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Lower Extremity Biomechanics During Single Leg Drop Landings in Individuals with Patellofemoral Pain

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LOWER EXTREMITY BIOMECHANICS DURING SINGLE LEG DROP LANDINGS IN INDIVIDUALS WITH PATELLOFEMORAL PAIN

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ABSTRACT

LOWER EXTREMITY BIOMECHANICS DURING SINGLE LEG DROP LANDINGS IN INDIVIDUALS WITH PATELLOFEMORAL PAIN

by

Stacey L. Gaven, ATC
Old Dominion University, 2013
Director: Bonnie Van Lunen

Patellofemoral joint pain (PFP) is one of the most common afflictions of the active population. While etiological factors encompassing the entire lower extremity have been associated with PFP, participation in athletic activities while fatigued may further influence abnormal biomechanics in individuals with this condition. The aim of Project I was to investigate the lower extremity (LE) biomechanics during a single leg(SL) drop landing in individuals with and without PFP. Project II aimed to investigate the LE biomechanics of individuals with PFP during a SL drop landing pre and post an aerobic exercise protocol. Project III investigated the LE biomechanics of individuals with PFP during a SL drop landing pre and post an isolated hip abduction fatigue protocol.

Twenty-two physically active individuals(11 PFP, 11 control) participated in Project I. Participants performed SL drop landings from three heights(20, 30, and 40cm). Eleven physically active individuals with PFP participated in Project II. Participants performed SL drop landings at three heights, pre and post an aerobic exercise protocol. Twenty physically active individuals with PFP participated in Project III. Participants in this study performed SL drop landings from three heights pre and post an isolated hip

abduction fatigue protocol. Three-dimensional kinematics and kinetics were recorded and assessed using 2x3 repeated measure ANOVAs($P \leq 0.05$) in all projects.

For Project I, the results demonstrated that individuals with PFP landed with less knee flexion(-48.43±7.16°) compared to the control group(-56.43±7.16°)($P=0.017$) at the instance of maximum knee flexion(MaxKF) suggests that the PFP group employ a stiffer landing pattern and may not attenuate the forces imposed on the LE as well as a healthy individual. In Project II, an increase in knee flexion at MaxKF was demonstrated in the post fatigue landings(-50.78±6.96°) compared to the pre fatigue landings(-48.43±6.37°)($P=0.49$) suggesting that individuals with PFP may demonstrate a decreased ability to control the forces of a SL landing due to fatigue. Project III, a decrease in hip external rotation moment was present following the fatigue protocol(Pre:0.25±0.12Nm, Post;0.28±0.10Nm;$P=0.047$) at MaxKF despite this result, project III does not support a significant link between altered LE biomechanics during SL landings following an isolated hip abduction fatigue protocol.

ACKNOWLEDGEMENTS

Well, I have finally made it to the end of my PhD. journey. When I first started at ODU I was unsure of what this journey had in store for me, but I am grateful for the opportunities I have had, the people I have met, and the person I have become.

I would like to thank Bonnie, for taking a chance on the "quiet" kid from Jersey and allowing me this opportunity to pursue my PhD. I have learned far more than I would have ever expected and although challenging at times, I have enjoyed this journey. So for that, please know that I am extremely appreciative of your time and effort that you have given to me.

To my parents for always believing in me and encouraging me to spread my wings and go with the opportunities that life provides. You have both been a constant support in my life and have provided me with so much. You provided me with a solid foundation to become the person I am today and for that I thank you. To the rest of my family, we may be a big, loud, crazy bunch, but I wouldn't trade the love and support we have for each other for anything in this world. I am grateful for all the support you have provided me with.

To my wolf pack, what can I say, it's been a heck of an adventure with you ladies and I know that there are only more shenanigans together in our future! Dorice, thanks for being a voice of reason and constant support, I know one day that you will find your love for running. Manspeaker, thanks for showing me the teaching ropes and all of your support these past 4 years and providing me with crazy things....purple unitard...enough said! Cailee, thanks for being a great officemate and friend, I'm not sure anyone else has as much skills as we do with office chair races.

To the Wades, two of the finest people I have ever met! Josh and Shannon, thanks for your constant support and encouragement. You are both an amazing example of where a positive attitude can get you in life and what that provides to others. I love all the races we have been part of together as both runners and cheer squad members and I can't wait to do more with you guys!

To my fellow doc students both past and present, thanks for the support and friendships throughout this journey. Only those who are fully involved in this process understand what it takes to survive, plus you always need someone to have 50 cent tacos with. To the master students who I have had the pleasure of interacting with during my time at ODU, I thank each of you for the different ways you have enriched my life. While at times we may have been on the struggle bus together, we have all accomplished what we set out to do and for that we should all be proud.

There are many others who played a role in this journey and for all who have been involved in this some way at some time with me, I thank you. I'll leave the rest of my thoughts with one of my favorite Dr. Seuss quotes " You have brains in your head. You have feet in your shoes, You can steer yourself any direction you choose. You're on your own. And you know what you know. And YOU are the guy who'll decide where to go." So thanks to all who have enriched the brain in my head, increased the confidence in the feet in my shoes, and support the directions I choose to go!

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LIST OF PUBLICATIONS

The following manuscripts support the compilation of this dissertation:

Gaven, SL., Glass, MJ., Weinhandl, J., & Van Lunen, BL. (2013). Lower extremity biomechanics in individuals with and without patellofemoral pain during a single leg drop landing. To be submitted to *Clinical Journal of Sports Medicine.*

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Gaven, SL., Boling, MC., Russell, DM., & Van Lunen, BL. (2013). Single leg landing biomechanics in individuals with patellofemoral pain following an isolated hip abduction fatigue protocol. To be submitted to *Journal of Orthopaedic and Sports Physical Therapy.*

CHAPTER I

INTRODUCTION

Generalized anterior knee pain (AKP) or patellofemoral joint pain (PFP) is one of the most common afflictions of the active population (Almeida, Trone, Leone, Shaffer, Patheal, & Long 1999; Hutchinson & Ireland, 1995; Brindle, Mattacola, McCrory, 2003). Anterior knee pain, a symptom common in overuse knee disorders, is often used synonymously with PFP because it is often a precursor to the syndrome (Van Tiggelen, Witvrouw, Roget, Cambier, Danneels, & Verdonk, 2004; Lorberboym, Ben Ami, Zin, Nikolov, & Adar, 2003; Naslund, Naslund, Odenbring, & Lundeberg, 2006). The more chronic condition of PFP is deemed as the most common orthopedic complaint with respect to young individuals, especially the female population (Devereaux & Lachmann, 1984, Sanchis-Alfonso, Rosello-Sastre, Martinez-Sanjuan, 1999, Tauton, Ryan, Clement, McKenzie, Llyod-Smith, & Zumbo, 2002, Wilson & Davis, 2007). Nearly 10% of all sports injury clinic visits by physically active individuals and up to 40% of clinical visits for knee problems are attributed to patellofemoral pain (Kannus, Aho, Jarvinen, Niittymaki, 1987; Waryasz & McDermott, 2008; Myer, Ford, Barber Foss, Goodman, Ceasar, Rauh, Divine, & Hewett, 2010). Individuals who suffer from PFP present with insidious and diffuse pain in the anterior aspect of the knee that is aggravated during ascending or descending stairs, squatting, and prolonged sitting (Heintjes, Berger, Bierna-Zeinstra, Bernsen, Verhaar, & Koes, 2000; Nakagawa, Muniz, Baldon, Maciel, Amorim, & Serrao, 2010). In addition, walking, running, ascending and descending slopes and kneeling have also been found to aggravate symptoms of PFP (Gross, & Foxworth, 2003; Barton, Munteanu, Menz, & Crossley, 2010).

Despite having a clear picture of what activities aggravate the symptoms of PFP, the specific cause of PFP is unknown as there could be multiple contributing factors (Earl & Hoch, 2011). Biomechanical and musculoskeletal factors both proximal and distal to the patellofemoral joint have been attributed to being causative factors of PFP. Previous research has attributed an abnormally large quadriceps angle, a high pelvis width to femoral length ratio, an imbalance between the vastus lateralis and vastus medialis muscles, and tibiofemoral abduction angular impulse as being some of the factors associated with PFP (Cowan, Bennell, Hodges, Crossley, & McConnell, 2001; Fulkerson & Arendt, 2000; Horton & Hall, 1989; Powers, 2003; Stefanyshyn, Stergiou, Lun, Meeuwisse, & Worobets, 2006; Wilson, Binder-Macleod, & Davis, 2008). Each of these factors may alter the orientation of the pull of the quadriceps, thereby changing the distribution of load across the retropatellar surface and in turn increasing retropatellar stress (Wilson et al., 2008). Recently the influence of hip muscular strength, especially the hip abductors and external rotators, has been a focal point of PFP research (Wilson et al., 2008; Powers, 2003; Piva, Fitzgerald, Irrgang, Jones, Hando, Browder, & Childs, 2005). Poor hip control may lead to maltracking of the patella which in turn can result in increased pressure on the patellofemoral joint and lead to wearing of the articular cartilage (Powers, 2003). Weakness in the hip abductors and hip external rotators may result in increased femoral rotation and knee valgus moments thereby increasing the compressive forces at the patellofemoral joint (Piva et al., 2005). Repetitive movements with this malalignment during functional activities can overload the patellar retinaculum and retropatellar articular cartilage and cause pain (Baldon et al., 2009). Repetitive exposure to high levels of stress is believed to lead to degeneration of the inert patellar cartilage, which further increases the load to underlying subchondral bone, resulting in pain (Willson et al., 2008). Certain high loading conditions of the patellofemoral joint can be of sufficient magnitude to induce the symptomatic loss of tissue homeostasis so that once initiated, may persist indefinitely (Dye, 2005).

In addition to these etiological factors proximal to the patellofemoral joint, PFP has been highly correlated with excessive foot pronation (James, Bates, Osternig, 1978; Jernick & Heifitz, 1979; McConnell, 1984, Eng & Peirrynowski, 1993). The excessive subtalar pronation during the stance phase can alter the degree of tibial rotation thereby altering the normal biomechanics of the patellofemoral joint (James et al., 1978; Muller, 1983; Tiberio, 1987; Eng & Pierrynowski, 1993). Hyperpronation of the foot and the resulting increased internal rotation of the tibia and femur during gait may increase the lateral tracking of the patella on the distal femur and create abnormal patellofemoral joint reaction forces (Tiberio, 1987; Hertel, Sloss, & Earl, 2005). This excessive pronation of the foot during weight bearing may lead to increased strain on soft tissue and compression forces on the joints, which can become symptomatic (Tiberio, 1987; Khamis & Yizhar, 2007). It has been demonstrated that individuals with pes planus foot structure are at an increased risk for sustaining ankle sprains, knee injuries, and other overuse injuries such as metatarsal stress fractures and PFP (Kaufman, Brodine, Shaffer, Johnson, & Cullison, 1999; Levy, Mizel, Wilson, Fox, McHale, & Taylor, 2006; Simkin, Leichter, & Giladi, 1989; Williams, McClay, & Hamill, 2001, Queen, Mall, Nunley, & Chuckpaiwong, 2008). Consequences of PFP may include pain during functional activities (Crossley. Zhang, Schache, Bryant, & Cowan. 2011), a reduction in activity level, (Earl & Hoch, 2011), and an increased risk of developing patellofemoral osteoarthritis later in life (Utting, Davies, & Newman, 2005).

While etiological factors encompassing the entire lower extremity have been associated with PFP, participation in athletic activities while fatigued may further influence abnormal biomechanics in individuals with this condition (Willson et al., 2008). Reaction time, (Hakkinen & Komi 1986; Kellis & Kouvelioti, 2009) movement coordination and motor control precision, (Sparto, Parniarpour, Reinsel, & Simon, 1997; Kellis & Kouvelioti, 2009) and a reduction in muscle force generation capacity (Nicol, Komi, & Marconnet, 1991a; Kellis & Kouvelioti, 2009) have been found to be affected by prolonged physical exertion. When an individual is fatigued the adverse effects of fatigue may cause changes to neuromuscular control (McLean, Felin, Suedekum, Calabrese, Passerallo, & Joy, 2007; Benjaminse, Habu, Sell, Abt, Fu, Myers, & Lephart, 2007). Fatigue has also been shown to have an effect on the vastus medials oblique to vastus lateralis ratio in individuals with PFP (Callaghan, McCarthy, & Oldham, 2001; Ott, Cosby, Grindstaff, & Hart, 2011). The altered lower extremity mechanics may increase the associated risk for PFP, while the individual is in a fatigued state in addition to the altered activation of the VMO and VL (Coventry, O'Connor, Hart, Earl, & Ebersole, 2006; Madigan & Pidocoe, 2003;Willson et al., 2008).

As the specific cause of PFP is not well understood and may be from a variety of factors, gaining an understanding of how the condition impacts the lower extremity biomechanics of individuals with PFP may provide the clinician or researcher with valuable information pertaining to the treatment of those with the condition (Crossley, Bennel, Cowan, & Green, 2004). The use of appropriate measurement tools are imperative for the clinician to effectively monitor treatment and patient response and for the researcher to make informed decisions about treatment effects in clinical trials (Crossley et al., 2004). Disability, pain, and function are most often assessed in PFP (Crossley et al., 2004). The symptom of pain is the most prevalent in individuals with PFP making the use of a pain scale important in assessing what activities exacerbate patients' symptoms of pain (Crossley et al., 2004). The numeric rating scale (NRS) allows an individual to subjectively rate their pain on an 11-point scale where 0 represents "no pain" and 10 represents "worst pain possible"(Selfe, Bourguigon, & Taylor, 2008). Patellofemoral pain has an impact on many aspects of daily life, including the ability to perform exercise or work related activities. The utilization of the anterior knee pain scale (AKPS or Kujala) can be implemented in the clinical setting to allow the individual to self-assess how their PFP affects the function of their knee (Crossley et al., 2004). Additionally, the global rating of change (GRoc) allows the individual to quantify their improvement or deterioration in their knee pain and function over time (Kamper, Maher, & Mackay, 2009). While there is no standard measure to assess outcomes of treatment for PFP, studies have traditionally used a combination of outcome measures that assess pain, disability, and functional capacity of individuals with PFP (Crossley et al., 2004).

When investigating causes of PFP, it is important to track an individual's pain and function while performing tasks that may exacerbate PFP symptoms. The majority of previous research has utilized two legged landings, while many activities (running, cutting, landing from a jump) occur on a single leg (Coventry et al., 2006). Gaining an understanding of how the joints of the lower extremity act to absorb a single leg landing is important in understanding the mechanics employed that may differ from a two legged landing. The vertical ground reaction forces during single leg landings are high and have been shown to reach 11 times body weight (McNitt-Gray, 1991;Kellis & Kouvelioti, 2009). It is important to consider the role of all lower extremity joints in controlling the body as the joints of the lower extremity act in concert to regulate the transfer of mechanical energy absorption during the landing process (Prilutsky & Zatsiorsky, 1994: Schmitz, Kulals, Perrin, Riemann, & Schultz, 2007). The internal and external forces on the joints of the lower extremity can be altered by changing the kinematic patterns (i.e. flexion/extension, adduction/abduction, rotation) of the lower extremity (Zhang, Bates, & Dufek, 2000; Devita & Skelly, 1992; Schmitz et al., 2007). Since landing is a dynamic task requiring movement at multiple joints, individuals may use altered activation and movement strategies when fatigued (Kellis & Kouvelioti, 2009). Muscles are thought to play a primary role in energy and shock absorption during landing, it has been hypothesized that reduced muscular function as a result of fatigue, decreases the shock absorbing capacity of the body and subsequently can lead to an increased chance of injury (Radin, 1986; Verbitsky, Mizrani, Boloshin, Treiger, & Isakov, 1998; Voloshin, Mizrani, Verbitsky, & Isakov, 1998; Coventry et al., 2006). Participation in athletic activities while fatigued may lead to the increased tendency to utilize altered lower extremity mechanics and increase associated risks for PFP (Willson et al., 2008).

Individuals with PFP experience peripatellar pain during repetitive knee flexion associated with weight-bearing activities such as running, jumping, and climbing stairs, (Willson et al., 2008) all which involve single leg landings; therefore having an understanding of the biomechanics during single leg landings in individuals with PFP may help the clinician in the evaluation and treatment of these individuals. Furthermore, investigating the lower extremity biomechanics during single leg landings after prolonged exertional activity may provide the clinician with a better understanding as to whether the biomechanics are altered due to fatigue or if altered biomechanics are present as a result of PFP. A better understanding of the effects of fatigue on the lower extremity biomechanics in individuals with PFP may lead to improvements in injury prevention and rehabilitation techniques to minimize the occurrence of fatigue-related injuries.

Project I

Statement of the Problem

The purpose of this study is to compare lower extremity kinetics and kinematics in individuals with and without PFP during single leg drop landings from various heights.

Aim of Research

We aim to identify lower extremity kinetics and kinematics that may be different in individuals with PFP compared to healthy individuals during single leg drop landings from various heights.

Null Hypothesis

There will be no statistically significant differences in the lower extremity kinetics and kinematics in individuals with PFP compared to healthy individuals during single leg drop landings from various heights at the point of initial contact and maximum knee flexion.

Research Hypotheses

1. There will be a statistically significant difference in the lower extremity kinematics during single leg drop landings from various heights in individuals with PFP compared to healthy individuals at the point of initial contact and maximum knee flexion.

1A. There will be a statistically significant increase in rearfoot eversion (Chuter & Janse de Jonge, 2012), decrease in ankle dorsiflexion (Chuter & Janse de Jonge, 2012), decrease in knee flexion (Abbas & Diss, 2011), increase in knee abduction (Munkh-Erdene, Sakamoto, Nakazawa, Aoyagi, & Kasuyama, 2011, increase in knee internal rotation (Dierks, Davis, & Hamill, 2010), decreases in hip flexion (Olson, Chebny, Willson, Kernozek, & Straker, 2011), increase in hip adduction (Willson & Davis, 2009), and increase in hip internal rotation (Munkh-Erdene et al., 2011) in the PFP group compared to those in the healthy group during single leg drop landings at initial contact.

1B. There will be a statistically significant increase in rearfoot eversion (Chuter & Janse de Jonge, 2012), decrease in ankle dorsiflexion (Chuter & Janse de Jonge, 2012), decrease in knee flexion (Abbas & Diss, 2011), increase in knee abduction (Munkh-Erdene et al., 2011), increase in knee internal rotation (Munkh-Erdene et al., 2011) decreases in hip flexion (Olson et al., 2011), increase in hip adduction (Willson & Davis, 2009), and increase in hip internal rotation (Munkh-Erdene et al., 2011) in the PFP group compared to those in the healthy group during single leg drop landings at maximum knee flexion.

2. There will be a statistically significant difference in the lower extremity kinetics during single leg drop landings from various heights in individuals with PFP compared to healthy individuals at initial contact and maximum knee flexion.

2A. There will be a statistically significant increase in rearfoot inversion moment (Chuter & Janse de Jonge, 2012), decrease in ankle plantarflexion moment (Chuter & Janse de Jonge, 2012), decrease in knee extension moment (Abbas & Diss, 2011), increase in knee adduction moment (Munkh-Erdene et al., 2011), increase in knee external rotation moment (Munkh-Erdene et al., 2011), decrease in hip extension moment (Olson et al., 2011), increase in hip abduction moment (Willson & Davis, 2009), and increase in hip external rotation moment (Munkh-Erdene et al., 2011) in the PFP group compared to those in the healthy group during single leg drop landings at maximum knee flexion.

3. There will be a statistically significant increase in NRS scores after completing the single leg drop landings in individuals with PFP.

Independent Variables

1. Group
    - A. PFP
    - B. Control
2. Drop Landing Heights
    - A. 20 centimeters (cm)
    - B. 30 cm
    - C. 40 cm

Dependent Variables

1. Kinematic (At Initial Contact and Maximum Knee Flexion)
    - A. Rearfoot Eversion (degrees)
    - B. Ankle Dorsiflexion (degrees)

C. Knee Flexion (degrees)

D. Knee Abduction (degrees)

E. Knee Internal Rotation (degrees)

F. Hip Flexion (degrees)

G. Hip Adduction (degrees)

H. Hip Internal Rotation (degrees)

2. Kinetic (At Maximum Knee Flexion)

A. Rearfoot Inversion Moment (Newton meters)(Nm)

B. Ankle Plantarflexion Moment (Nm)

C. Knee Extension Moment (Nm)

D. Knee Adduction Moment (Nm)

E. Knee External Rotation Moment (Nm)

F. Hip Extension Moment (Nm)

G. Hip Abduction Moment (Nm)

H. Hip External Rotation Moment (Nm)

Assumptions

1. The motion capture cameras and force plates will be accurately calibrated for each subject throughout the experiments.
2. All subjects will be truthful when completing the inclusion questionnaire.
3. All subjects in the PFP group will be truthful when answering all the demographic questionnaires (Kujala and NRS).
4. Each subject will perform the drop landings as requested by the researcher.

Limitations

1. All subjects will not be tested at the same time of day. This may be a limitation as subjects tested later in the day may be at elevated levels of pain due to performing activities of daily living (ADLs) that exacerbate their symptoms.
2. Each subject will have varying degrees of participation in activities and years of sport participation that may influence their drop landing skills.
3. Foot type of the subjects will not be assessed. Foot posture is commonly assessed in individuals with lower extremity overuse injuries such as PFP as it has been theorized that excessive foot pronation is linked to kinematic variables that play a role in the loading of the patellofemoral joint (Powers, Ward, Fredericson, Guillet, & Shellock, 2003; Lee, Morris, & Csintalan, 2003; Boling, Padua, Marshall, Guskiewicz, Pyne, & Beutler, 2009; Barton, Levinger, Crossley, Webster, & Menz, 2011).

Delimitations

1. All subjects will wear the same athletic shoes for testing.
2. All subjects will be physically active, which is defined as participating in exercise for at least 30 minutes per day, 3 times per week, with at least 2 of those days including participation in activities that require jumping or landing (i.e. tennis, soccer, basketball, running, plyometrics, etc).
3. Subjects with a history of cardiovascular abnormality or a history of previous knee surgery or any lower extremity (hip, knee, ankle, foot) injury in the past 6 months will be excluded from participation.
4. Subjects who are pregnant or can not perform the tasks required of the study will be excluded.

5. Subjects who are between the ages of 18 and 30 years old will participate in this study.

Project II

Statement of the Problem

The purpose of this study is to compare lower extremity kinetics and kinematics in individuals with PFP during single leg drop landings from various heights after an aerobic exercise protocol.

Aim of Research

We aim to identify lower extremity kinetics and kinematics that may be altered during single leg drop landings from various heights in individuals with PFP after participating in an aerobic exercise protocol.

Null Hypothesis

1. There will be no statistically significant differences in the lower extremity kinetics and kinematics in individuals with PFP during single leg drop landings from various heights at the point of initial contact and maximum knee flexion after participating in an aerobic exercise protocol.
2. There will be no statistically significant difference in NRS scores or GRoc scores in individuals with PFP after participating in an aerobic exercise protocol.

Research Hypotheses

1. There will be a statistically significant difference in the lower extremity kinematics during single leg drop landings from various heights at the point of initial contact and maximum knee flexion in individuals with PFP after participating in an aerobic exercise protocol.

1A. There will be a statistically significant increase in rearfoot eversion (Chuter & Janse de Jonge, 2012), decrease in ankle dorsiflexion (Chuter & Janse de Jonge, 2012), decrease in knee flexion (Abbas & Diss, 2011), increase in knee abduction (Munkh-Erdene, Sakamoto, Nakazawa, Aoyagi, & Kasuyama, 2011, increase in knee internal rotation (Dierks, Davis, & Hamill, 2010), decreases in hip flexion (Olson, Chebny, Willson, Kernozek, & Straker, 2011), increase in hip adduction (Willson & Davis, 2009), and increase in hip internal rotation (Munkh-Erdene et al., 2011) during single leg drop landings at the point of initial contact in individuals with PFP after participating in an aerobic exercise protocol.

1B. There will be a statistically significant increase in rearfoot eversion (Chuter & Janse de Jonge, 2012), decrease in ankle dorsiflexion (Chuter & Janse de Jonge, 2012), decrease in knee flexion (Abbas & Diss, 2011), increase in knee abduction (Munkh-Erdene, Sakamoto, Nakazawa, Aoyagi, & Kasuyama, 2011, increase in knee internal rotation (Dierks, Davis, & Hamill, 2010), decreases in hip flexion (Olson, Chebny, Willson, Kernozek, & Straker, 2011), increase in hip adduction (Willson & Davis, 2009), and increase in hip internal rotation (Munkh-Erdene et al., 2011) during single leg drop landings at the point of maximum knee flexion in individuals with PFP after participating in an aerobic exercise protocol.

2. There will be a statistically significant difference in the lower extremity kinetics during single leg drop landings from various heights at the point of initial contact and maximum knee flexion in individuals with PFP after participating in an aerobic exercise protocol.

2A. There will be a statistically significant increase in rearfoot inversion moment (Chuter & Janse de Jonge, 2012), decrease in ankle plantarflexion moment (Chuter &

Janse de Jonge, 2012), decrease in knee extension moment (Abbas & Diss, 2011), increase in knee adduction moment (Munkh-Erdene et al., 2011), increase in knee external rotation moment (Munkh-Erdene et al., 2011), decrease in hip extension moment (Olson et al., 2011), increase in hip abduction moment (Willson & Davis, 2009), and increase in hip external rotation moment (Munkh-Erdene et al., 2011) during single leg drop landings at the point of maximum knee flexion in individuals with PFP after participating in an aerobic exercise protocol.

3. There will be a statistically significant increase in NRS scores after completing the single leg drop landings and post aerobic exercise protocol in individuals with PFP.

Independent Variables

1. Time
    - A. Pre Aerobic Exercise Protocol
    - B. Post Aerobic Exercise Protocol
2. Drop Landing Heights
    - A. 20 centimeters (cm)
    - B. 30 cm
    - C. 40 cm

Dependent Variables

1. Kinematic (At Initial Contact and Maximum Knee Flexion)
    - A. Rearfoot Eversion (degrees)
    - B. Ankle Dorsiflexion (degrees)
    - C. Knee Flexion (degrees)
    - D. Knee Abduction (degrees)

E. Knee Internal Rotation (degrees)

F. Hip Flexion (degrees)

G. Hip Adduction (degrees)

H. Hip Internal Rotation (degrees)

2. Kinetic (At Maximum Knee Flexion)

A. Rearfoot Inversion Moment (Newton meters)(Nm)

B. Ankle Plantarflexion Moment (Nm)

C. Knee Extension Moment (Nm)

D. Knee Adduction Moment (Nm)

E. Knee External Rotation Moment (Nm)

F. Hip Extension Moment (Nm)

G. Hip Abduction Moment (Nm)

H. Hip External Rotation Moment (Nm)

3. Pain Scale

A. Numeric Rating Scale Score (0-10)

Assumptions

1. The motion capture cameras and force plates will be accurately calibrated for each subject throughout the experiments.
2. All subjects will be truthful when completing the inclusion questionnaire.
3. All subjects will be truthful when answering the Kujala and NRS.
4. Each subject will perform the drop landings as requested by the researcher.
5. Each subject will perform the aerobic exercise protocol until they indicate they can no longer continue as determined by the subjects indicating they are at a 10

on the Borg CR-10 or their pain has reached an intensity of 8 or higher and they perceive they can no longer continue due to their pain.

Limitations

1. All subjects will not be tested at the same time of day. This may be a limitation as subjects tested later in the day may be at elevated levels of pain due to performing activities of daily living (ADLs) that exacerbate their symptoms.
2. Each subject will have varying degrees of participation in activities and years of sport participation that may influence their drop landing skills.
3. Subjects may discontinue the aerobic exercise protocol prior to exhaustion due to intensity of knee pain.

Delimitations

1. All subjects will wear the same athletic shoes for testing.
2. All subjects will be physically active which is defined as participating in exercise for at least 30 minutes per day, 3 times per week, with at least 2 of those days including participation in activities that required jumping or landing (i.e. tennis, soccer, basketball, running, plyometrics, etc).
3. Subjects with a history of cardiovascular abnormality or a history of previous knee surgery or any lower extremity (hip, knee, ankle, foot) injury in the past 6 months will be excluded from participation.
4. Subjects who are pregnant or cannot perform the tasks required of the study will be excluded.
5. Subjects who are between the ages of 18 and 30 years old will participate in this study.

Project III

Statement of the Problem

The purpose of this study is to compare lower extremity kinetics and kinematics in individuals with PFP during single leg drop landings from various heights after an isometric hip abduction fatigue protocol.

Aim of Research

We aim to identify lower extremity kinetics and kinematics that may be altered during single leg drop landings from various heights in individuals with PFP after participating in an isometric hip abduction fatigue protocol.

Null Hypothesis

1. There will be no statistically significant differences in the lower extremity kinetics and kinematics in individuals with PFP during single leg drop landings from various heights at the point of initial contact and maximum knee flexion after participating in an isometric hip abduction protocol.

2. There will be no statistically significant difference in NRS scores or GRoc scores in individuals with PFP after participating in an isometric hip abduction protocol.

Research Hypotheses

1. There will be a statistically significant difference in the lower extremity kinematics during single leg drop landings from various heights at the point of initial contact and maximum knee flexion in individuals with PFP after participating in an isometric hip abduction protocol.

1A. There will be a statistically significant increase in rearfoot eversion (Chuter & Janse de Jonge, 2012), decrease in ankle dorsiflexion (Chuter & Janse de Jonge, 2012), decrease in knee flexion (Abbas & Diss, 2011), increase in knee abduction (Munkh-Erdene, Sakamoto, Nakazawa, Aoyagi, & Kasuyama, 2011, increase in knee internal rotation (Dierks, Davis, & Hamill, 2010), decreases in hip flexion (Olson, Chebny, Willson, Kernozek, & Straker, 2011), increase in hip adduction (Willson & Davis, 2009), and increase in hip internal rotation (Munkh-Erdene et al., 2011) during single leg drop landings at the point of initial contact in individuals with PFP after participating in an isometric hip abduction protocol.

1B. There will be a statistically significant increase in rearfoot eversion (Chuter & Janse de Jonge, 2012), decrease in ankle dorsiflexion (Chuter & Janse de Jonge, 2012), decrease in knee flexion (Abbas & Diss, 2011), increase in knee abduction (Munkh-Erdene, Sakamoto, Nakazawa, Aoyagi, & Kasuyama, 2011, increase in knee internal rotation (Dierks, Davis, & Hamill, 2010), decreases in hip flexion (Olson, Chebny, Willson, Kernozek, & Straker, 2011), increase in hip adduction (Willson & Davis, 2009), and increase in hip internal rotation (Munkh-Erdene et al., 2011) during single leg drop landings at the point of maximum knee flexion in individuals with PFP after participating in an isometric hip abduction protocol.

2. There will be a statistically significant difference in the lower extremity kinetics during single leg drop landings from various heights at the point of initial contact and maximum knee flexion in individuals with PFP after participating in an isometric hip abduction protocol.

2A. There will be a statistically significant increase in rearfoot inversion moment (Chuter & Janse de Jonge, 2012), decrease in ankle plantarflexion moment (Chuter & Janse de Jonge, 2012), decrease in knee extension moment (Abbas & Diss, 2011), increase in knee adduction moment (Munkh-Erdene et al., 2011), increase in knee external rotation moment (Munkh-Erdene et al., 2011), decrease in hip extension moment (Olson et al., 2011), increase in hip abduction moment (Willson & Davis, 2009), and increase in hip external rotation moment (Munkh-Erdene et al., 2011) during single leg landings at the point of maximum knee flexion in individuals with PFP after participating in an isometric hip abduction protocol.

3. There will be a statistically significant increase in NRS and decrease in GRoc scores after completing the single leg drop landings and post isometric hip abduction protocol in individuals with PFP.

Independent Variables

1. Time
    - A. Pre Isometric Hip Abduction Fatigue Protocol
    - B. Post Isometric Hip Abduction Fatigue Protocol
2. Drop Landing Heights
    - A. 20 centimeters (cm)
    - B. 30 cm
    - C. 40 cm

Dependent Variables

1. Kinematic (At Initial Contact and Maximum Knee Flexion)
    - A. Rearfoot Eversion (degrees)
    - B. Ankle Dorsiflexion (degrees)
    - C. Knee Flexion (degrees)
    - D. Knee Abduction (degrees)

E. Knee Internal Rotation (degrees)

F. Hip Flexion (degrees)

G. Hip Adduction (degrees)

H. Hip Internal Rotation (degrees)

I. Trunk Flexion (degrees)

2. Kinetic (At Maximum Knee Flexion)

A. Rearfoot Inversion Moment (Newton meters)(Nm)

B. Ankle Plantarflexion Moment (Nm)

C. Knee Extension Moment (Nm)

D. Knee Adduction Moment (Nm)

E. Knee External Rotation Moment (Nm)

F. Hip Extension Moment (Nm)

G. Hip Abduction Moment (Nm)

H. Hip External Rotation Moment (Nm)

3. Pain Scale

A. Numeric Rating Scale Score (0-10)

Assumptions

1. The motion capture cameras and force plates will be accurately calibrated for each subject throughout the experiments.
2. All subjects will be truthful when completing the inclusion questionnaire.
3. All subjects will be truthful when answering the Kujala and NRS.
4. Each subject will perform the drop landings as requested by the researcher.
5. All subjects will give full effort during the fatigue protocol.

Limitations

1. All subjects will not be tested at the same time of day. This may be a limitation as subjects tested later in the day may be at elevated levels of pain due to performing activities of daily living (ADLs) that exacerbate their symptoms.
2. Each subject will have varying degrees of participation in activities and years of sport participation that may influence their drop landing skills.

Delimitations

1. All subjects will wear the same athletic shoes for testing.
2. All subjects will be physically active which is defined as participating in exercise for at least 30 minutes per day, 3 times per week, with at least 2 of those days including participation in activities that required jumping or landing (i.e. tennis, soccer, basketball, running, plyometrics, etc).
3. Subjects with a history of cardiovascular abnormality or a history of previous knee surgery or any lower extremity (hip, knee, ankle, foot) injury in the past 6 months will be excluded from participation.
4. Subjects who are pregnant or cannot perform the tasks required of the study will be excluded.
5. Subjects who are between the ages of 18 and 45 years old will participate in this study.

Operational Definitions

- Patellofemoral pain: Individuals who meet the following criteria will be placed in the PFP group; having anterior knee pain for three weeks or longer that is of insidious onset and not as a result of an injury, pain that is present during one or more of the following tasks; repetitive knee flexion associated with weight-bearing activities such as running, jumping, and climbing stairs

- Physically active: The subjects will be considered physically active if they participate in aerobic physical activity for a minimum of 20 minutes on three days each week (Oñate, Guskiewicz, Marshall, Giuliani, Yu, & Garrett, 2005).
- Single Leg Drop Landing Task: The single leg drop landing task will consist of the subject landing with the test leg on the force plate after performing a vertical drop landing from a jump box of various heights (20 cm, 30 cm, and 40 cm) (Weinhandl, Joshi, & O'Connell, 2010).
- Aerobic Exercise Protocol: The aerobic exercise protocol requires that the subject perform both walking and jogging on a treadmill until they can no longer continue. The speeds will range from 3.0 to 6.0 mph and the incline of the treadmill will range from 0-15% (Ott et al., 2011).
- Borg's category ratio scale (Borg CR-10): The subject's RPE will be measured using Borg's category ratio (CR) scale. The RPE is a subjective patient measure that allows the individual to report what their rate of perceived exertion is. Commonly referred to as the Borg CR-10, the scale ranges from zero-10. Zero indicates that the individual is not working at all and a score of ten indicates all out exhaustion (Borg, 1990).
- Numeric rating scale (NRS): The NRS is an 11-point pain scale in which the patient rates the level of pain according to the pain description at each level. The total range of scores is from zero (no pain) to 10 (severe pain or also commonly referred to as the worst pain you have ever felt). The NRS has demonstrated both

validity and reliability (Selfe, Bourguignon, & Taylor, 2008). A clinically significant reduction in pain is considered when the NRS score decreases by two points or 30% (Selfe et al., 2008).

- Global rating of change (GRoc): The GRoc is designed to quantify a subject's improvement or deterioration over time due to an intervention or to simply chart their clinical progress. The subject's GRoc pain score will be assessed at three instances of time and the 11-point scale will be used. The scores on the 11-point scale range from -5 to 5 with -5 indicating the individual is very much worse, 0 indicates no change, and +5 indicates that the individual is completely recovered. The 11-point scoring scale has a test-retest interclass coefficient (ICC) of 0.90(Kamper et al., 2009). The minimal detectable change (MDC) on the 11-point scale is 0.45 points and the minimally clinically important change is two points (Kamper et al., 2009).
- Kujala Questionnaire: The Kujala is a self-administered 13-item questionnaire that assesses one's PFP during different items relating to both function and activity. The overall index score ranges from zero-100 points with a score of 100 representing no disability. An improvement of eight-10 points is considered clinically significant. The Kujala demonstrates high internal consistency of knee specific patient outcomes with a Cronbach α >0.80 (Paxton, Fithian, Stone, & Silva, 2003). The Kujala has also demonstrated good test-retest reliability with a coefficient of 0.86 (Paxton et al., 2003).
- Foot Posture Index (FPI): The FPI is comprised of a series of criterion-based observations that combine to provide a quantification of postural variation in three

major regions of the foot (rearfoot, midfoot, forefoot) in the three cardinal planes of the body (Keenan et al., 2007). A five point Likert scale with scores ranging from – 2 to + 2 is used to score each measure. Final scores can range from -12 to + 12 with a normal foot being a score ranging from 0 to – 5, pronated foot ranging from + 6 to + 12, and a supinated foot ranging from – 6 to – 12 (Redmond, Crosbie, & Ouvrier, 2006).

- Initial Contact (IC): Initial contact is defined as the instance when the forceplate registers more than 10 Newtons of force.
- Maximum Knee Flexion (MaxKF): Maximum knee flexion is defined as the point in the single leg drop landing when the subject has reached their greatest degree of knee flexion.

CHAPTER II

REVIEW OF LITERATURE

The following review of literature will focus on the patellofemoral joint and the associated concerns of anterior knee pain. Patellofemoral pain syndrome (PFP) is a common clinical assessment that encompasses pathologies dealing with the articulation of the undersurface of the patella with the femur (Loudon, Wiesner, Goist-Foley, Asjes, & Loudon, 2002). The knee is a common site for injuries with PFP being one of the most common ailments affecting the knee (Arroll, Ellis-Pegler, Edwards, & Sutcliffe, 1997). The onset of pain is gradual in nature and not as a result of a traumatic event. There have been numerous definitions of PFP that have been reported with all having the following diagnostic features; pain which is diffuse and of insidious onset and is exacerbated by 1) ascending or descending stairs, 2) squatting or kneeling, 3) sitting with knee in flexion, and 4) rising after long periods of sitting (Arroll et al., 1997). Understanding the relationship of the patella and femur, allows us to investigate possible etiologies of PFP. Furthermore, investigating biomechanical and muscular factors both proximal and distal to the patellofemoral joint provides the clinician with a better understanding of the role of the kinetic chain in PFP.

Anatomy

Abnormal anatomy and congruence of the patellofemoral joint may lead to patellofemoral dysfunction and abnormal stresses on the patellofemoral joint (Yang, Tan, Yang, Dai, & Guo, 2009). The patellofemoral joint is an integral part of the knee and is the articulation of the patella and the trochlear groove of the femur. The patella is the largest sesamoid bone in the body and functions to increase the mechanical advantage of the quadriceps muscle group and to protect the tibiofemoral joint (Waryasz & McDermott, 2008). The patella is triangular in shape and has a wider proximal pole and narrower distal pole (Siliski, 1994). The articular surface consists of seven facets that are situated on the proximal two-thirds of the underlying surface of the patella (Tecklenburg, Dejour, Hoser, & Fink, 2006). Three quarters of the articular surface of the patella is covered with a thick hyaline cartilage which, when healthy, provides a low-friction aneural surface capable of bearing high, compressive loads (Tumia & Maffulli, 2002).

The femoral condyles are rounded asymmetrical prominences of the distal femur that form the trochlea groove of the femur that serves as the point of articulation with the posterior aspect of the patella (Siliski, 1994). The lateral facet of the trochlea is larger and more prominent thereby preventing lateral movement of the patella as it enters the groove as flexion begins (O'Brien, 2001). The patellofemoral contact area varies with the degree of flexion with maximum contact at 45° (Siliski, 1994). The lateral facet of the patella generally experiences more contact pressure then the medial facets; however, at no point is the entire articular surface of the patella in contact with the femur (O'Brien, 2001). During knee flexion and extension, the patella's position is maintained by both passive and active soft tissue restraints (Elliott & Diduch, 2001). Boling et al., (2009) state that many researchers speculate that abnormal alignment of the patella in the trochlear groove of the femur may lead to PFP.

The lateral retinaculum of the knee is comprised of two layers; the superficial oblique and a deep transverse retinaculum (Waryasz & McDermott, 2008). The superficial oblique retinaculum is a combination of the patella tendon, the vastus lateralis, and iliotibial band (Waryasz & McDermott, 2008). The deep transverse retinaculum is comprised of the lateral patellofemoral ligament, the midportion, which originates from the iliotibial band and attaches to the lateral patella, and the patellotibial band (Waryasz & McDermott, 2008). The medial retinaculum is thinner than the lateral retinaculum and is comprised of the medial patellofemoral ligament, medial patellomeniscal ligament, and the medial patellotibial ligament (Waryasz & McDermott, 2008). The medial patellofemoral ligament combines with the vastus medialis oblique to form the primary restrictive mechanism for excessive lateral patella deviation during lower degrees of knee flexion especially as it approaches full extension (Waryasz & McDermott, 2008). In addition to the medial and lateral retinaculum, the quadriceps muscle group, especially the vastus medialis oblique, are some of the important soft tissues structures that influence the function of the patellofemoral joint. The vastus lateralis and the vastus medialis insert on each respective side of the patella and control the position of the patella in the femoral trochlear groove (O'Brien, 2001). In addition to the quadriceps muscle group, factors proximal to the patellofemoral joint, notably hip muscle weakness have been shown to contribute to the onset of PFP (Baldon et al., 2009).

Epidemiology

Patellofemoral joint pain is one of the most common afflictions of the active population (Almeida et al., 1999; Hutchinson & Ireland, 1995; Brindle, Mattacola, McCrory, 2003). Patellofemoral pain occurs frequently with nine prospective cohort studies reporting incidence rates of seven to 15% in armed forces recruits (Almeida, Trone, & Leone, 1999; Almeida, Williams, & Shaffer, 1999; Heir, & Glomasker, 1996; Jones, Cowan, & Tomlinson, 1993; Kowal, 1980; Milgrom, Finestone, Elad, & Shlamkovitch, 1991; Schwellnus, Jordaan, & Noakes, 1990; Shwayhat, Linengar, Hofherr, Slymen, & Johnson, 1994; Crossley, Cowan, Bennell, & McConnell, 2004). Crossley et al., (2002) noted that PFP is a particularly regular symptom of patients seen at sports medicine practices with reported incidence rates ranging from two to 30%. Patellofemoral pain syndrome has been reported to affect the physically active population at a rate of one out of every four people (DeHaven & Litner, 1986; Deveraux & Lachmann, 1984). Patellofemoral pain syndrome has been demonstrated to have an association with the development of patellofemoral osteoarthritis (Utting et al., 2005). Utting et al., (2005) found that 22% of 118 patients with patellofemoral osteoarthritis reported symptoms of PFP as an adolescent. Due to this factor, PFP may be considered a public health concern due to its association with patellofemoral osteoarthritis (Boling et al., 2009).

Anterior Knee Pain Compared With Patellofemoral Pain

The term "anterior knee pain" encompasses all pain-related problems to the anterior portion of the knee, and covers conditions such as chondromalacia patella, patellofemoral arthralgia, patellar pain, patellar pain syndrome, and patellofemoral pain (Tumia & Maffulli, 2002). Patellofemoral pain syndrome is a term for a variety of pathologies or anatomical abnormalities leading to a type of anterior knee pain (Witvrouw, Werner, Mikkelsen, Van Tiggelen, Berghe, Vanden, & Cerulli, 2005; Waryasz & McDermott, 2008). Individuals with a clinical presentation of anterior knee pain with a lack of inarticular, tendon, plica syndrome, Sinding Larsen, and Osgood Schlatter pathologies, may be diagnosed with PFP. (Thomee, Augustsson, & Karlsson, 1999; Johnson, 1997; Tumia & Maffulli, 2002). Patellofemoral pain encompasses disorders in which pain and point tenderness are present in or around the patellofemoral joint (Boling et al., 2009). The term "patellofemoral" seems appropriate, since no distinction can be made as to which specific structure of the patella or femur is affected (Witvrouw et al., 2005).

Pain is of insidious onset and reported as peripatellar and/or retropatellar, ranges from mild to severe, and is often provoked by physical activity (Tumia & Mafulli, 2002; Cheung, Ng, & Chen, 2006). Physical activities such as climbing stairs, squatting, jumping, running, and/or sitting with the knees flexed for prolonged periods of time have been found to exacerbate pain in the peripatellar area of the knee (Earl & Hoch, 2011). The prevalence of this condition is high since it can occur in individuals with a wide range of physical activity levels and the symptoms often cause disability with exercise participation and activities of daily living (Earl & Hoch, 2011).

Biomechanical and Musculoskeletal Contributions to Patellofemoral Pain

Despite having a clear picture of what activities aggravate the symptoms of PFP, the specific cause of PFP is unknown as there could be multiple contributing factors (Earl & Hoch, 2011). Biomechanical and musculoskeletal factors both proximal and distal to the patellofemoral joint have been attributed to being causative factors of PFP. Contrary to other knee dysfunctions (eg, anterior cruciate ligament injury), which often have a specific onset and mechanism of injury, the specific cause of PFP is unknown (Bolgla, Malone, Umberger, & Uhl, 2008). Clinicians postulate PFP to result from abnormal patella tracking resulting in excessive compression to the lateral patella facets (Fulkerson 2002; Dye 2001; Bolgla & Boling, 2011). A myriad of factors that may contribute to abnormal patella tracking include quadriceps weakness, quadriceps muscle imbalances, excessive knee soft tissue tightness, an increased quadriceps angle (Q-angle), hip weakness, and altered foot kinematics (Bolgla & Boling, 2011). In addition, abnormal motions of the tibia and femur in the transverse and frontal planes are believed to have an effect on patellofemoral joint mechanics and therefore PFP (Powers, 2003).

Vastus Medialis versus Vastus Lateralis Musculature

The dynamic and static components of the patellofemoral joint control its biomechanics (Tang, Chih-Kuang, Hsu, Chou, Hong, & Lew, 2001). The primary dynamic components are the four muscles that make up the quadriceps femoris complex with support from the iliotibial band, the adductor magnus and longus, the pes anserine group, and the biceps femoris (Tang et al., 2001). The gradual onset of PFP has been theorized to result from neuromuscular imbalances of the vastus medialis obliquus (VMO) and the vastus lateralis (VL) muscles (Tang et al., 2001; Akkurt, Salli, Ozerbil, & Ugