined only healthy adults. None of the articles compared moment-angle (strength) curves with variable positions of the knee. Additionally, no articles compared individuals with no pathology to moment-angle relationships in the presence of lower extremity pathology. This is a limitation of the extant literature.

2.4.1 Healthy Population

The work of Kulig et al. (1984) examined data from healthy subjects with no presence of pathology. With the use of computer modeling, Arnold et al. (2010) determined the maximum isometric joint moments, at various joints, as a function of joint angle by summing the moments generated by all muscles that could possibly contribute to a joint moment over a range of angles. They predicted a peak abduction moment of 127 Nm. This peak abduction moment was stated to occur “in the abducted position, which decreased…..with increasing adduction” (Arnold et al., 2010). This was a slight descending-ascending moment-angle curve. Conversely, experimental data from Neumann, Soderberg and Cook (1988) showed a descending only moment-angle relationship when tested, and is also in agreement with Kulig et al. (1984).

Explanations for these differences in moment-angle curves require explanation. The researchers in Arnold et al. (2010) made assumptions in their model and normalized the fiber lengths of the some of the muscles under investigation. For example, the gluteus medius measurement locations did not match the lines of action used in the model. Therefore, the average optimal fiber length and average pennation angle from the three measurements were used in each compartment (Arnold et al., 2010). This may explain some of the discrepancy between the modeling and experimental data.
2.4.2 Influence of Aging

In addition to pathology, age can also affect moment production at a joint. Alway et al. (1996) found that on average, older men (average age 62 ± 2 years) demonstrated 23% lower moment production of the plantarflexors than their younger counterparts (27 ± 2 years), regardless if they were untrained or endurance-trained. Similar changes were found in the peak isometric torque of the hip abductors (34% less) and hip adductors (24% less) of older females compared with younger females (Johnson et al., 2004). Interestingly, all muscles do not seem to be affected in the same fashion. Lanza et al. (2003) found that the concentric torque of the dorsiflexors of older healthy adults (72 ± 6 yrs) was 26% less than the young healthy adults (26 ± 5 yrs), whereas the knee extensors were affected differently throughout the aging process, with the knee extensors of the older group producing 32% less concentric torque than the younger subjects. The largest discrepancy in the knee extensors was at knee flexion angles greater than 90 degrees. This may be an important factor in the prevalence of hip muscle weakness as individuals age, with greater variability at higher ranges of motion, and alteration of the moment-angle curve.

2.4.3 Populations with Pathologies

A search of the current literature showed no examples of studies examining moment-angle relationships of hip musculature of individuals in the presence of knee pathology or ankle pathology. This confirms a gap in the current literature and solidifies a purpose for this dissertation (See Chapter 1).

2.5 Hip Musculature and Joint Pathologies

For many years researchers have been investigating the relationship between joints along a sequential chain. In the rehabilitation spectrum of patellofemoral pain (PFP), literature exists to support the treatment of the joint or segment displaying abnormal symptoms. Fagan and Delahunt (2008) found in a review of literature that quadriceps retraining is associated with good clinical outcomes for PFP. Although there have been case studies to support the strengthening of hip joint musculature, no randomized controlled trials are apparent (Fagan and Delahunt, 2008). Other researchers have
demonstrated that the hip has a relationship with Iliotibial band (ITB) pathologies at the knee (Fredericson et al., 2000) and with ankle sprains (Beckman and Buchanan, 1995).

2.5.1 Knee Joint Function

Individuals with PFP have shown to be at a very high probability of exhibiting weakness of the hip extensors and hip abductors (Powers, 2010; Souza and Powers, 2009). Powers (2010) described how the hip, being the proximal attachment site of the femur, directly affects the joint kinematics of the distal femur at the tibiofemoral joint, (i.e. the knee). Valgus is defined as a medial tibiofemoral angle of greater than 185 degrees. Dynamic knee valgus has been shown to contribute to numerous knee injuries, such as anterior cruciate ligament injury (Hewett et al., 2005) and patellofemoral joint dysfunction (Powers, 2003). Powers (2010) reported that hip adduction and internal rotation are the primary contributors to this valgus. The eccentric actions of the muscles which oppose these motions, the hip abductors and external rotators, are vital in stabilizing and controlling this motion. The largest, based on PCSA, of the hip abductors is the GMed (Ward et al., 2009), and the most potent external rotator, based on PCSA and moment arm, is the GMax, also a hip extensor (Delp et al., 1999).

Souza and Powers (2009) examined 41 females between 18 and 45 years old; 21 had a diagnosis of PFP, and 20 were age matched control subjects. Subjects underwent isometric moment assessment of the hip extensors and hip abductors. The researchers found, on average, a 16% decrease in hip extensor moment production of subjects with PFP. In addition, a 15% deficit was found in hip abductor strength of the PFP group compared with the control group. Interestingly, electromyography (EMG) data showed that subjects with PFP exhibited 91% greater GMax muscle activity during running than the control group. Souza and Powers (2009) explained this as PFP subjects attempting to recruit a weak muscle, and compensating with the attempt of motor recruitment. Their explanation was that the muscular recruitment was not a deficit, as evidenced by the high EMG data. The GMax simply did not have the moment producing capability through force generation. In other words, the GMax lacked the ability to generate muscle force. However, they observed no differences in GMed EMG between groups.
Another correlation between the hip and knee is found in individuals who have undergone knee surgeries. Subjects after having undergone total knee arthroplasties (TKA) have demonstrated weakness about the post-surgical hip joint compared with the uninvolved side. Piva et al. (2011) assessed 31 patients who had undergone a TKA between 2-6 months prior to testing. Patients’ hip abduction strength was tested isometrically for the involved lower extremity on an isokinetic dynamometer. Tests determined that hip abduction strength explained 22% and 17% of variance on a Figure-of-8 Walk Test and 5-Chair Rise Test, respectively. Also, the unique variance explained by hip abduction strength ranged from 3% to 22%. This was threefold higher than variance explained by quadriceps muscle strength, indicating that following TKA, hip abduction weakness contributes to functional limitations over quadriceps strength (Piva et al., 2011).

Iliotibial band syndrome is another knee pathology that has been correlated with hip weakness (Fredericson et al., 2000). In Fredericson’s study, 24 distance runners with history and physical examination findings typical for Iliotibial Band syndrome (ITBS) and 30 distance runners with no symptoms were examined. Hip abductor moment was measured with a Nicholas Manual Muscle Tester. Following a 6-week program of rehabilitation focused on hip abductor strengthening, 22 of 24 athletes were painfree, and hip abductor moment increased 34.9% in the females’ injured limbs and 51.4% in the males’ injured limbs. The researchers demonstrated there was a significant correlation between ITBS and hip abductor weakness.

Brindle et al. (2003) looked at electromyographic (EMG) changes in the GMed during stair ascent in subjects with anterior knee pain. The subjects were 16 individuals who had had generalized anterior knee pain for at least 2 months. Twelve age-matched asymptomatic individuals served as the control group. Surface EMG data were collected from the vastus medialis oblique (VMO), vastus lateralis (VL), and GMed. Subjects then ascended and descended a set of five stairs. After analysis, the researchers found a later onset of GMed EMG during stair ascent and a shorter duration of activity than control subjects. They concluded that significant temporal differences existed, in particular delayed onset
and diminished duration, in lower extremity firing patterns of the GMed in subjects with anterior knee pain compared with a control group without knee pain.

Cowan et al. (2009) also showed altered EMG patterns and delayed GMed recruitment in individuals with diagnosed PFP. They had 10 PFP subjects and 27 asymptomatic controls. EMG activity of the VMO, VL, anterior GMed, and posterior GMed were recorded, in addition to strength measures made using handheld dynamometry. Although the results showed no difference in strength of the hip abductors and external rotators between groups, as Souza and Powers (2009) found, there was a delayed onset in both the anterior and posterior portions of the GMed in PFP subjects compared to the control group. The researchers supposed that PFP issues are of a neuromotor (See 2.6 Force fluctuations) cause of the hip abductors compared with hip abduction or external rotation strength.

2.5.2 Ankle Joint Function

Although more distal than the knee, the ankle is a component of the kinematic chain. Friel et al. (2006) examined the relationship of hip abductor strength to chronic ankle sprains. Twenty-three individuals, with a minimum of two ipsilateral ankle sprains and no injury occurring within three months of the assessment, participated in the study. The researchers found decreased hip abduction strength on the involved sides, indicating a possible relationship between ankle instability and hip control in the frontal plane. There was no significant difference in hip extensor strength between sides.

A similarly altered pattern of GMed recruitment in the presence of knee pathology has also been shown with ankle hypermobility (Beckman and Buchanan, 1995). Subjects, having either normal or hypermobility of the ankle, were asked to stand on a platform such that either ankle could be instantaneously inverted. EMG signals of each GMed were recorded. Significant EMG latency differences were found in the hypermobile ankle’s ipsilateral GMed when the ankle was perturbated. These data suggest altered hip muscle recruitment patterns exist when distal joints (i.e. ankle) lack sufficient stabilization.
2.5.3 Contrary Findings

Although considerable evidence exists supporting the relationship between hip muscle deficits and lower extremity pathology, there are some who have found the contrary. Piva et al. (2005) found no difference in hip external rotator strength or hip abductor strength in patellofemoral subjects and controls. The researchers looked at 30 subjects with PFP and compared them to 30 age and gender-matched controls without PFP. Strength was measured with hand-held dynamometry for abduction and external rotation. Their results showed no difference in the strength of hip abduction or external rotation between subjects with PFP and those without. This is in contradiction to the findings of Souza and Powers (2009).

Thijs et al. (2011) showed that hip abductor strength was not a predictor of patellofemoral pain in recreational runners, and questioned whether hip muscle weakness is a consequence of lower extremity pathologies rather than a cause. The researchers in this study examined the isometric hip strength of 77 novice female runners using a handheld dynamometer. Following the initiation of a 10-week running program, an orthopaedic surgeon diagnosed and registered musculoskeletal injuries of the lower extremities. Results showed PFP was diagnosed in 17 of the 77 runners. The researchers found and reported that none of the different hip muscle groups of the female runners who developed PFP differed significantly from those who did not develop symptoms. Based upon this, they could not conclude that decreased muscle strength of the hip musculature predisposes people to patellofemoral symptoms. It was proposed that the neuromuscular control of the hip musculature, rather than hip muscle strength, might be a predisposing factor for PFP. An interesting note is that both Piva et al. (2005) and Thijs et al. (2011) used handheld dynamometers rather than the isokinetic dynamometers used by Souza and Powers (2009) and Piva et al. (2011). Hand held dynamometers are less accurate than isokinetic dynamometers (Surburg et al., 1992).

2.6 Force Fluctuation

In addition to peak isometric moment as a measure of muscle performance, the fluctuation of moment during an isometric contraction has also been proposed to identify possible differences and
deficits in muscle performance. Enoka et al. (2003) stated that muscle forces always fluctuate about an average value when subjects perform “steady” contractions. Although older adults frequently have greater force fluctuations than young subjects during submaximal contractions, Enoka et al. (2003) suggested it is due to the force capacity of muscle and variability of motor unit discharge. Hamilton et al. (2004) examined this concept of muscle moment as related to motor unit recruitment as well. They found that stronger, more proximal joints in the human arm had lower levels of motor noise than weaker more distal joints. If this experimental finding is found in the lower extremity, the hip musculature should then show less force fluctuation than that found about the joints of the distal lower extremity. No literature has been found which examined the force fluctuation of the hip abductors or hip extensors although Hyngstrom et al. (2011) did examine the neuromuscular fatigue of the hip flexors in patients with strokes.

2.6.1 Quantifying Force Fluctuations

A difficulty with muscle force or joint moment fluctuation is to quantify it over a time series. Approximate entropy was proposed as a regularity statistic for medical data in 1991 (Pincus, 1991). Since then it has been utilized in various manners such as cardiovascular regularity (Richman and Moorman, 2000) and isometric moment regularity (Challis, 2006). Signal regularity has been examined comparing isometric muscle actions of the plantarflexors in old and young subjects (Challis, 2006). However, no studies to date have examined either the signal regularity of the hip musculature of individuals or the signal regularity of proximal joint muscles in individuals with current lower extremity pathology.

2.6.2 Sources of Fluctuations

Research has shown that the hip muscle deficits may be not simply the mechanical producing capacity of the musculature but also the neurological system’s control (Brindle et al., 2003; Cowan et al., 2009). The nervous system has two means by which it can vary the force exerted by skeletal muscle: by
altering the number of motor units that are active (termed motor recruitment), and by modulating the rate of action-potential impulses (termed rate coding) (Fuglevand et al., 1993).

Tracy et al. (2007) investigated the force variability of the first dorsal interosseous muscle, the elbow flexors, and the knee extensors. Their results showed lower fluctuations in muscles with large motor unit pools (elbow flexors, knee extensors) compared with the first dorsal interosseous. However, the authors also noted that the relative strength of a muscle is not a consistent predictor of the force fluctuations it will exhibit (Tracy et al., 2007). This explains how strength (moment) of hip musculature may not be the sole deficit seen in a pathological population.

2.6.3 Muscle Force Fluctuations in Special Populations

Hortobagyi et al. (2004) examined quadriceps muscle force in patients with knee osteoarthritis (OA). They used age matched controls to compare subjects with knee OA to those without. Their data showed 155% greater variation in producing force smoothly by the subjects with OA compared with the healthy subjects. Their data also suggested that the impaired ability to control force was not the result of reduced maximal quadriceps’ strength.

Subjects showing symptoms of subacromial impingement syndrome were compared with healthy controls in a study by Bandholm et al. (2006). The researchers examined the isometric steadiness of the shoulder abductors at ninety degrees. Data showed no between-group differences in steadiness at three target force levels, differing from the authors’ hypothesis (Bandholm et al., 2006). However, both of the articles, Hortobagyi et al. (2004) and Bandholm et al. (2006), were examining the specific joint in which the pathology was present. None to date have examined the force fluctuation of a joint proximal to the involvement.

2.7 Summary

In summary, there is a relationship between deficits in hip musculature and pathologies of the distal joints (knee and ankle) of the lower extremity. Many researchers have shown decreased hip muscle
strength in the presence of knee or ankle joint pathology. However, it remains unclear whether these deficits originate in the properties of the muscle, or have a neuromuscular origin, or both. It is also unclear whether the normal peak moment-angle relationship of the hip complex is simply decreased in the presence of this pathology, or whether the relationship, or shape of the moment-angle curve, is altered completely. By identifying these unknowns, rehabilitation can be more specific and effective to address either strength, neuromuscular control, or both.

2.8 References

Alway, SE; Coggan AR; Sproul MS; Abduljalil AM; Robitaille PM. (1996). Muscle torque in young and older untrained and endurance-trained men. *The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences*, 51; 195-201.


Brand, RA; Crowninshield, RD; Wittstock, CE; Pedersen, DR; Clark, CR. (1982). A model of lower extremity muscular anatomy. *Journal of Biomechanics*, 104; 304-310.


Johnson, ME; Mille, ML; Martinez, KM; Crombie, G; Rogers, MW. (2004). Age-related changes in hip abductor and adductor joint torques. *Archives of Physical Medicine and Rehabilitation*, 85; 593-597.


Chapter 3

Moment-Angle Properties of the Hip Musculature

3.1 Abstract

Understanding the strength curve of a particular joint is vital in its efficient rehabilitation. In particular, the hip joint has been the focus of much research. The musculature of the hip joint, especially the hip abductors and hip extensors, has shown to correlate to the presence of patellofemoral syndrome in addition to other knee and ankle pathologies. Strength curves for these hip motions have not been assessed when varying the position of the knee. Bi-articular muscles which cross the hip and the knee can be affected, through their force-length properties, when altering the position of the knee (0° and 90°) during hip motions. Maximum isometric moments were measured at four different angles of hip abduction and hip extension, at the two knee positions. It was shown that both hip abduction and hip extension strength curves operate on a descending curve. The position of the knee did not cause a statistically significant change in the gradient of the moment-angle curve for either hip abduction or extension. The results indicate that position of the knee for hip abduction does not significantly change the normalized peak moment, but the position of the knee for hip extension does significantly change the normalized peak moment. This demonstrates that the bi-articular muscles of the hip complex make a significant contribution during hip extension. However, the motion of hip abduction is primarily produced by uniarticular muscles and is not significantly affected by knee position. This provides a baseline reference of hip moment production, and can be utilized when assessing a population with a pathology.

3.2 Introduction

Muscle strength is a determinant of human movement in both health and disease. Strength can be defined in many ways (e.g., Chaffin et al., 2006), where the joint positioning and joint angular velocity
can all influence the quantification of strength. Assessing the peak moment at a joint under static (isometric) conditions at a single joint angle ignores the fact that as joint angles vary, so can the peak moment. To understand the strength capability at a joint, we need to consider the moment producing capabilities at a joint for the range of joint angles and, ideally, for a range of joint angular velocities.

One simple way of describing joint strength is to assess the peak isometric joint moment across the range of the joint’s motion; this is termed the moment-angle relationship or the strength curve. Kulig et al. (1984) reported moment-angle relationships for many human joints. Numerous factors contribute to the net moment created at a joint. These factors include the physiological cross sectional area (PCSA) of the muscles, the individual moment arms of the muscles, and the position of each active muscle on its force-length curve. In addition, it relies on the ability of subjects to maximally activate their muscles, and decrease the activation of the relevant antagonist muscles. For most joints the difficulty with assessing these strength curves is further compounded by the presence of bi-articular muscles. For example, as well as the hamstring muscles, the bi-articular gastrocnemius is also a contributor to knee flexion (Galucci and Challis, 2002). Therefore, when assessing the strength-curve at a joint, the measured joint can be influenced by the angle of an adjacent joint, as this joint angle influences where on its force-length curve the bi-articular muscles operate and thus the moment it can contribute to the joint under investigation.

A common diagnosis involving strength deficits is patellofemoral syndrome (Souza and Powers, 2009; Brindle et al., 2003). Patellofemoral syndrome is a clinical condition that is characterized by retropatellar and/or peripatellar pain associated with activities involving lower limb loading (e.g., walking, running, jumping, stair climbing, and prolonged sitting and kneeling) (Davis and Powers, 2010). Several researchers have reported a correlation between hip muscle deficits and patellofemoral syndrome (Powers, 2010; Souza and Powers, 2009; Brindle et al., 2003; Cowan et al., 2009), but correlation does not necessarily mean causation. Some researchers have questioned whether patellofemoral syndrome is actually caused by weakness in hip musculature, or alternatively, if patellofemoral syndrome causes impaired lower extremity kinematics and kinetics, leading to weakness in the hip musculature (Davis and Powers, 2010; Thijs et al., 2011). By understanding the strength curves of the hip musculature,
researchers might gain greater insight into their potential role in patellofemoral syndrome. The hip musculature features a number of bi-articular muscles; for hip abduction these include the tensor fascia latae and sartorius, and for hip extension these include the biceps femoris, semitendinosus, and semimembranosus (i.e., hamstrings). Therefore, while research does exist examining the strength curves for hip abduction and hip extension (Murray and Sepic, 1968; Kulig et al., 1984; Neumann et al., 1988), no research to date has accounted for the potential influence of these bi-articular muscles. Yet many rehabilitation exercises for the hip abductors or hip extensors vary the position of the knee anywhere from full extension (0°) to flexion (90°) (DiStefano et al., 2009).

The purpose of this study was to assess the strength curves for hip abduction and hip extension, with two knee positions: 0° (fully extended), and 90° (of flexion), thus systematically changing the contribution of the bi-articular hip musculature. Although the hip musculature has been implicated in patellofemoral syndrome, this study was designed to assess hip musculature strength curves in a healthy population to provide a point of comparison for data from subjects with patellofemoral syndrome. It is hypothesized that the peak moments of hip abduction and extension will not vary significantly between the two knee positions of 0° and 90°; in addition, the gradient (curve) for both hip abduction and hip extension will not vary significantly between the two knee positions of 0° and 90°.

### 3.3 Methods

In overview, subjects were recruited and their strength curves assessed for hip abduction and hip extension using a Biodex dynamometer.

### 3.3.1 Subjects

Subjects between the ages of 18-64 years of age were recruited to participate in this study. The procedures and protocols in this study were approved by the institutional review boards of the Pennsylvania State University and of Saint Francis University. Potential subjects had to be free from any
hip, knee, or ankle pathology and pain. Volunteers were assessed for their lower limb joint health (Appendix A), and a general screen of the joints of their lower extremity was performed by a licensed Physical Therapist. Subjects who successfully completed this screening came to the laboratory, provided informed consent (Appendix B), and had their height and mass measured. The eventual subject pool consisted of twenty-one subjects (11 females, 10 males: age, 33.9 ± 14.9 years old; height, 170.6 ± 9.2 cm; mass, 80.3 ± 22.6 kg).

3.3.2 Subject Testing

On the day of strength testing all subjects had their hip, knee, and ankle joint ranges of motion (Table 3.1) measured by a licensed Physical Therapist using a goniometer (Sammons Preston EZ Read Goniometer, model #7514). Then they warmed-up on a recumbent stationery bike at a self-selected speed for five minutes. Strength curves were assessed for hip abduction and hip extension using a Biodex dynamometer (Biodex 4 Systems Pro, Biodex Medical Systems, Shirley, NY). For both sets of strength curves the subjects were instructed to maximally attempt to lift the lower extremity against isometric resistance. The time to ramp up and hold their effort was 10 seconds. For both strength curves eight conditions (sets of hip and knee joint angles) were examined with one trial at each condition, and 30 seconds of rest between trials. The peak moment was measured for each trial.
Table 3.1: Table of measured joint motions with a standard goniometer (Norkin and White, 2009).

<table>
<thead>
<tr>
<th>Motion</th>
<th>Position</th>
<th>Image</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip Extension</td>
<td>Prone</td>
<td><img src="image1" alt="Image of Hip Extension in Prone Position" /></td>
</tr>
<tr>
<td>Hip Abduction</td>
<td>Supine</td>
<td><img src="image2" alt="Image of Hip Abduction in Supine Position" /></td>
</tr>
<tr>
<td>Knee Flexion/Extension (Full extension = 0°)</td>
<td>Supine</td>
<td><img src="image3" alt="Image of Knee Flexion/Extension in Supine Position" /></td>
</tr>
<tr>
<td>Ankle Dorsiflexion (Knee flexed to 90°)</td>
<td>Seated</td>
<td><img src="image4" alt="Image of Ankle Dorsiflexion in Seated Position" /></td>
</tr>
<tr>
<td>Ankle Dorsiflexion (Knee extended)</td>
<td>Supine</td>
<td><img src="image5" alt="Image of Ankle Dorsiflexion in Supine Position" /></td>
</tr>
</tbody>
</table>
For the assessment of the hip abduction strength curve, the subjects adopted a side-lying posture (Piva, 2011). In this posture the subjects lay on their side facing the dynamometer (Figure 3.1). The dynamometer axis of rotation was aligned with the subject’s superior hip joint (just inferior to the anterior superior iliac spine). The resistance arm pad was positioned on the lateral thigh of the superior lower extremity approximately 3 cm above the lateral femoral epicondyle. The contralateral lower extremity was flexed at the knee for comfort and stability. The angles analyzed for hip abduction were: -15° (15° of adduction), 0°, 15° (pictured in Figure 3.1), and 30°, with two knee angles used 0° and 90°.

**Figure 3.1:** Subject is right side-lying performing isometric left hip abduction with the knee flexed to 90°. Left hip is in 15° of abduction.

For the assessment of the hip extension strength curve the subjects adopted a prone position (Souza and Powers, 2009). In this position the subjects were positioned standing but flexed at the waist
over the seat of the dynamometer (Figure 3.2). The axis of the dynamometer was aligned with the subject’s greater trochanter, and the resistance arm pad was positioned over the posterior aspect of the distal femur just proximal to the popliteal fossa. The contralateral lower extremity was allowed to contact the floor for support. The angles analyzed for hip extension were: -45° (hip flexion), -30°, -15°, and 0° (neutral) (pictured in Figure 3.2), with two different knee angles (0° and 90°).

**Figure 3.2:** Subject is prone-lying and performing left isometric hip extension with the knee extended. Left hip is in 0° (neutral) position.

### 3.3.3 Data Analysis

For each subject the joint range of motion and the peak isometric moments measured under a variety of hip and knee angles were determined. The moment data were normalized with respect to each subject’s body weight. Basic descriptive statistics were determined for these metrics (See Appendix C). To quantify the shape of the strength curves, least-squares polynomials were fitted to the angle
normalized moment data. The degree of the polynomial used to represent these data was selected based on the residual between the fit and the actual data. To compare between the gradient of the strength curves with the knee in different positions paired t-tests were performed. This was done because the only condition that changed was the knee position from one test to another. Repeat measures analysis of variance was performed on normalized moment data for both hip abduction and hip extension with the knee flexed and extended. Post-hoc pair wise comparisons were performed using the Tukey method. A p-value less than 0.05 was used to assess statistical significance. All statistical analyses were performed in Minitab 15 (Minitab Inc., State College).

3.4 Results

All subjects had joint ranges of motion that exceeded those required experimentally during the strength testing. The joint ranges of motion were statistically different between the male and female subjects except for dorsiflexion angle with the knee extended (Table 3.2).

<table>
<thead>
<tr>
<th>Table 3.2:</th>
<th>The means (± standard deviation) of the joint ranges of motion for the whole subject group, and the male and female sub-groups.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All subjects (n= 21)</td>
</tr>
<tr>
<td><strong>Hip</strong></td>
<td></td>
</tr>
<tr>
<td>Extension</td>
<td>30.3° ± 3.8</td>
</tr>
<tr>
<td>Abduction</td>
<td>43.2° ± 4.3</td>
</tr>
<tr>
<td><strong>Knee</strong></td>
<td></td>
</tr>
<tr>
<td>Flexion</td>
<td>140.3° ± 6.4</td>
</tr>
<tr>
<td>Extension</td>
<td>3.1° ± 3.8</td>
</tr>
<tr>
<td><strong>Ankle</strong></td>
<td></td>
</tr>
<tr>
<td>Dorsiflexion-Knee flexed</td>
<td>16.9° ± 4.2</td>
</tr>
<tr>
<td>Dorsiflexion- Knee extended</td>
<td>12.5° ± 3.3</td>
</tr>
</tbody>
</table>
There were no statistically significant differences between the moment data for the left and the right hip, therefore the data for each subject was averaged across limbs. Once the moment data had been normalized with respect to body mass there were no statistically significant differences between conditions for the male and female data, therefore these data are considered as one group. Results separated by sex are presented in Appendix D.

There were no statistically significant differences between the knee extended and knee flexed positions for hip abduction; therefore, trends will be outlined (Table 3.3). The highest peak moment/body weight (BW) for hip abduction with the knee extended across all subjects occurred at the -15° abduction position (15° of adduction), with 40 out of 42 measures occurring at this position. However, this angle moved closer to neutral (more abducted) when the knee was in a position of flexion (90°), with only 35 of the 42 measures occurring at -15°. The gradient of the relationship between angle-hip abduction-resultant joint moment was negative for all subjects, but had a steeper slope when the knee was flexed (Figure 3.3).

**Table 3.3:** The means (± standard deviation) of the peak hip abduction moment and the angle at which it occurred for the whole subject group. In addition the gradient of the line of the joint angle-moment relationship is reported.

<table>
<thead>
<tr>
<th>Hip Abduction</th>
<th>Knee Extended</th>
<th>Knee Flexed</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Moment (N.m)</td>
<td>113.6 ± 33.0</td>
<td>110.0 ± 33.5</td>
<td>0.547</td>
</tr>
<tr>
<td>Peak Moment (N.m/BW)</td>
<td>0.15 ± 0.04</td>
<td>0.14 ± 0.04</td>
<td>0.531</td>
</tr>
<tr>
<td>Angle of Peak Moment (degrees)</td>
<td>-14.3 ± 3.27</td>
<td>-12.5 ± 4.9</td>
<td>0.056</td>
</tr>
<tr>
<td>Gradient of Angle-Moment Relationship ( (N.m/BW)/degree )</td>
<td>-0.0014 ± 0.00051</td>
<td>-0.0012 ± 0.00064</td>
<td>0.088</td>
</tr>
</tbody>
</table>
Figure 3.3: Linear regression of the moment-angle relationship of hip abduction. Solid line represents hip abduction with the knee extended. Dashed line represents hip abduction with the knee flexed 90°.

The highest peak moment/body weight (BW) for hip extension with the knee extended occurred at the -45° position (45° of hip flexion) (Table 3.4), with 39 out of the 42 peak moments occurring at that angle. Three of the 42 measurements had a peak moment at the -30° position. This changed when the knee was in a position of flexion (90°). Only 32 of the 42 measurements demonstrated a peak moment at the -45° position, whereas 9 of the 42 occurred at -30° and even one occurred at the -15° position. The normalized peak moments were significantly different between the knee extended and flexed condition. Analysis of variance using a pair wise comparison (Tukey) showed a significant difference of normalized peak moment at each pair of joint angles (-45°, -30°, -15°, 0°) of hip extension. The gradient of the relationship between angle-hip extension-resultant joint moment was negative for all subjects, but had a
A steeper slope when the knee was flexed (Figure 3.4). However, this difference was not statistically significant.

Table 3.4: The means ($\pm$ standard deviation) of the peak hip extension moment and the angle at which it occurred for the whole subject group. In addition the gradient of the line of the joint angle-moment relationship is reported.

<table>
<thead>
<tr>
<th>Hip Extension</th>
<th>Knee Extended</th>
<th>Knee Flexed</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Moment (N.m)</td>
<td>165.1 ± 61.7</td>
<td>140.6 ± 49.0</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Peak Moment (N.m/BW)</td>
<td>0.22 ± 0.072</td>
<td>0.19 ± 0.060</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Angle of Peak Moment (degrees)</td>
<td>-43.9 ± 2.69</td>
<td>-41.1 ± 6.1</td>
<td>0.029</td>
</tr>
<tr>
<td>Gradient of Angle-Moment Relationship ( (N.m/BW)/degree )</td>
<td>-0.0020 ± 0.00086</td>
<td>-0.0017 ± 0.00099</td>
<td>0.073</td>
</tr>
</tbody>
</table>
Figure 3.4: Linear regression of the moment-angle relationship of hip extension. Solid line represents hip extension with the knee extended. Dashed line represents hip extension with the knee flexed 90°.

3.5 Discussion

The relationship between hip abduction angle and the maximum moment was investigated; the results demonstrated a descending moment-angle relationship (negative gradient) with increasing hip abduction angle. The tensor fasciae latae and sartorius are hip abductors which cross the knee joint (Flack et al., 2012); therefore by flexing the knee the length of these muscles would presumably change and therefore change their position on the force-length curve. Such a change could influence the net moment at the hip joint to abduct. The study did not find a change in the magnitude of the moments or the gradient of the curve describing the strength curve during hip abduction with the knee extended compared with the knee flexed, suggesting any changes in position on the force-length curve of the multi-articular
muscles which cross both the hip and knee and contribute to the hip abduction moment were small. Therefore, the hypothesis that there is a difference between the peak moments during abduction with the knee in different positions, evaluated by comparing the gradient of the moment-angle curves, was rejected. The nature of the obtained curves was in agreement with the work of Neumann et al. (1988), although they only tested their subjects with the knee in an extended position. The model of Arnold et al. (2010) predicted a more level strength curve, which is therefore at variance with experimental data; indeed none of the curves, including those in Neumann et al. (1988), Kulig et al. (1984), or the present study were a close match for the theoretical curve of Arnold et al. (2010).

The relationship between hip extension angle and the maximum moment was investigated; the results demonstrated a descending moment-angle relationship (negative gradient) with increasing hip extension angle. The curves in the present study were in accordance with those reported by Kulig et al. (1984). This study did not find a statistically significant difference between moment-angle relationship gradients (curve) between positions of the knee (0° and 90°) with hip extension. However, the magnitudes of the normalized peak moments were greater when the knee was in the extended position than the flexed position. The overall results lead to a rejection of the hypothesis that the hip extension moment-angle relationships would be significantly different with the knee flexed and extended.

There are bi-articular hamstring muscles (biceps femoris, semitendinosus, and semimembranosus) which are capable of producing a hip extension moment that also cross the knee. By changing the knee angle, the lengths of these muscles will change and therefore their relative position on their force-length curves, and thus the net joint moment. The greatest hip extension moment for the entire group was produced at an average of 43.9° of hip flexion when the knee was extended, and 41.1° when the knee was flexed.

It is feasible that the subjects did not have their joint center appropriately aligned with the axis of the rotation of the dynamometer, but such differences would have been consistent across conditions, so
should not have influenced the evaluation of the hypotheses. An additional concern is that the subjects did not provide maximum effort on all trials. To obviate the effect of varying effort on each trial, the order of the presentation of conditions was randomized and the subjects were given verbal encouragement on all trials. Finally, it should be acknowledged that these subjects were relatively young and healthy so it may not be possible to generalize these results to older and or diseased populations. Future studies will examine these curves in subjects with knee pain; in addition the steadiness of the force production will also be investigated. By investigating the force fluctuations, some aspects of the neurological component of the neuromuscular unit can be assessed.

Measurement of peak moment does not necessarily correlate to functional use of the same musculature. For example, Lyons et al. (1983) found that for the hip abductors and hip extensors, peak EMG activity was about 30% maximum during normal gait. In addition, although the deficit of the musculature assumed to contribute to patellofemoral syndrome exists when operating in closed chain, isokinetic dynamometry involves testing the musculature in an open chained position. However, no procedures exist to test joint moments in a closed chain manner.

The slope and direction of moment-angle curves have great clinical relevance to muscle strengthening and, in turn, to rehabilitation. In order to effectively strengthen musculature, the moment of resistance must be matched to the moment of effort (joint moment). With the current findings of the descending curve of hip abduction and hip extension, the moment of resistance (i.e., exercise resistance) should also occur in a descending gradient (slope). In other words, the greatest resistance moment should be provided at initiation of abduction with a gradual decrease throughout the joint motion. Ironically, one of the popular hip abduction exercises, clamshells (See Appendix D), displays the inverse of these moments. In brief the clamshell exercise involves an individual lying on their side with a resistance band wrapped around both knees. The individual then lifts the superior lower extremity away from the inferior one (hip abduction and external rotation). As this exercise utilizes a Thera-Band®, or equivalent elasticated band, its elastic properties mean the the force of resistance increases as the individual moves
through the range of motion, thus increasing the resistance moment (Figure 3.5). While using these bands, the moment arm of the force will change through the range of motion. This change in moment arm would not be sufficient to change the gradient of the resistance to provide a closer match to the strength curve seen in this muscle group.

![Plot of tension relative to change in length of a green Theraband®.](image)

**Figure 3.5:** Plot of tension relative to change in length of a green Theraband®. (Based on data from Page et al., 2000.)

Theoretically, this exercise would either underwhelm the moment of the abductors at the beginning of the exercise, or overwhelm them toward the end range of the exercise, causing the individual to not be able to complete the movement. Potentially a better exercise for the hip abductors would be basic isometrics at multiple angles, or sidelying hip abduction using the weight of the limb as resistance or, if additional load was required, a weight cuff at the ankle joint (Figure 3.6).
Figure 3.6 Calculated moment–angle relationship of sidelying hip abduction based on average segment weight (N) and center of mass (m) location. Anthropometric data were calculated utilizing the data of Winter (1990). This resistance moment-angle gradient (strength curve) more closely resembles the one found in this study.

This study has identified that both the hip abduction and hip extension strength curves have descending moment-angle slopes, regardless of the position of the knee. Flexion of the knee does change the moment producing capability (magnitude) of the hip extensors, but not the hip abductors. Strength curves are important to understanding muscle function in vivo, and for designing effective strengthening protocols. The data presented here provide a useful comparison with the strength curves obtained from individuals with clinical conditions – such as patellofemoral syndrome. Reports have linked patellofemoral syndrome with hip muscular disfunction (e.g., Davis and Powers, 2010; Tijs et al., 2011). One candidate would be the multi-articular muscles which cross both the hip and knee joints. The experimental data presented in this study show different contributions of the multi-articular muscles for
hip abduction and extension, and it would be interesting to see if those with patellofemoral syndrome have similar differences.

3.6 References


Chapter 4

Moment-Angle Relationship of the Hip Abductors and the Hip Extensors in Patello-femoral Subjects

4.1 Abstract

Strength deficits of hip abduction and hip extension in individuals with patellofemoral syndrome are commonly reported in the literature. No literature to date has examined these deficits with variable positions of the knee, altering the length and therefore potentially the force produced by the biarticular muscles. In addition, strength curves have been reported for hip joint moments for abduction and extension, but not for individuals in the presence of patellofemoral syndrome. Subjects consisted of a group of individuals with signs and symptoms of patellofemoral syndrome (n=9), and a group of age and size matched controls with no symptoms (n=9). Maximum isometric joint moments for hip abduction and hip extension were measured at four points within the joint’s range of motion, at two different knee positions (0° and 90°) for each group. The results indicate that no significant differences were found between the groups of subjects for the hip abduction moments with either knee position or the joint moments of hip extension with the knee extended (0°). However, there was a significant difference between the groups for the joint moments of hip extension with the knee flexed. This demonstrates that individuals with patellofemoral syndrome either have less gluteus maximus strength (hip extension with knee flexed) than age and size matched controls, or individuals with patellofemoral syndrome have increased hamstring strength compared with age and size matched controls. No differences were found in strength curves between the two groups for any configurations, indicating that in the presence of patellofemoral syndrome, strength deficits are uniform throughout the entire joint range of motion. This supports rehabilitation of this syndrome by strengthening the entire joint range of motion (hip extension).

4.2 Introduction

Patellofemoral syndrome is a clinical condition that is characterized by retropatellar and/or peripatellar pain associated with activities involving lower limb loading, such as walking, running,
jumping, stair climbing, and prolonged sitting and kneeling (Davis and Powers, 2010). Patellofemoral syndrome has been reported as the most frequently diagnosed condition in adolescents and adults with knee complaints (Lankhorst et al., 2013). For example, in a group of adolescent female athletes, 26.6% reported incidence of patellofemoral syndrome (Barber Foss et al., 2012). Despite its prevalence the cause(s) of patellofemoral syndrome are still not clear.

Patellar malalignment and/or abnormal patellar tracking is thought to be one of the primary precursors of patellofemoral joint pathology (Powers, 2003). It has been theorized that patellofemoral joint dysfunction may arise due to aspects of hip joint control and the manner in which it influences the knee (Souza and Powers, 2009). Powers et al. (2003) found that individuals with documented patellar subluxations had increased femoral internal rotation in weight-bearing positions. Souza and Powers (2009) determined that individuals with patellofemoral syndrome exhibited increased femoral internal rotation compared with a symptom-free control group. This data suggests that abnormal patellofemoral kinematics could be as much a result of aberrant femoral movement as patellar movement, and therefore be due to, at least in part, poor hip control.

Femoral movements that have been found to contribute to patellofemoral syndrome are hip adduction and hip internal rotation (Powers, 2010). These motions are opposed by the actions of the hip abductors and hip external rotators when acting eccentrically. In a systematic review, Prins and van der Wurff (2009) found strong evidence for a decrease in hip external rotation and abduction strength, in addition to a decrease in hip extension strength, in females with patellofemoral syndrome compared with healthy controls.

The inclusion of hip extension strength in the deficient muscle groups may not be initially clear. It is commonly accepted that the hip external rotators prevent the femur from internally rotating. However, the gluteus maximus, a potent external rotator of the hip (Delp et al., 1999), is also the chief extensor of the hip (Neumann, 2010). Therefore, if the gluteus maximus lacks moment producing capacity for hip extension, it will contribute to similar weakness during hip external rotation. This
explains the inclusion of the examination of hip extension strength in subjects with patellofemoral syndrome.

Research has shown the hip musculature to be deficient in individuals exhibiting signs and symptoms of patellofemoral syndrome (Powers, 2010; Souza and Powers, 2009; Brindle et al. 2003; Cowan et al. 2009). However, the precise nature of this weakness has yet to be identified. Is this an overall reduction in the mechanical force producing capacity of the muscles? Is it a change in the muscle properties which results in changes in the force the muscles can produce at certain lengths? Or is it a deficit in the neuromuscular control of the femur and/or patella during functional activities?

Joint moment-angle relationships, or strength curves, define the magnitude of the moment at a joint throughout an arc of joint motion. To date no reports in the literature have examined the moment-angle relationship of hip musculature in the presence of knee pathology such as patellofemoral syndrome. Such an analysis may provide insights into the etiology of patellofemoral syndrome.

The purpose of this study was to examine the moment-angle relationship of hip musculature of subjects with patellofemoral syndrome and compare it with those subjects with no known pathology. The hypotheses of this study are:

**Hypothesis I** – subjects with patellofemoral syndrome will have weaker strength curves, demonstrated by a decrease in magnitude in their normalized peak moments, compared with healthy controls.

**Hypothesis II** – subjects with patellofemoral syndrome will have different shaped strength curves compared with healthy controls.

Increased knowledge of the strength curves of hip musculature in a subject population with pathology will aid in determination of the cause of the pathology. In addition, this information will assist in more efficient rehabilitation of any deficits and also contribute to possible preventative measures. For example, if it is found that the hip musculature tends to be deficient near the joint’s beginning range (longer muscle lengths), then that particular joint position could be the focus of rehabilitation.
4.3 Methods

In overview, subjects, both with signs and symptoms of patellofemoral syndrome, and without signs and symptoms of patellofemoral syndrome, were recruited and their strength curves assessed for hip abduction and hip extension using a Biodex dynamometer.

4.3.1 Subjects

Subjects between the ages of 18-64 years of age were recruited to participate in this study. The procedures and protocols in this study were approved by the institutional review boards of the Pennsylvania State University and of Saint Francis University. Potential subjects for the control group had to be free from any hip, knee, or ankle pathology and pain. For the patellofemoral group, inclusion criteria consisted of current knee pain of at least 3 out of 10 on a 1-10 scale when performing at least 2 of the following activities: ascending or descending stairs, prolonged sitting, squatting, kneeling, running, or hopping/jumping (Souza and Powers, 2009). Potential subjects for both groups had to be free from any knee surgeries in the past. In addition, subjects in either group were not permitted to have had hip or ankle surgeries in the past year and no current diagnoses of these joints (osteoarthritis, ankle sprain, tendinitis, bursitis). Volunteers were assessed for their lower limb joint health (Appendix A), and a general screen of the joints of their lower extremity was performed by a licensed Physical Therapist. Subjects who successfully completed this screening came to the laboratory, provided informed consent (Appendix B) and had their height and mass measured. The eventual subject pool consisted of two groups of nine subjects which were matched for gender, age, mass, and height (Table 4.1).
Table 4.1: Descriptive statistics comparing control group subjects and patellofemoral group subjects. A t-test indicated no significant differences between the groups for age, mass, or height (p < 0.05).

<table>
<thead>
<tr>
<th></th>
<th>Control group (n=9)</th>
<th>Patellofemoral group (n=9)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gender</strong></td>
<td>8 females, 1 male</td>
<td>8 females, 1 male</td>
</tr>
<tr>
<td><strong>Age (years)</strong></td>
<td>37.4 ± 16.8</td>
<td>39.7 ± 14.2</td>
</tr>
<tr>
<td><strong>Mass (kg)</strong></td>
<td>71.5 ± 12.7</td>
<td>70.5 ± 13.1</td>
</tr>
<tr>
<td><strong>Height (cm)</strong></td>
<td>165.7 ± 5.8</td>
<td>166.1 ± 7.1</td>
</tr>
</tbody>
</table>

4.3.2 Subject Testing

On the day of strength testing all subjects had their hip, knee, and ankle joint ranges of motion (Table 4.2) measured by a licensed Physical Therapist using a goniometer (Sammons Preston EZ Read Goniometer, model #7514). Subjects then warmed-up on a recumbent stationery bike at a self-selected speed for five minutes. Strength curves were assessed for hip abduction and hip extension using a Biodex dynamometer (Biodex 4 Systems Pro, Biodex Medical Systems, Shirley, NY). For both sets of strength curves the subjects were instructed to maximally attempt to lift the lower extremity against isometric resistance. The time to ramp up and hold their effort was 10 seconds. For both strength curves eight conditions (sets of hip and knee joint angles) were examined with one trial at each condition, and 30 seconds of rest between trials. The peak moment was measured for each trial. For the group with patellofemoral symptoms, the limb exhibiting the symptoms was utilized.
Table 4.2: Table of measured joint motions with a standard goniometer (Norkin and White, 2009).

<table>
<thead>
<tr>
<th>Motion</th>
<th>Position</th>
<th>Image</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip Extension</td>
<td>Prone</td>
<td><img src="image1.png" alt="Image of Hip Extension Prone" /></td>
</tr>
<tr>
<td>Hip Abduction</td>
<td>Supine</td>
<td><img src="image2.png" alt="Image of Hip Abduction Supine" /></td>
</tr>
<tr>
<td>Knee Flexion/Extension (Full extension = 0°)</td>
<td>Supine</td>
<td><img src="image3.png" alt="Image of Knee Flexion Supine" /></td>
</tr>
<tr>
<td>Ankle Dorsiflexion (Knee flexed to 90°)</td>
<td>Seated</td>
<td><img src="image4.png" alt="Image of Ankle Dorsiflexion Seated" /></td>
</tr>
<tr>
<td>Ankle Dorsiflexion (Knee extended)</td>
<td>Supine</td>
<td><img src="image5.png" alt="Image of Ankle Dorsiflexion Supine" /></td>
</tr>
</tbody>
</table>
For the assessment of the hip abduction strength curve, the subjects adopted a side-lying posture (Piva, 2011). In this posture the subjects lay on their side facing the dynamometer (Figure 4.1). The dynamometer axis of rotation was aligned with the subject’s superior hip joint (just inferior to the anterior superior iliac spine). The resistance arm pad was positioned on the lateral thigh of the superior lower extremity approximately 3 cm above the lateral femoral epicondyle. The contralateral lower extremity was flexed at the knee for comfort and stability. The angles analyzed for hip abduction were: -15° (15° of adduction), 0°, 15°, and 30°, with two knee angles used 0° and 90°.

Figure 4.1 Subject is left side-lying performing isometric right hip abduction with the knee flexed to 90°. The hip is in 15° of abduction.
For the assessment of the hip extension strength curve the subjects adopted a prone position (Souza and Powers, 2009). In this position the subjects were positioned standing but flexed at the waist over the seat of the dynamometer (Figure 4.2). The axis of the dynamometer was aligned with the subject’s greater trochanter, and the resistance arm pad was positioned over the posterior aspect of the distal femur just proximal to the popliteal fossa. The contralateral lower extremity was allowed to contact the floor for support. The angles analyzed for hip extension were: -45° (hip flexion), -30°, -15° (pictured in Figure 4.2), and 0° (neutral), with two different knee angles (0° and 90°).

**Figure 4.2** Subject is prone-lying and performing left isometric hip extension with the knee flexed to 90°. Left hip is in -15° (flexion) position.
4.3.3 Data Analysis

For each subject the joint range of motion and the peak isometric moments measured under a range of hip and knee angles were determined. The moment data were normalized with respect to each subject’s body weight. For the control group, the moment data were averaged between the two limbs. In the patellofemoral group, the data of the limb that the subject was reporting current complaints of patellofemoral symptoms was utilized. To quantify the shape of the strength curves, least-squares polynomials were fitted to the angle normalized moment data. The degree of the polynomial used to represent these data was selected based on the residual between the fit and the actual data. To compare peak moments between the groups of patellofemoral subjects and the healthy controls, t-tests were performed. In addition, the gradients of the strength curves of the control group and patellofemoral group were compared using t-tests. A p-value less than 0.05 was used to assess statistical significance. All statistical analyses were performed in Minitab 15 (Minitab Inc., State College).

4.4 Results

All subjects had joint ranges of motion that exceeded those required experimentally during the strength testing. No specific ranges of motion produced statistically significant differences (p < 0.05) between the control subjects and patellofemoral subjects (Table 4.3).
Table 4.3: The means (± standard deviation) of the joint ranges of motion for the control subject group and the patellofemoral subject group.

<table>
<thead>
<tr>
<th></th>
<th>Control subjects (n= 9)</th>
<th>Patellofemoral subjects (n=9)</th>
<th>p value (control versus P-F subjects)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hip</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extension</td>
<td>30.8° ± 3.3</td>
<td>27.9° ± 6.1</td>
<td>0.23</td>
</tr>
<tr>
<td>Abduction</td>
<td>44.7° ± 3.6</td>
<td>43.4° ± 2.8</td>
<td>0.43</td>
</tr>
<tr>
<td><strong>Knee</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexion</td>
<td>141.8° ± 5.7</td>
<td>142.6° ± 4.4</td>
<td>0.75</td>
</tr>
<tr>
<td>Extension</td>
<td>3.8° ± 3.8</td>
<td>1.6° ± 4.2</td>
<td>0.24</td>
</tr>
<tr>
<td><strong>Ankle</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dorsiflexion-Knee flexed</td>
<td>15.7° ± 4.1</td>
<td>18.8° ± 3.7</td>
<td>0.12</td>
</tr>
<tr>
<td>Dorsiflexion- Knee extended</td>
<td>11.9° ± 3.1</td>
<td>14.7° ± 3.7</td>
<td>0.11</td>
</tr>
</tbody>
</table>

All joint moment data were normalized with respect to body weight. The normalized peak hip abduction joint moment data were not statistically significant between the control group and the patellofemoral group (Table 4.4). The mean normalized hip abduction joint moment was less in the patellofemoral group compared with the control subject group both with the knee extended (p = 0.54) and with the knee flexed (p = 0.33), but these differences were not statistically different. The position of the knee (flexed vs. extended) did not show significant differences in hip abduction as well (Table 4.4). For the control group the normalized peak moments produced with the knee flexed was not statistically different to the normalized peak moments when the knee was fully extended (p = 0.39). Similarly, for the patellofemoral group there was no statistically significant difference (p = 0.81), whether the knee was in a position of flexion or extension. The gradient or slope of the moment-angle relationship was very similar.
between the two groups for both knee positions (Figure 4.3), and was not statistically significant whether the knee was flexed (p = 0.44) or extended (p = 0.71).

Table 4.4: The means (± standard deviation) of the peak hip abduction joint moment and the angle at which it occurred for the subject groups. In addition the the gradient of the line of the joint angle-moment relationship is reported. No significant difference was found between the patellofemoral group and control group for hip abduction.

<table>
<thead>
<tr>
<th>Hip Abduction</th>
<th>Control Subjects (n=9)</th>
<th>Patellofemoral Subjects (n=9)</th>
<th>p-value (Control vs. P-F)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Knee Extended</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak Moment (N.m)</td>
<td>93.9 ± 17.9</td>
<td>86.7 ± 29.6</td>
<td>0.55</td>
</tr>
<tr>
<td>Peak Moment (N.m/BW)</td>
<td>0.14 ± 0.03</td>
<td>0.13 ± 0.04</td>
<td>0.54</td>
</tr>
<tr>
<td>Angle of Peak Moment (degrees)</td>
<td>-15.0 ± 0.05</td>
<td>-15.0 ± 0.05</td>
<td>1.00</td>
</tr>
<tr>
<td>Gradient of Angle-Moment Relationship ( (N.m/BW)/degree )</td>
<td>-0.0013 ± 0.00036</td>
<td>-0.0014 ± 0.00037</td>
<td>0.71</td>
</tr>
<tr>
<td><strong>Knee Flexed</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak Moment (N.m)</td>
<td>99.8 ± 32.5</td>
<td>84.0 ± 36.4</td>
<td>0.35</td>
</tr>
<tr>
<td>Peak Moment (N.m/BW)</td>
<td>0.14 ± 0.04</td>
<td>0.12 ± 0.049</td>
<td>0.33</td>
</tr>
<tr>
<td>Angle of Peak Moment (degrees)</td>
<td>-13.3 ± 5.0</td>
<td>-10.0 ± 10.6</td>
<td>0.41</td>
</tr>
<tr>
<td>Gradient of Angle-Moment Relationship ( (N.m/BW)/degree )</td>
<td>-0.0013 ± 0.00076</td>
<td>-0.0011 ± 0.00056</td>
<td>0.44</td>
</tr>
</tbody>
</table>
Figure 4.3 The moment-angle relationship of hip abduction comparing patellofemoral subjects to control subjects with the knee extended.
Figure 4.4 The moment-angle relationship of hip abduction comparing patellofemoral subjects to control subjects with the knee flexed 90°.

Normalized hip extension peak joint moment did not show statistically significant differences between the control subject group and the patellofemoral subject group with the knee extended (Table 4.5). However, the normalized peak moment was significantly less (p < 0.05) in the patellofemoral group compared with the control group with the knee in a position of flexion (Table 4.5). In addition, significant differences were found between the average normalized hip extension peak moment of the patellofemoral subjects at the two different knee positions (flexed vs. extended) (p < 0.01); however there was no statistical difference between the knee positions of the control group during hip extension (p = 0.12). The gradients of the joint moment-angle relationship of hip extension were also analyzed, and showed no statistically significant differences between the two groups for both conditions (knee flexed (p
= 0.63) or extended (p = 0.91)) (Figure 4.4). Additionally, the gradients of the joint moment-angle relationship of hip extension were analyzed for the two knee conditions (flexed vs extended) within each group and showed no statistical significance (control group (p = 0.23) and patellofemoral group (p = 0.34)).

**Table 4.5:** The means (± standard deviation) of the peak hip extension moment and the angle at which it occurred for the subject groups. In addition the gradient of the line of the joint angle-moment relationship is reported. Significant differences are indicated by (*).

<table>
<thead>
<tr>
<th>Hip Extension</th>
<th>Control Subjects (n=9)</th>
<th>Patellofemoral Subjects (n=9)</th>
<th>p-value (Control vs P-F)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Knee Extended</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak Moment (N.m)</td>
<td>131.9 ± 32.3</td>
<td>106.4 ± 51.7</td>
<td>0.23</td>
</tr>
<tr>
<td>Peak Moment (N.m/BW)</td>
<td>0.19 ± 0.058</td>
<td>0.16 ± 0.071</td>
<td>0.26</td>
</tr>
<tr>
<td>Angle of Peak Moment (degrees)</td>
<td>-43.8 ± 3.8</td>
<td>-43.3 ± 5.0</td>
<td>0.84</td>
</tr>
<tr>
<td>Gradient of Angle-Moment Relationship ( (N.m/BW)/degree )</td>
<td>-0.0016 ± 0.00056</td>
<td>-0.0017 ± 0.00090</td>
<td>0.91</td>
</tr>
<tr>
<td><strong>Knee Flexed</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak Moment (N.m)</td>
<td>119.6 ± 28.9</td>
<td>77.8 ± 42.0</td>
<td>0.03*</td>
</tr>
<tr>
<td>Peak Moment (N.m/BW)</td>
<td>0.17 ± 0.044</td>
<td>0.11 ± 0.058</td>
<td>0.03*</td>
</tr>
<tr>
<td>Angle of Peak Moment (degrees)</td>
<td>-38.3 ± 7.9</td>
<td>-43.3 ± 5.0</td>
<td>0.13</td>
</tr>
<tr>
<td>Gradient of Angle-Moment Relationship ( (N.m/BW)/degree )</td>
<td>-0.0013 ± 0.00081</td>
<td>-0.0015 ± 0.00075</td>
<td>0.63</td>
</tr>
</tbody>
</table>
Figure 4.5  Moment-angle relationship of hip extension of patellofemoral subjects vs. control subjects with the knee extended.
Figure 4.6  Moment-angle relationship of hip extension of patellofemoral subjects vs. control subjects with the knee flexed.

4.5  Discussion

Decreased hip abduction joint strength (moment) in subjects with patellofemoral syndrome has been reported (Prins and van der Wurff, 2009; Souza and Powers, 2009; Lankhorst et al., 2013). The results of this study do not support these previous studies showing hip abductor weakness, although the trend was for the peak moments of hip abduction to be less in the patellofemoral subjects. One other study that did not show strength deficits of the hip abductors in a group of subjects with patellofemoral symptoms was by Piva et al. (2005). The sample size of this study was nine experimental subjects, which were age and size matched with controls. A statistical power analysis for normalized moment in this study demonstrated that with nine subjects, a standard deviation of 0.04, and difference of 0.6, statistical power was 0.85. Previous studies have not altered the position of the knee when assessing hip abduction
joint moments, and the results of this study show that the changes in knee position do not alter the hip abduction joint moment.

Decreased hip extension joint moment in a group of patellofemoral subjects has been reported in the literature (Prins and van der Wurff, 2009; Souza and Powers, 2009). Souza and Powers (2009) reported a 16% deficit in hip extensor strength of a patellofemoral group compared with a control group. The researchers performed their study with the subject’s knee in 90° of flexion, similar to one condition in this study. However, they only studied one isometric position for hip extension (30°, which isolates the hip in 30° of hip flexion), whereas this study utilized four different isometric hip extension angles (-45°, -30°, -15°, and 0°). Similar to that study, in this study there was a statistically significant decrease in the peak moment of hip extension with the knee flexed for the patellofemoral group compared with the control subject group. This study found a 35% deficit of peak hip extension moment (with the knee flexed) in the patellofemoral group compared with a control group, which occurred at the (-45°) hip extension position. Whereas Souza and Powers (2009) only measured one isometric hip extension angle (-30°) and demonstrated a 16% deficit in hip extension moment (knee flexed), this study found a 42% deficit at the (-30°) hip angle in the patellofemoral group when compared with the control group. As hip extension increased, the percent disparity between the joint moments of the patellofemoral group and the control group increased: (47% at -15° angle; 60% at 0° angle).

The decrease in peak magnitude of the hip extension joint moment of the patellofemoral group compared with the control group was significantly less when the knee was flexed, but not when the knee was extended. With the knee in extension, the biarticular hamstrings are lengthened at the knee compared with the flexed position, and presumably able to generate increased force as a consequence of being on a more favorable portion of their force-length curve. However, with the knee flexed to 90°, the biarticular hamstrings are shortened on their force-length curve, and their force generating capacity is decreased. The gluteus maximus is a uniarticular muscle (Dostal et al., 1986), and the position of the knee does not affect it. The hip extension moment with the knee flexed therefore requires the gluteus maximus, which is on a more favorable portion of its force length curve, to produce more force than that required with the
knee extended to generate the hip extension moment (Waters et al., 1974). Mohamed et al. (2002) found that knee flexion joint moment increased as the hamstrings lengthen. This was theorized to be due to either the lengthening of the non-contractile passive components of the muscle (both in parallel and series), or the more adequate actin-myosin overlap due to the migration on the force-length curve, or both. Likewise, when producing hip extension moment in this study, the knee flexed position shortens the hamstrings and mitigates their ability to create hip extension moment. Because the peak moment difference in this study for subjects with patellofemoral subjects was significantly decreased with the knee flexed to 90° compared with the knee extended, this suggests that the gluteus maximus could be weaker in the patellofemoral group. Therefore, the strength of the gluteus maximus might be a central factor in patellofemoral symptoms.

Another possibility is that the hamstrings of the patellofemoral group are actually stronger than the control group subjects, possibly compensating for gluteus maximus weakness. This explains the lack of statistical difference when the hamstrings are in a more lengthened position (knee extension). A further study examining the force-length properties of the hamstring and gluteus maximus musculature is warranted. This study could measure not only hip extension joint moment, but also knee flexion joint moment in various hip and knee joint angles, similar to Mohamed et al. (2002). A comparison could take place between subjects with patellofemoral syndrome and control subjects. This would help identify the specific contributions of the hamstrings and gluteus maximus.

The gluteus maximus is not only an extensor of the hip, but also a potent external rotator (Delp et al., 1999). A hip external rotation joint moment, occurring in the transverse plane, prevents the femur from internally rotating. Patellofemoral pain typically arises during activities that place loads across the joint, such as squatting, and the support phases of ascending/descending stairs and running (Draper et al., 2011), all closed chain activities. During closed chain femoral internal rotation, the patella remains relatively stationery (Powers et al., 2003). However, the result is a relative lateral tracking of the patella (Souza and Powers, 2009), and is a major cause of pain and dysfunction in individuals with patellofemoral syndrome. This study suggests weakness of the gluteus maximus in individuals with
patellofemoral syndrome, plausibly causing aberrant transverse plane kinematics of the femur and therefore relative lateral tracking of the patella.

The analyses of the current study suggest that targeted interventions for subjects with patellofemoral symptoms should focus on the uniarticular gluteus maximus. Because of the importance of the gluteus maximus in moment production with the knee flexed, and its ability to control transverse plane kinematics of the femur, it is hypothetically the muscle with the greatest deficit. In addition, because of the statistical significance of only the hip extension moment with the knee flexed, the results of this study suggest either gluteus maximus weakness or increased compensatory strength of the hamstrings in patellofemoral subjects when compared to age and size matched control subjects.

The moment-angle relationships for the patellofemoral syndrome group and the control group were the same in shape as assessed by determining the gradient of the moment-angle data after determining that a first order polynomial was appropriate for modeling the moment-angle curves. If there had been a difference in gradient this would have indicated a difference in the relative strength of the muscle groups at different joint angles. There is evidence that the force-length properties of muscles can differ between subjects (e.g., Winter and Challis, 2010), so it might be expected that subjects with patellofemoral syndrome might have different shaped moment-angle curves compared with controls, but this was not the case for hip extension or hip abduction.

The first hypothesis for this study was that subjects with patellofemoral syndrome will have weaker strength curves, demonstrated by a decrease in magnitude in their normalized peak moments, compared with healthy controls. The results supported this for hip extension with the knee flexed, but not hip extension with the knee extended or hip abduction in either knee position. Therefore, this hypothesis was accepted for hip extension with the knee flexed, but rejected for hip extension with the knee extended and hip abduction in either knee position.

The second hypothesis for this study was subjects with patellofemoral syndrome will have different shaped strength curves with the knee in two different positions (90° and 0°) compared with
healthy controls. This hypothesis was rejected because for both hip abduction and extension in two knee positions, the moment-angle gradients (strength curves) were found to be similar.

This study examined the joint moment production during hip abduction and hip extension. However, only the mechanical factors such as joint angle and muscle length (i.e., knee position) were evaluated. A joint moment is also determined by neurological contributions such as motor unit recruitment and firing rate. Researchers have shown deficits in the neurological factors contributing to joint moment production in individuals with patellofemoral syndrome (Brindle et al., 2003; Cowan et al., 2009). Further studies could examine this component of these moments in both normal subjects and those with patellofemoral syndrome.

A possible limitation of the current study was that although extraneous motions of the hip, such as internal and external rotation, were not observed, it does not necessarily mean they did not occur. However, with the limb fixed to the dynamometer, any such motion would be sufficiently small so as to not influence the results of this study. For the different knee positions, subjects maintained their knee in either full extension (0°) or flexion (90°). Initially, during pilot testing, a knee brace was utilized, but it was determined that it adversely affected the normal hip joint moment production, and would decrease accuracy.

In conclusion, in the comparison of subjects with patellofemoral syndrome to control subjects, only hip extension with the knee flexed was found to be significantly less in peak moment production. Hip extension with the knee extended and hip abduction in either knee position (flexed or extended) showed no significant differences. These findings highlight the importance of the gluteus maximus in moment production and control of the femur for knee pathologies such as patellofemoral syndrome.

4.6 References


Draper, CE; Besier, TF; Fredericson, M; Santos, JM; Beaupre, GS; Delp, SL; Gold, GE. (2011). Differences in patellofemoral kinematics between weight-bearing and non-weight-bearing conditions in patients with patellofemoral pain. *Journal of Orthopedic Research*, 29; 312-317.


Chapter 5
Steadiness of the Hip Musculature in Patellofemoral Subjects and Control Subjects

5.1 Abstract
The steadiness, or fluctuation, of a held isometric joint moment has implications for the successful control of muscle force and movement. Neuromuscular control can be assessed through the analysis of isometric joint moment steadiness. Statistical analyses include Coefficient of Variation (CV), Approximate Entropy (ApEn), Detrended Fluctuation Analysis (DFA), and Signal power. Nine subjects with patellofemoral symptoms and nine age- and size-matched controls were analyzed for the steadiness of their isometric hip abduction and hip extension joint moments, with two different knee positions (flexion and extension). Results showed hip extension CV values to be significantly higher in the patellofemoral group compared with the control group, indicating greater signal noise and therefore poorer control of the hip extensor musculature. Additionally, the scaling parameter alpha, determined by DFA, was significantly different for hip extension in both groups when the knee was in a position of extension compared with knee flexion. No differences were found in any of the statistical analyses for hip abduction joint moments. These findings demonstrate that individuals with patellofemoral syndrome exhibit deficiencies of a neuromuscular nature of their hip extensor musculature, but not their hip abductors, and their rehabilitation should address this deficiency.

5.2 Introduction
Measurement of joint moments is an assessment performed to quantify the strength of muscles about a joint. Deficits in these moments can be related to decreased force producing capacity of the muscles, or inadequate moment arm length. Because moment arm length varies little from individual to individual (Blazevich et al., 2009), and therefore does not change with injury or pathology, the force producing capability of the muscle(s) is more commonly the culprit for strength deficits. However, efficient movement requires more than simply strength. It requires the coordination of the neurological
and muscular systems. It has been shown that deficiencies in these neuromuscular mechanisms are correlated to pathologies such as patellofemoral syndrome (Brindle et al., 2003; Cowan et al., 2009).

Enoka et al. (2003) stated that muscle forces always fluctuate about an average value when performing isometric contractions, when the goal is to maintain a constant force. *In vivo*, these fluctuations are manifested by fluctuations in the joint moment produced at the relevant joint. This is termed moment fluctuation. Because during isometric moments the moment arm is unchanging, researchers often term moment fluctuations as force fluctuations. Signal properties can be determined from a moment fluctuation signal, and can be utilized to quantify a signal. The coefficient of variation (CV) is a statistical measure that has been used by researchers to determine the magnitude of variability in force or moment production (Hamilton et al., 2004). CV is determined by dividing the standard deviation by the mean of the data. These researchers concluded that stronger muscle groups, having more motor units, had lower CV’s than smaller weaker muscle groups (Hamilton et al., 2004). One concern with the use of CV is it is only appropriate for use for data with a normal distribution. This is not always the case in the presence of aging, disease, and injury. However, other statistical measures exist that can determine the predictability of the variability of biological processes (Forrest et al., 2014). These include Approximate Entropy (ApEn) and Detrended Fluctuation Analysis (DFA).

Under basal resting conditions, most healthy physiologic systems demonstrate irregular, complex dynamics that represent multiple interacting influences operating over multiple time scales (Lipsitz, 2002). These processes create a highly adaptive organism which can respond to internal or external factors. This complexity maintains a level of regularity within the organism (Lipsitz, 2002). The more complex a system, the more capable it is of maintaining that level of regularity. The use of entropy as a measure of the complexity of biological signals has provided insight into physiological changes associated with aging and disease (Pincus and Goldberger, 1994). It is important to recognize the difference between complexity and variability. Variability implies variations in signal amplitude, such as a sine wave. However, a sine wave actually has very low complexity because of its regularity. Disease
conditions have been identified as having reduced signal complexity compared with the healthy state (Lipsitz, 2002).

If this joint moment signal is analyzed in the time domain to quantify signal regularity, then ApEn is often utilized. ApEn was designed for the analysis of medical data (Pincus, 1991). ApEn has been used to analyze many biologic signals such as fetal heart rates (Richman and Moorman, 2000), and to quantify the moment fluctuations exhibited by muscles about a joint (Challis, 2006). By quantifying the ApEn of an isometric force record, it has also served to provide insight into motor control strategies and how they change with aging or disease (Forrest et al., 2014). An ApEn value close to zero signifies regularity (for example, a sine wave); whereas random samples such as white noise have an ApEn value close to two. For the calculation of ApEn refer to Appendix E.

The DFA is a data analysis technique which has been utilized to determine the presence of long or short term correlations in moment data in the time domain (e.g., Vaillancourt and Newell, 2003). The DFA has been used to analyze a variety of biological signals, in its original presentation (Peng et al., 1994) for example, it was used to examine DNA sequences. Using this statistic, the moment signal is integrated to form an accumulated sum. Then the signal is divided into sections, and the linear trend is determined for each box. The signal in each box is detrended using a linear fit, and the residuals are averaged for all boxes and the square root or mean residual is composed. This process is repeated for a range of box sizes (from 4 to n/4). The gradient of the plot log of box size against log of the mean residuals indicates some type of power-law is present in the data. The gradient, or scaling exponent, is referred to as alpha (α) (see Appendix F).

Patellofemoral syndrome is a clinical condition that is characterized by retropatellar and/or peripatellar pain associated with activities involving lower limb loading such as walking, running, jumping, stair climbing, and prolonged sitting and kneeling (Davis and Powers, 2010). Patellofemoral syndrome has been reported as the most frequently diagnosed condition in adolescents and adults with knee complaints (Lankhorst et al., 2013). In a systematic review, Prins and van der Wurff (2009) found strong evidence for a decrease in hip external rotation, abduction, and extension strength in females with
patellofemoral syndrome compared with healthy controls. However, Thijs et al. (2011) showed that hip abductor strength was not a predictor of patellofemoral syndrome in recreational runners, and questioned whether hip muscle weakness is a consequence of lower extremity pathologies rather than a cause. These researchers proposed that the neuromuscular control of the hip musculature, rather than hip muscle strength, might be a predisposing factor for patellofemoral syndrome.

Brindle et al. (2003) compared individuals with patellofemoral syndrome with a control group, and concluded that significant temporal differences existed in lower extremity firing patterns of the Gluteus medius (GMed) in the subjects with anterior knee pain (patellofemoral syndrome). Cowan et al. (2009) performed a similar study, and the researchers proposed that patellofemoral syndrome symptoms are caused by delays in muscle activation as indicated by EMG of the hip abductors rather than the force producing capacity of the hip abductors or external rotators.

To quantify the neuromotor control of hip abduction and hip extension the CV has been utilized. Hamilton et al. (2004) concluded that moment fluctuations with a lower CV indicate stronger muscles with more motor units. In order to determine the neuromuscular complexity (regularity versus irregularity) of control of the hip musculature, ApEn and DFA of the hip joint moment can be utilized. These statistical measures offer insight into whether subjects in the presence of a pathology such as patellofemoral syndrome have altered ApEn and DFA values compared with healthy control subjects, and therefore altered neuromuscular control. Based on the theory of Lipsitz (2002), it is anticipated that less complex signals will be demonstrated in the presence of pathology. The aim of this study was to quantify the moment fluctuation of the strength curves of the hip abductors and hip extensors in a group of subjects with patellofemoral syndrome, and in healthy controls. Moment fluctuation is used here as a measure of neuromuscular control. There are two hypotheses:

Hypothesis I – subjects with patellofemoral syndrome will have isometric time moment signals of greater signal regularity as indicated by ApEn, with more random properties as indicated by the DFA,
and have greater noise as indicated by a larger CV during hip abduction and hip extension compared with healthy controls.

**Hypothesis II** – subjects with patellofemoral syndrome will have isometric time moment signals of greater signal regularity as indicated by ApEn, with more random properties as indicated by the DFA, and have greater noise as indicated by a larger CV during hip abduction and hip extension with the knee flexed compared with the knee extended compared with healthy controls.

### 5.3 Methods

In overview, subjects were recruited in two groups (one with signs of patellofemoral syndrome and the other without knee pain) and the moment fluctuations of their isometric strength curves assessed for hip abduction and hip extension using a Biodex dynamometer.

#### 5.3.1 Subjects

Subjects between the ages of 18-64 years of age were recruited to participate in this study. The procedures and protocols in this study were approved by the Institutional Review Boards of the Pennsylvania State University and of Saint Francis University. Two groups of subjects were recruited: the first had to be free from any hip, knee, or ankle pathology and pain; the second consisted of individuals with current knee pain of at least 3 out of 10 on a 1-10 scale when performing at least 2 of the following activities: ascending or descending stairs, prolonged sitting, squatting, kneeling, running, or hopping/jumping (Souza and Powers, 2009). Volunteers were assessed for their lower limb joint health (Appendix A), and a general screen of the joints of their lower extremity was performed by a licensed Physical Therapist. Subjects who successfully completed this screening came to the laboratory, provided informed consent (Appendix B), and had their height and mass measured. The eventual subject pool consisted of nine age and size-matched subjects (Table 5.1). No significant differences existed between subject groups for age, mass, or height.
Table 5.1: Descriptive statistics comparing control group subjects and patellofemoral group subjects.

No statistical significant differences were found between the groups (p < 0.05).

<table>
<thead>
<tr>
<th></th>
<th>Control group (n=9)</th>
<th>Patellofemoral group (n=9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender</td>
<td>8 females, 1 male</td>
<td>8 females, 1 male</td>
</tr>
<tr>
<td>Age (years)</td>
<td>37.4 ± 16.8</td>
<td>39.7 ± 14.2</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>71.5 ± 12.7</td>
<td>70.5 ± 13.1</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>165.7 ± 5.8</td>
<td>166.1 ± 7.1</td>
</tr>
</tbody>
</table>

5.3.2 Subject Testing

On the day of strength testing all subjects warmed-up on a recumbent stationery bike at a self-selected speed for five minutes. Hip joint moments were assessed for abduction and extension using a Biodex dynamometer (Biodex 4 Systems Pro, Biodex Medical Systems, Shirley, NY). For both sets of testing, the subjects were instructed to maximally attempt to lift the lower extremity against isometric resistance. The time to ramp up and hold their effort was 10 seconds. For both hip motions eight conditions (sets of hip and knee joint angles) were examined with one trial at each condition, and 30 seconds of rest between trials.

5.3.3 Data Analysis

Subject peak joint moments were measured for all conditions, and described by the mean and standard deviation. These moment data were normalized with respect to subject weight. Custom written MATLAB code was used to further process the data. For each subject’s moment-time profile, there was a period where the moment was built up to a maximum and they then tried to hold it for as long as possible,
with a maximum data collection period of 10 seconds. For analysis of data steadiness or regularity within the 10 second data window, the two second minimum variance window was identified for further analysis. ApEn was computed for each trial’s two second window using the method described by Pincus (1991). In the ApEn algorithm, the following have to be specified: the sample length, the length of the compared runs (m), and the noise level (r). Sample lengths were the same for all data sets (201). In common with other analyses of time-moment data, m was set to 2 (e.g., Challis, 2006; Rose et al., 2009). Finally the noise level was set at the base noise level of the Biodex output (0.7 N.m). Higher values of ApEn indicate a less regular series. The same data window was also analyzed using the Detrended Fluctuation Analysis (DFA; Peng et al., 1994). The output from the DFA analysis, alpha, indicates the nature of the signal. If $\alpha$ has a value of 0.5 this corresponds to white noise, a random process. If $\alpha$ has a value greater than 0.5 and less than (or equal to) 1.0, this indicates persistent long range correlations, while a value less than 0.5 indicates long range anti-correlations. Finally a value of 1.5 indicates Brown noise. To determine signal power, the total power of this two second window was computed from the integrated area of the power spectrum of the window.

Using Minitab 15 (Minitab Inc., State College), means and standard deviations were calculated on all data. Additionally, a general linear model analysis of variance (ANOVA) was performed on the data values of ApEn, DFA, CV, and signal power under the conditions of knee position (flexion and extension) and the subject groups (patellofemoral and control). A p-value less than 0.05 was used to assess statistical significance.

### 5.4 Results

All joint moment data were normalized with respect to body weight (see Table 5.2). Subjects with patellofemoral syndrome demonstrated statistically significant less hip extension joint moment
values compared with control subjects when the knee was in a flexed position. All other joint moment data showed no statistically significant differences between the patellofemoral group and control group.

ApEn values for the fluctuations of the hip abduction moments ranged from 0.016 to 0.58 (see Figure 5.1). No statistically significant differences were found between the ApEn values for the fluctuations of the hip abduction moments with the knee extended compared with the knee flexed for both the control group and patellofemoral group. Additionally, no statistically significant differences were found between ApEn values for the fluctuations of the hip abduction joint moments of control subjects compared with patellofemoral subjects (see Table G.1).

Table 5.2 The means (± standard deviation) of the peak hip abduction and extension moments for the subject groups. Significant differences are indicated by (*).

<table>
<thead>
<tr>
<th>Hip Abduction</th>
<th>Control Subjects (n=9)</th>
<th>Patellofemoral Subjects (n=9)</th>
<th>p-value (Control vs. P-F)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Knee Extended</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak Moment (N.m)</td>
<td>93.9 ± 17.9</td>
<td>86.7 ± 29.6</td>
<td>0.55</td>
</tr>
<tr>
<td>Peak Moment (N.m/BW)</td>
<td>0.14 ± 0.03</td>
<td>0.13 ± 0.04</td>
<td>0.54</td>
</tr>
<tr>
<td><strong>Knee Flexed</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak Moment (N.m)</td>
<td>99.8 ± 32.5</td>
<td>84.0 ± 36.4</td>
<td>0.35</td>
</tr>
<tr>
<td>Peak Moment (N.m/BW)</td>
<td>0.14 ± 0.04</td>
<td>0.12 ± 0.049</td>
<td>0.33</td>
</tr>
<tr>
<td><strong>Hip Extension</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak Moment (N.m)</td>
<td>131.9 ± 32.3</td>
<td>106.4 ± 51.7</td>
<td>0.23</td>
</tr>
<tr>
<td>Peak Moment (N.m/BW)</td>
<td>0.19 ± 0.058</td>
<td>0.16 ± 0.071</td>
<td>0.26</td>
</tr>
<tr>
<td><strong>Knee Flexed</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak Moment (N.m)</td>
<td>119.6 ± 28.9</td>
<td>77.8 ± 42.0</td>
<td>0.03*</td>
</tr>
<tr>
<td>Peak Moment (N.m/BW)</td>
<td>0.17 ± 0.044</td>
<td>0.11 ± 0.058</td>
<td>0.03*</td>
</tr>
</tbody>
</table>
Figure 5.1 Chart of ApEn values for control subjects and patellofemoral subjects for the fluctuations of the hip abduction joint moments.

ApEn values for the fluctuations of the hip extension joint moments ranged from 0.09 to 0.75 (see Figure 5.2). No statistically significant differences were found between the ApEn values for the fluctuations of the hip extension moments with the knee extended compared with hip extension moments with the knee flexed for the control group or patellofemoral group. Additionally, no statistically significant differences were found between the ApEn values for the fluctuations of the hip extension joint moment of control subjects compared with patellofemoral subjects (see Table G.1).
Figure 5.2 Chart of ApEn values for control subjects and patellofemoral subjects for the fluctuations of the hip extension joint moments.

DFA values for the fluctuations of the hip abduction joint moments ranged from 1.10 to 1.74 (see Figure 5.3). No statistically significant differences were found in the alpha values for the fluctuations of the hip abduction moments with knee flexion or extension, or between the control group and the patellofemoral group (see Table G.2).
DFA values for the fluctuations of the hip extension moments ranged from 0.84 to 1.73 (see Figure 5.4). No statistically significant differences were found in alpha values for the fluctuations of the hip extension moments between the control subjects and patellofemoral subjects. There were statistically significant differences, comparing DFA alpha values comparing the knee flexed to extended at three angles of hip extension: (-45°, p=0.03), (-30°, p=0.01), (-15°, p=0.02) (see Table G.2). The alpha values indicated the presence of long-term correlations in the data, where these values decreased from the fluctuations of the hip extension moment with the knee extended to the fluctuations of the hip extension moment with the knee in a flexed position.
CV values for the fluctuations of the hip abduction joint moments ranged from 0.66 to 43.9 (see Figure 5.5). No statistically significant differences were found in the CV values for the fluctuations of the hip abduction moments between knee flexion and extension or between the control group and the patellofemoral group (see Table G.3).
CV values for the fluctuations of the hip extension joint moments ranged from 0.75 to 37.4 (see Figure 5.6). Results showed statistically significant increased CV values for the fluctuations of the hip extension joint moments of the patellofemoral subjects compared with the control subjects at -30°, -15°, and 0° (see Table G.3).
Figure 5.6 Chart of CV values for control subjects and patellofemoral subjects for the fluctuations of the hip extension joint moments.

Signal power values ranged from 7.2 to 16,550 for the fluctuations of the hip abduction (see Figure 5.7). No statistically significant differences were found for the fluctuations of the hip abduction moment data between knee flexion and extension or between the control group and patellofemoral group (see Table G.4).
Figure 5.7 Chart of signal power values for control subjects and patellofemoral subjects for the fluctuations of the hip abduction joint moments.

Signal power values ranged from 12.2 to 6,797 for the fluctuations of the hip extension joint moments (see Figure 5.8). No statistically significant differences were found for the fluctuations of the hip extension moments between knee flexion and extension or between the control group and patellofemoral group (see Table G.4).
Figure 5.8 Chart of signal power values for control subjects and patellofemoral subjects for the fluctuations of the hip extension joint moments.

5.5 Discussion

In this study, CV, ApEn, DFA, and signal power were utilized as measures of neuromuscular control. CV has been used in the analysis of hand musculature and the triceps musculature (Hamilton et al., 2004). ApEn and DFA have been used in the analysis of hand and ankle/foot musculature (Challis, 2006; Rose et al., 2009; Vaillancourt and Newell, 2003); however, no literature has been found on the analysis of hip musculature using these statistical measures. In particular no study to date has assessed neuromuscular control using ApEn, DFA, and CV in patellofemoral subjects. This study showed that the fluctuation of the hip abduction isometric moments, whether in knee flexion or extension, did not show any statistically significant differences in CV, ApEn, DFA or signal power. This is not surprising since
only the Tensor fascia lata (TFL) muscle crosses both the hip and the knee joint (Flack et al., 2012). It accounts for only 11% of the cross-sectional area of the hip abductors (Neumann, 2010), and is the only muscle that would be affected by the position of the knee. CV, ApEn, DFA, and signal power of hip abduction isometric moments of subjects with patellofemoral syndrome showed no statistically significant differences when compared with control subjects. This demonstrates there is no apparent difference in the neural firing rate and/or motor unit recruitment of the hip abductors between these two groups. Brindle et al. (2003) and Cowen et al. (2009) demonstrated a delay in hip abductor EMG timing, but did not assess moment fluctuations or statistical measures to examine neuromuscular control while the hip abductors were actively contracting.

Hip extensor weakness has also been associated with individuals with patellofemoral syndrome (Prins and van der Wurff, 2009; Souza and Powers, 2009). However, it is not evident whether weakness is secondary to muscle structure, such as physiological cross-sectional area, or if it is of a neuromuscular nature. In this study ApEn and signal power of the fluctuations of the isometric moments showed no statistically significant difference whether the knee was extended or flexed, and no statistically significant difference between patellofemoral subjects and control subjects. DFA also showed no statistically significant differences between patellofemoral and control subjects. This shows that individuals with patellofemoral syndrome do not show deficits in signal properties, as determined by ApEn or DFA, of the hip extensor musculature.

There was a statistically significant difference in DFA alpha values for the fluctuations of the hip extension isometric moments when the subjects’ knees were flexed compared with extended. This is likely attributed to the fact that the hip extension moment with the knee extended requires both the gluteus maximus and the hamstrings to contribute. When the knee is flexed, the hamstrings are shortened on their force-length curve (Mohamed et al., 2002). A possible explanation for this decrease in signal properties is that by shortening the hamstrings, the force-length properties are affected and therefore alter the regularity of the joint moment fluctuation. This has been demonstrated in the ankle dorsiflexors, but not in the hip or knee musculature (Mela et al., 2001).
The CV demonstrated a statistically significant increase in the fluctuations of the hip extension joint moment of the patellofemoral group compared with the control group. According to the conclusions of Hamilton et al. (2004), with the patellofemoral group having a greater CV value, there is therefore poorer control of this muscle group compared to healthy controls. This supports the concept of decreased neuromuscular control of the hip extensors in individuals with patellofemoral syndrome.

The first hypothesis is that subjects with patellofemoral syndrome will have isometric time moment signals of greater signal regularity as indicated by ApEn, with more random properties as indicated by the DFA, and have greater noise as indicated by a larger CV compared with during hip abduction and hip extension than healthy controls. This hypothesis is rejected for signal regularity and random properties because no differences were found in ApEn or DFA, respectively, between the patellofemoral subjects and control subjects. The hypothesis is partially accepted because subjects with patellofemoral syndrome demonstrated greater isometric signal noise, as indicated by a larger CV, than healthy controls during hip extension. The second hypothesis is that subjects with patellofemoral syndrome will have isometric time moment signals of greater signal regularity as indicated by ApEn, with more random properties as indicated by the DFA, and have greater noise as indicated by a larger CV compared with curves during hip abduction and hip extension with the knee flexed compared with the knee extended compared with healthy controls. This hypothesis is rejected for signal regularity (ApEn) and signal noise (CV), but DFA alpha values demonstrated a significant difference between hip extension joint moments in subjects with knees extended compared with knees flexed.

Clinically, the results of this study demonstrate no statistically significant neuromuscular differences in the hip abductors of subjects with patellofemoral syndrome compared with control subjects. However, the signal noise amplitude differences in hip extension joint moments with the knee flexed between the two groups shows that strength deficits, at least in part, are due to neuromuscular mechanisms, such as motor unit recruitment or firing rates. Therefore, clinicians should target the hip
extensors and focus on the neuromuscular control such as timing, isometric holds, and eccentric control when performing therapeutic exercise for patients with patellofemoral syndrome.

This is the only study in the available literature to examine the joint moment fluctuations of the hip musculature. Future studies could expand on examining other musculature such as the hip flexors. Also, EMG could be utilized along with joint moment fluctuations to define the neuromotor properties, such as the timing or intensity, of these muscles. Furthermore, because of the difference in signal regularity of the two positions of the knee, smaller increments of knee flexion could be analyzed to further determine muscle length’s influence on neuromuscular control.

In summary, differences in signal regularity, as measured by ApEn and DFA of the hip joint isometric moments, did not seem to be associated with individuals with patellofemoral syndrome compared with control subjects. However, CV, as a measure of neuromuscular noise amplitude, did correspond with weaker hip extensor musculature in patellofemoral subjects compared with control subjects. Additionally, the position of the knee joint, and its resultant effect on the length of hip extension moment producing musculature (such as the hamstrings), did significantly affect the signal properties of DFA, and therefore neuromotor control of the involved muscles.

5.6 References


Forrest, SM; Challis, JH; Winter, SL. (2014). The effect of signal acquisition and processing choices on ApEn values: Towards a “gold standard” for distinguishing effort levels from isometric force records. *Medical Engineering and Physics*, 36; 676-683.


Chapter 6

Discussion

6.1 Overview

Clinicians persistently search for more effective and efficient manners of treatment for individuals with knee pathologies, specifically, patellofemoral syndrome, as it is the most frequently diagnosed knee condition in adolescents and adults (Lankhorst et al., 2013). While the muscles crossing the knee joint have been widely accepted as having a role to play in knee pathology, muscles of the hip joint have also been correlated to pathologies such as patellofemoral syndrome (Souza and Powers, 2009; Prins and Van der Wurff, 2009). Speculation exists whether these muscles lack strength and/or neuromuscular control, and therefore influence patellofemoral syndrome. Information regarding the characteristics of hip musculature is needed to comprehensively understand this relationship. This dissertation consisted of three studies designed to analyze the moment-angle relationship of hip musculature, specifically the hip abductors and hip extensors. This moment-angle relationship is analyzed in multiple facets: the peak joint moment at pre-determined positions throughout an arc of motion, the gradient of the aforementioned peak moments across the arc of motion, and the joint moment fluctuations for a range of hip positions.

In the first study, subjects were examined to determine a standard of the moment-angle relationship of the hip abductors and hip extensors. Subjects produced maximal isometric joint moments on an isokinetic dynamometer at four joint positions for both hip abduction and hip extension. In addition to the four hip joint angles, two knee orientations were examined: knee extended and knee flexed to ninety degrees.

In the second study, subjects with current complaints of patellofemoral syndrome (inclusion criteria of current knee pain of at least 3 out of 10 on a 1-10 scale when performing at least two of the
following activities: ascending or descending stairs, prolonged sitting, squatting, kneeling, running, or hopping/jumping (Souza and Powers, 2009)) volunteered and were assessed for their peak hip joint moments in hip abduction and hip extension. These subjects were age and size-matched with a control group, and their data were compared.

The third study consisted of recruiting subjects with patellofemoral symptoms (inclusion criteria consisted of current knee pain of at least 3 out of 10 on a 1-10 scale when performing at least 2 of the following activities: ascending or descending stairs, prolonged sitting, squatting, kneeling, running, or hopping/jumping (Souza and Powers, 2009). These subjects were age and size-matched with a control group, and then assessed for hip joint moment fluctuations in hip abduction and hip extension. Subjects were asked to produce maximal isometric contractions for 10 seconds at pre-determined joint positions. The fluctuations of the joint moments at each position were then analyzed using approximate entropy analysis (ApEn), Detrended Fluctuation Analysis (DFA), and by computing the Coefficient of Variation (CV), and signal power.

6.2 General Findings

The subjects in study one produced a descending joint moment-angle relationship for both hip abduction and hip extension. The peak hip joint moment occurred at -15° for hip abduction, and -45° for hip extension. Peak hip joint moments did not change during abduction whether the subject’s knee was extended or flexed, however, the peak hip joint moments during extension were found to be greater with the subjects’ knees in extension compared with flexion.

The second study demonstrated that the peak hip abduction moment for the group of patellofemoral subjects did not differ from the control group’s abduction joint moment, with the knee flexed or extended. In addition, the peak hip extension moment also did not differ between the
patellofemoral group and the control group, provided the knee was in extension. However, when the knee was positioned in flexion, a difference was found in the hip extension moment between the control group and patellofemoral group, as the patellofemoral subjects exhibited less joint moment than the control subjects.

Study three provided results that showed no statistically significant differences in analysis of the fluctuations of isometric moments between the control group and the patellofemoral group, regardless of whether the knee was positioned in flexion or extension. However, DFA did demonstrate statistically significant differences between the knee positions during hip extension at hip positions of -45°, -30°, and -15°. When the knee was extended, the alpha value was close to Brown noise, which has been associated with aging and disease. When the knee was flexed, then alpha was reduced by greater than 1, which indicates an unbounded stationary signal. Additionally, CV demonstrated statistically significant differences between the control group and patellofemoral group for hip extension, with the patellofemoral group exhibiting larger CV values. This indicated the presence of greater signal noise in the hip extensor musculature of the patellofemoral group than the control group.

6.3 Discussion of Results

Study one demonstrated that knee position seems to have no effect on the isometric hip abduction joint moments. This may be due to the fact that the tensor fascia lata (TFL) is the only hip abductor to cross the knee joint and it contributes a mere 11% to the total physiological cross-sectional area of the hip abductors (Flack et al., 2012). Therefore altering knee position did not demonstrate a statistically significant difference in hip abduction joint moment. On the contrary, knee position had a statistically significant effect on the hip extension joint moment. The primary hip extensors are the uniarticular gluteus maximus (GMax) and the biarticular hamstrings. Knee flexion moves the biarticular hamstrings
to a shorter position on their force-length curve, and therefore contributes to a smaller hip extension joint moment.

The second study confirms the findings of Souza and Powers (2009) and Prins and Van der Wurff (2009) that subjects with patellofemoral symptoms demonstrate hip extensor weakness compared with control subjects. However, a difference was not found when the knee was in a position of extension. Rather a difference only occurred when the knee was in the flexed position. This position emphasizes the role of the gluteus maximus (GMax) in the production of the hip extension moment, because the position of the hamstrings on their force-length curve is shortened. The previous studies only examined hip extension with the knee in 90° of flexion, but not fully extended. It is difficult for those studies to determine the contribution of the hamstring musculature. Therefore, the results of this study indicate one of two possibilities: the group of patellofemoral subjects had weakness of the GMax, or had stronger hamstrings than their control group counterparts. Contrary to previous literature (Powers, 2010; Prins and Van der Wurff, 2009), in this study no statistically significant differences were found in the hip abduction joint moments between the control group and the patellofemoral group.

The third study attempted to assess the findings of Brindle et al. (2003) and Cowan et al. (2009), who both demonstrated neuromuscular deficits, identified through EMG, of the hip abductors in a group of patellofemoral subjects compared to a control group. Specifically, they found differences in the timing or the activation of those muscles. Through the use of ApEn, DFA, CV, and signal power analysis, no difference in the fluctuations of the moment signal produced by the hip abductors were found in this study between a group of patellofemoral subjects and a group of control subjects. In addition, no statistically significant differences were found in the signal properties of isometric hip extension moments between the two groups through ApEn, DFA, and signal power analysis. However, CV did show a statistically significant difference between the two groups, at hip extension positions of -30°, -15°, and 0°. This demonstrates that the fluctuations of the group with patellofemoral symptoms were much larger than the control group, and therefore their moment profiles had a greater amplitude of noise, indicating changes in
the neuromuscular control. These data contribute to the literature supporting deficits of the neuromuscular control of the hip musculature, specifically the hip extensors, in individuals with patellofemoral symptoms. In combination with the results of Brindle et al. (2003) and Cowan et al. (2009), the results of this study show that neural factors in two ways are deficient in patellofemoral subjects.

6.4 Clinical Implications

There are numerous clinical implications that can be inferred from the results of studies in this dissertation. In study one, since the moment-angle relationships for both hip abduction and hip extension were descending, clinicians can apply this when strengthening this musculature. For example, when performing hip abduction, the abduction joint moment decreases as the patient moves into hip abduction. Therefore, the resistance moment should mimic the joint moment, and gradually decrease as the limb is moved into hip abduction (see Chapter 3). For example, in some exercises, such as those that utilize Thera-band®, the resistance increases linearly throughout the joint’s range of motion. In addition, the position of the knee has no effect on the joint moment for hip abduction, but it plays a significant role in hip extension joint moment. Therefore, strengthening of the hip extensors should include movements against resistance with both the knee extended and the knee flexed.

In study two, although previous studies have found deficits in the hip abductors of individuals with patellofemoral symptoms, this study found more significant deficits in the hip extensors, particularly the uniarticular muscles (GMax). When treating an individual with patellofemoral symptoms, the GMax should be properly assessed and, if deficient, strengthened accordingly. Interestingly, the hip extensors were not significantly deficient with the knee extended, so another possibility from this study is the biarticular muscles (hamstrings) of patellofemoral subjects demonstrate increased strength when
compared with control subjects. There is no extent of literature showing increased strength of this biarticular musculature in subjects with patellofemoral syndrome, and whether it has been evaluated previously is unknown.

In study three, the analysis of joint moment fluctuations demonstrated that individuals with patellofemoral symptoms have greater variation, noise, in the fluctuations of their isometric hip extension joint moments. Therefore, clinicians need to be aware of the importance of neuromuscular control of this muscle group. Exercises that focus on slow eccentric control, or isometric holds of the hip extensors are just as vital as increasing the intensity of concentric exercises. This combination of activities to target strength and neuromuscular control of the hip extensors should be paramount in any comprehensive treatment program for patellofemoral pathology.

The results of these studies demonstrated that subjects with patellofemoral syndrome were found to be deficient in strength, as well as neuromuscular control, for hip extension joint moments. Specifically, the deficits occurred when the knee was flexed. This is not surprising because most complaints of pain with patellofemoral syndrome take place when the knee is in a flexed position. Clinically the hip extensor musculature should be strengthened when rehabilitating individuals with patellofemoral syndrome. In addition to strength (joint moment), the neuromuscular control, manifested by the ability of an individual to hold an isometric contraction or control an eccentric lengthening of the muscle, should be trained in individuals with this pathology.

### 6.5 Limitations of the Study

As with all studies, there are limitations in the current study. The knee positions of 0° and 90° were held statically by the subjects. A knee brace was used in a pilot study, but the bulkiness of the device interfered with accurate data collection. Whether the firing of the hamstring musculature to
stabilize the knee at 90° affected the hip joint moment being assessed is unknown. However, this method
was replicated from Souza and Powers (2009). Strength of the subjects’ abdominals, lumbar extensors,
and overall core musculature was not assessed. Deficits in any of these muscle groups may have affected
joint moment production of the hip extensors and/or hip abductors due to a lack of stability of the
common site of origin, the pelvis.

Assessing a subject’s maximum isometric joint moment is only effective if the subject is
providing maximum effort. This study made the assumption that this was the case. It is unclear if the
differences seen in the patellofemoral syndrome group were the cause of their pathology or a result of
their pathology. The data were collected under static conditions but pain is most prevalent in
patellofemoral subjects during dynamic conditions. Subjects in the patellofemoral group could have been
experiencing pain during testing, especially with the knee flexed to 90°, that may have contributed to
inhibition of the musculature during joint moment assessment, although none reported pain.

Individuals that participated in the patellofemoral group reported anterior knee pain, but there
exists a possibility that their symptoms were secondary to an inflamed infrapatellar fat pad (Dragoo et al.,
2012). While the position of knee flexion utilized in the study (90°) is not typically achieved in normal
gait kinematics, researchers have found knee flexion ranges of 83°-105° in females when descending
stairs (Livingston et al., 1991). Jevsevar et al. (1993) also reported averages of 90.3° in young subjects
and 84.1° in older subjects when descending stairs. Therefore, the position of knee flexion used in the
study does correspond to stair negotiation, a task of individuals with patellofemoral syndrome commonly
refer to as causing pain (Souza and Powers, 2009).
6.6 Clinical Relevance

The slope and direction of joint moment-angle curves have great clinical relevance to muscle strengthening and rehabilitation. In order to effectively strengthen the musculature, the moment of resistance must be matched to the moment of effort (joint moment). A typical therapeutic exercise for the hip abductors is the sidelying clamshell (Selkowitz et al., 2013) (see Appendix D). However, the resistance moment for this exercise increases linearly with an increase in hip abduction, the direct opposite of the hip abduction strength curve (see Chapter 3). Therefore, when prescribing exercises for individuals for the motions of hip abduction or hip extension, exercises that either require a descending resistance moment, or maximum isometrics at multiple angles, should be chosen in order to more closely match the hip abduction strength curve.

Through the demonstration of weakness of isometric hip extension joint moments with the knee flexed in subjects with patellofemoral syndrome (Chapter 4), clinicians should target this musculature in individuals with this pathology. An example of an exercise is quadruped hip extension with the knee flexed (Figure 6.1). The resistance moment decreases similar to the hip extension moment angle relationship found in Chapter 3; in addition, the knee is flexed to isolate the uniarticular GMax. A similar example is a unilateral bridge (Figure 6.2). The results of this study have implications for both of these exercises, which are considered appropriate for early stages of rehabilitation. Some closed chain exercises that have been shown to be appropriate for the hip abductors and hip extensors are a single limb squat and one leg deadlift (DiStefano et al., 2009). However, this study did not specifically examine closed chain activities, although such activities are appropriate for therapeutic exercises in the later stages of rehabilitation.
Figure 6.1 (Quadruped hip extension with the knee flexed, isolating the uniarticular gluteus maximus from Selkowitz et al., 2013).

Figure 6.2 (Unilateral bridge isolating the uniarticular gluteus maximus from Selkowitz et al., 2013).

Due to the deficits found in isometric hip extension joint moments as well as neuromuscular control in patellofemoral subjects compared with healthy controls, therapeutic exercises should include
specific activities to address deficits in neuromuscular control. These include activities such as isometric holds of joint moments. Other examples include improving steadiness of muscle contractions and eccentric control of joint motions, rather than focusing on increasing the intensity of resistance. For example, the exercises in Figure 6.1 and 6.2 can be slightly altered to incorporate neuromuscular control by having the subject hold the joint position for 5-10 seconds at end range, and then slowly lower the limb back to resting position (eccentric) for multiple trials.

6.7 Future Research

As stated previously, because of the uncertainty of the level of intensity of the hamstring musculature to stabilize the knee, future studies could include EMG of the musculature involved. This could provide specifically which muscles were active during the data collection. For example, is the posterior gluteus medius active when producing hip extension joint moment? Does altering the position of the hip in the transverse plane (hip internal or external rotation) change the hip extension joint moment and the musculature that contributes to it?

Multiple positions of the knee could also be assessed, therefore systematically altering the length of the hamstrings, in both subjects with patellofemoral symptoms and subjects without. This could provide data to determine the specific knee angle(s) when differences between hip extension joint moments occur. Also, collection of knee flexion joint moment could determine whether a discrepancy in hip extension joint moment, which was identified in Chapter 4, was due to the uniarticular (GMax) or the biarticular muscles.

Finally, further studies could examine the effectiveness of hip strengthening utilizing various methods; resistance moments that mimic the joint moment-angle relationships, compared with those that do not. A repeat of the current study with isokinetic joint moment assessment at various angular
velocities could determine if strength deficits of patellofemoral subjects are velocity dependent, and could address the study limitation of data being collected under static conditions.

6.8 Conclusions

In summary, it has been shown that:

1. The joint isometric moment-angle relationships of hip abduction and hip extension, from -15° to 30° and -45° to 0° respectively, exists as a descending curve. Hip extension joint moment demonstrated a statistically significant difference based on whether the knee is flexed or extended, whereas hip abduction joint moment is not dependent on knee position.

2. Subjects with patellofemoral symptoms demonstrated decreased hip extension isometric joint moments, produced with the knee in a flexed position. Subjects with patellofemoral problems showed no statistically significant differences in the peak hip abduction joint moments compared with control subjects.

3. In addition to strength deficits of the hip extensors, the subjects with patellofemoral symptoms also demonstrated greater variability, as measured by the CV, in the neuromuscular control of isometric hip extension moments than control subjects. Hip abductor musculature demonstrated no differences in neuromuscular control between individuals with patellofemoral symptoms compared with control subjects.

The hip extensor musculature has vital importance for the control of the knee joint complex. Both in its moment producing capacity and its joint moment fluctuation, the hip extensors have been shown to be deficient in patellofemoral subjects compared with healthy controls. The hip extensor musculature should be strengthened when rehabilitating individuals with patellofemoral syndrome, especially with the knee flexed. The hip extensors should also be trained for neuromuscular control, such as controlled eccentric exercise and static isometric holds at various joint angles.
6.9 References


Appendix A

Moment-Angle Relationship of Hip Musculature

Age____________ Gender (male/female)____________________

Do you have any documented cardiac conditions (arrhythmia, CHF, angina, etc.) that prevents you from engaging in physical activity? If so, please note.  Yes   No
______________________________________________

Do you have, or ever had, a diagnosis concerning one of your hips (Osteoarthritis, hip dysplasia, labral tear, surgery, etc.)?  If so, please note.  Yes   No
______________________________________________

Have you had surgery on one of your knees in the past 12 months? If so, please note.  Yes   No
______________________________________________

Have you ever been diagnosed with a knee pathology such as patellofemoral syndrome or chondromalacia patella?  Yes   No   If so, when?____________________

Do you ever experience pain in and around your patella (knee cap), especially when ascending or descending stairs, prolonged sitting, squatting, running, or hopping/jumping?  Yes   No

   If yes, which side?   Right   Left   Both

   If so, on a scale from 0-10, rate your pain underneath or around your patella. ____________
   (0=no pain, 10=excruciating pain)
Appendix B
Informed Consent Form for Biomedical Research
The Pennsylvania State University

Title of Project: Moment-Angle Relationship of Hip Musculature

Principal Investigator: John H. Challis, Ph.D.
Biomechanics Laboratory
29 Recreation Building
The Pennsylvania State University
University Park, PA 16802

Phone  +(814) 863-3675
Fax  +(814) 863-4755
Email  jhc10@psu.edu

Other Investigators: Curtis Kindel

1. Purpose of the Study: The purpose of this study is to determine the strength of the muscles around your hip joint (hip abductors, extensors, and flexors) and the relationship between hip position and strength. There is significant research lately showing a correlation between knee injuries and/or pathologies and hip muscle weakness, specifically the abductors and extensors. However, more research is required to determine WHY this weakness of the hip musculature is present.

2. Procedures to be followed: Three steps will be taken in this study. First, your height and mass will be measured. Next, you will be asked to perform a warm-up on a stationary bike for 5 minutes. Then, you will be asked to lie on your side and aligned with the Biodex (isokinetic dynamometer, a strength testing device) which will measure your hip muscle strength. Then you will be asked to lift your leg up as hard as you can into a pad at different hip positions for five repetitions. You will perform this on each leg. Then you will be asked to lean forward on your stomach and lift your thigh behind you as hard as you can for five times. We will repeat it on your other leg. The third assessment will have you lying on your back and lifting your thigh up similar to the other positions.

3. Discomforts and Risks: There are little to no risks associated with this experiment. You may feel slightly tired after performing the strength tests, but you are only asked to perform up to your maximum output for five trials. In addition, you may experience some soreness the next day if this is a muscle you do not frequently exercise with.

4. Benefits: The benefits to you from this experiment are minimal. You may realize that you need to strengthen some of the muscles around your hip. The benefits to society are a contribution to the growing body of knowledge of the relationship and possible cause of hip muscle weakness and its association to knee joint pathology/injury.

5. Duration/time of the procedures and study: Approximately 45 minutes will be required to complete participation in this research. There is only one session required for this project.
6. **Statement of confidentiality:** Your participation in this research is confidential. The data will be stored and secured at Penn State’s Biomechanics Laboratory in the Department of Kinesiology or Saint Francis University’s Department of Physical Therapy in a password protected file. In the event of any publication or presentation resulting from the research, no personally identifiable information will be shared. Records will be destroyed three years after the completion of the study.

The Pennsylvania State University’s Office for Research Protections and Institutional Review Board, and the Office for Human Research Protections in the Department of Health and Human Services may review records related to this project.

7. **Right to ask questions:** Please contact Curt Kindel at cxk444@psu.edu or ckindel@francis.edu or (814) 472-3198 with questions, complaints or concerns about the research. You can also call this number if you feel this study has harmed you. If you have any questions, concerns, problems about your rights as a research participant or would like to offer input, please contact The Pennsylvania State University’s Office for Research Protections (ORP) at (814) 865-1775. The ORP cannot answer questions about research procedures. Questions about research procedures can be answered by the research team.

8. **Voluntary participation:** Your decision to be in this research is voluntary. You can stop at any time. You do not have to answer any questions you do not want to answer. Refusal to take part in or withdrawing from this study will involve no penalty or loss of benefits you would receive otherwise. Grades and/or employment will not be affected, nor will your relationship with the principal investigator or co-investigator, if you choose to not participate or withdraw from this study.

9. **Injury Clause:** In the unlikely event you become injured as a result of your participation in this study, medical care is available. It is the policy of this institution to provide neither financial compensation nor free medical treatment for research-related injury. By signing this document, you are not waiving any rights that you have against The Pennsylvania State University/Saint Francis University for injury resulting from negligence of the University or its investigators.

You must be 18 years of age or older to take part in this research study. If you agree to take part in this research study and the information outlined above, please sign your name and indicate the date below.

You will be given a copy of this signed and dated consent form for your records.

______________________________________________  ___________________  
Participant Signature                                           Date

__________________________________________  ____________  
Person Obtaining Consent                                         Date
Appendix C

Table C.1 The means (± standard deviation) of the peak hip abduction moment and the angle at which it occurred for the male and female sub-groups. In addition the gradient of the line of the joint angle-moment relationship is reported.

<table>
<thead>
<tr>
<th>Hip Abduction (Knee extended)</th>
<th>Male Subjects (n=10)</th>
<th>Female Subjects (n=11)</th>
<th>P value (♂ versus ♀)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Moment (N.m)</td>
<td>132.5 ± 34.6</td>
<td>96.44 ± 20.7</td>
<td>0.012</td>
</tr>
<tr>
<td>Peak Moment (N.m/BW)</td>
<td>0.15 ± 0.04</td>
<td>0.15 ± 0.03</td>
<td>0.827</td>
</tr>
<tr>
<td>Angle of Peak Moment (degrees)</td>
<td>-13.5 ± 4.74</td>
<td>-15.0 ± 0.00</td>
<td>0.343</td>
</tr>
<tr>
<td>Gradient of Angle-Moment Relationship (N.m/BW/degrees)</td>
<td>-0.0014 ± 0.00058</td>
<td>-0.0015 ± 0.00045</td>
<td>0.846</td>
</tr>
</tbody>
</table>

| Hip Abduction (Knee flexed)   |                      |                        |                    |
| Peak Moment (N.m)             | 120.5 ± 33.6         | 100.5 ± 32.0           | 0.180              |
| Peak Moment (N.m/BW)          | 0.14 ± 0.04          | 0.15 ± 0.04            | 0.35               |
| Angle of Peak Moment (degrees)| -11.3 ± 5.3          | -13.6 ± 4.5            | 0.285              |
| Gradient of Angle-Moment Relationship (N.m/BW/degrees) | -0.00098 ± 0.00056 | -0.0014 ± 0.00068 | 0.187              |
Table C.2 The means (± standard deviation) of the peak hip extension moment and the angle at which it occurred for the male and female sub-groups. In addition the gradient of the line of the joint angle-moment relationship is reported.

<table>
<thead>
<tr>
<th>Hip Extension (Knee Extended)</th>
<th>Male Subjects (n=10)</th>
<th>Female Subjects (n=11)</th>
<th>P value (♂ versus ♀)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Moment (N.m)</td>
<td>199.6 ± 63.7</td>
<td>133.8 ± 41.2</td>
<td>0.014</td>
</tr>
<tr>
<td>Peak Moment (N.m/BW)</td>
<td>0.23 ± 0.084</td>
<td>0.20 ± 0.062</td>
<td>0.467</td>
</tr>
<tr>
<td>Angle of Peak Moment (degrees)</td>
<td>-44.3 ± 2.37</td>
<td>-43.6 ± 3.03</td>
<td>0.610</td>
</tr>
<tr>
<td>Gradient of Angle-Moment Relationship (N.m/BW/degrees)</td>
<td>-0.0023 ± 0.00094</td>
<td>-0.0018 ± 0.00075</td>
<td>0.193</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Hip Extension (Knee Flexed)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Moment (N.m)</td>
<td>159.2 ± 57.0</td>
<td>123.7 ± 34.9</td>
<td>0.111</td>
</tr>
<tr>
<td>Peak Moment (N.m/BW)</td>
<td>0.18 ± 0.076</td>
<td>0.19 ± 0.044</td>
<td>0.901</td>
</tr>
<tr>
<td>Angle of Peak Moment (degrees)</td>
<td>-42.0 ± 5.24</td>
<td>-40.2 ± 6.93</td>
<td>0.515</td>
</tr>
<tr>
<td>Gradient of Angle-Moment Relationship (N.m/BW/degrees)</td>
<td>-0.0018 ± 0.0012</td>
<td>-0.0016 ± 0.00079</td>
<td>0.721</td>
</tr>
</tbody>
</table>
Appendix D

A common exercise used during the stages of hip abductor strengthening is the “clam” or “clamshell” (Mascal et al., 2003). The hip abductors are often targeted for low back pain, iliotibial band syndrome, and patellofemoral syndrome (Willcox and Burden, 2013, Brindle et al., 2003).

Figure D.1 Clamshell exercise- while lying on the side with the knees bent, rotate the top leg outward against the resistance of an elastic band (Selkowitz et al., 2013). Then slowly return the top leg to its original position.
Appendix E

“Approximate Entropy- ApEn”

ApEn quantifies the negative natural logarithm of the conditional probability that a template is repeated during a time series. Matching templates that remain arbitrarily similar (within the tolerance, r) are then counted, the number of matches to the ith template of length m is designated $B_i$. Then the number of these matches that remain similar for the $m+1^{th}$ point is counted, this number for the $i^{th}$ template is designated $A_i$. The conditional probability that the template including the $m+1^{th}$ data point matches given that the template of length $m$ is then calculated for each template match. The negative logarithm of the conditional probability is calculated for all templates and the results averaged (Equation). If the data is highly ordered then templates are similar for $m$ points are likely to also be similar for $m+1$ points. For such data sets the conditional probability will therefore be close to 1, and the negative log and therefore the entropy will be close to zero (Richman et al., 2004).

$$ApEn(m, r, N) = \frac{1}{N-m} \sum_{i=1}^{N-m} \log \frac{A_i}{B_i}$$ [e.1]

Low ApEn values correspond to regular time series, while high values correspond to irregular series (Figure E.1).
Figure E.1 Examples of ApEn values, for different signals: a) Saw-tooth, b) Sine wave, c) White noise.
Appendix F

“Detrended Fluctuation Analysis- DFA”

Detrended Fluctuation Analysis (DFA) is an analysis technique designed to examine for the presence of long or short term correlations. The DFA is a data analysis technique which has been utilized to determine the presence of long or short term correlations in moment data in the time domain (e.g., Vaillancourt and Newell, 2003). The DFA has been used to analyze a variety of biological signals, in its original presentation (Peng et al., 1994) for example, it was used to examine DNA sequences. Using this statistic, the moment signal is integrated to form an accumulated sum (Figure F.1b). Then the signal is divided into sections (Figure F.1c), and the linear trend is determined for each box. The signal in each box is detrended using linear fit, and the residuals are averaged for all boxes and the square root or mean residual is composed. This process is repeated for a range of box sizes (from 4 to n/4). The gradient of the plot log of box size against log of the mean residuals indicates some type of power-law is present in the data (Figure F.1d). The gradient, or scaling exponent, is referred to as alpha ($\alpha$). $0 < \alpha < 0.5$ indicates long-range anti-correlations in the data set, an alpha value of 0.5 indicates completely uncorrelated or white noise, $0.5 < \alpha < 1.0$ indicates long-range correlations, an alpha value of 1.0 indicates 1/f noise, and an alpha of 1.5 indicates Brown noise.

It has been proposed that aging and disease are associated with either random noise or Brown noise (Goldberger et al., 2002).
Figure F.1 Demonstration of the DFA procedure: a) white noise, b) integrated white noise, c) integrated white noise with a linear trend identified, d) the slope of the log-log plot is the scaling parameter, $\alpha$. 
Appendix G

The joint moment data was analyzed from Chapter 5 using ApEn, DFA, CV, and signal power. Individual hip joint positions were compared across two knee positions (flexion and extension) and pathology (patellofemoral subjects versus control subjects). The following tables provide the p-values from the analysis of variance (ANOVA).

Table G.1 Approximate Entropy- Analysis of variance of knee position, presence of pathology, and interaction of both across each angle of hip abduction and hip extension examined. No statistically significant differences were found.

<table>
<thead>
<tr>
<th>Approximate Entropy (ApEn)</th>
<th>Knee position (flexed vs extended) (p-value)</th>
<th>Pathology (P-F vs controls) (p-value)</th>
<th>Interaction (Knee position * Pathology) (p-value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip Abduction (-15°)</td>
<td>0.41</td>
<td>0.44</td>
<td>0.94</td>
</tr>
<tr>
<td>Hip Abduction- (0°)</td>
<td>0.93</td>
<td>0.90</td>
<td>0.91</td>
</tr>
<tr>
<td>Hip Abduction- (15°)</td>
<td>0.90</td>
<td>0.26</td>
<td>0.40</td>
</tr>
<tr>
<td>Hip Abduction- (30°)</td>
<td>0.80</td>
<td>0.27</td>
<td>0.90</td>
</tr>
<tr>
<td>Hip Extension (-45°)</td>
<td>0.19</td>
<td>0.99</td>
<td>0.86</td>
</tr>
<tr>
<td>Hip Extension- (-30°)</td>
<td>0.08</td>
<td>0.41</td>
<td>0.78</td>
</tr>
<tr>
<td>Hip Extension- (-15°)</td>
<td>0.16</td>
<td>0.35</td>
<td>0.95</td>
</tr>
<tr>
<td>Hip Extension- (0°)</td>
<td>0.63</td>
<td>0.55</td>
<td>0.91</td>
</tr>
</tbody>
</table>
Table G.2 Detrended Fluctuation Analysis- Analysis of variance of knee position, presence of pathology, and interaction of both across each angle of hip abduction and hip extension examined. (asterisk denotes statistical significance)

<table>
<thead>
<tr>
<th>Detrended Fluctuation Analysis (DFA)</th>
<th>Knee position (flexed vs extended) (p-value)</th>
<th>Pathology (P-F vs controls) (p-value)</th>
<th>Interaction (Knee position * Pathology) (p-value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip Abduction (-15°)</td>
<td>0.26</td>
<td>0.34</td>
<td>0.07</td>
</tr>
<tr>
<td>Hip Abduction- (0°)</td>
<td>0.98</td>
<td>0.37</td>
<td>0.43</td>
</tr>
<tr>
<td>Hip Abduction- (15°)</td>
<td>0.46</td>
<td>0.14</td>
<td>0.75</td>
</tr>
<tr>
<td>Hip Abduction- (30°)</td>
<td>0.50</td>
<td>0.13</td>
<td>0.79</td>
</tr>
<tr>
<td>Hip Extension (-45°)</td>
<td>0.03*</td>
<td>0.37</td>
<td>0.35</td>
</tr>
<tr>
<td>Hip Extension- (-30°)</td>
<td>0.01*</td>
<td>0.78</td>
<td>0.30</td>
</tr>
<tr>
<td>Hip Extension- (-15°)</td>
<td>0.03*</td>
<td>0.34</td>
<td>0.58</td>
</tr>
<tr>
<td>Hip Extension- (0°)</td>
<td>0.41</td>
<td>0.98</td>
<td>0.31</td>
</tr>
</tbody>
</table>
Table G.3 Coefficient of Variation- Coefficient of variation of knee position, presence of pathology, and interaction of both across each angle of hip abduction and hip extension examined. (asterisk denotes statistical significance)

<table>
<thead>
<tr>
<th>Coefficient of Variation</th>
<th>Knee position (flexed vs extended) (p-value)</th>
<th>Pathology (P-F vs controls) (p-value)</th>
<th>Interaction (Knee position * Pathology) (p-value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip Abduction (-15°)</td>
<td>0.98</td>
<td>0.85</td>
<td>0.88</td>
</tr>
<tr>
<td>Hip Abduction- (0°)</td>
<td>0.31</td>
<td>0.77</td>
<td>0.19</td>
</tr>
<tr>
<td>Hip Abduction- (15°)</td>
<td>0.20</td>
<td>0.53</td>
<td>0.40</td>
</tr>
<tr>
<td>Hip Abduction- (30°)</td>
<td>0.46</td>
<td>0.66</td>
<td>0.97</td>
</tr>
<tr>
<td>Hip Extension (-45°)</td>
<td>0.20</td>
<td>0.26</td>
<td>0.07</td>
</tr>
<tr>
<td>Hip Extension- (-30°)</td>
<td>0.03*</td>
<td>0.02*</td>
<td>0.15</td>
</tr>
<tr>
<td>Hip Extension- (-15°)</td>
<td>0.14</td>
<td>0.06*</td>
<td>0.05*</td>
</tr>
<tr>
<td>Hip Extension- (0°)</td>
<td>0.18</td>
<td>0.02*</td>
<td>0.24</td>
</tr>
</tbody>
</table>
Table G.4 Signal Power- Signal power of knee position, presence of pathology, and interaction of both across each angle of hip abduction and hip extension examined.

<table>
<thead>
<tr>
<th>Power</th>
<th>Knee position (flexed vs extended) (p-value)</th>
<th>Pathology (P-F vs controls) (p-value)</th>
<th>Interaction (Knee position * Pathology) (p-value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip Abduction (-15°)</td>
<td>0.40</td>
<td>0.94</td>
<td>0.18</td>
</tr>
<tr>
<td>Hip Abduction- (0°)</td>
<td>0.28</td>
<td>0.37</td>
<td>0.37</td>
</tr>
<tr>
<td>Hip Abduction- (15°)</td>
<td>0.27</td>
<td>0.01</td>
<td>0.80</td>
</tr>
<tr>
<td>Hip Abduction- (30°)</td>
<td>0.69</td>
<td>0.71</td>
<td>0.87</td>
</tr>
<tr>
<td>Hip Extension (-45°)</td>
<td>0.79</td>
<td>0.48</td>
<td>0.45</td>
</tr>
<tr>
<td>Hip Extension- (-30°)</td>
<td>0.77</td>
<td>0.36</td>
<td>0.65</td>
</tr>
<tr>
<td>Hip Extension- (-15°)</td>
<td>0.45</td>
<td>0.20</td>
<td>0.79</td>
</tr>
<tr>
<td>Hip Extension- (0°)</td>
<td>0.91</td>
<td>0.36</td>
<td>0.82</td>
</tr>
</tbody>
</table>
VITA

Curtis C. Kindel

CURTIS C. KINDEL PT, MPT, OCS
Department of Physical Therapy, Saint Francis University
PO Bo 600, Loretto, PA 15940
(814) 472-3198 ckindel@francis.edu

Education: The Pennsylvania State University
University Park, PA
2010-present
Ph.D. in Kinesiology/ Anticipated graduation- May 2015

Saint Francis University Loretto, PA
1998-2001
Master of Physical Therapy 2001

Saint Francis University Loretto, PA
1995-1999
Bachelor of Health Science 1999

Employment and Positions Held:
Assistant Professor of Physical Therapy
Saint Francis University 2007-present

Staff Physical Therapist-per diem
Drayer Physical Therapy Institute 2008-present

Adjunct Instructor/ Lab Assistant
Saint Francis University 2003-2007

Clinical Director/Physical Therapist
ProCare Health Systems Inc. 2003-2007

Presentations: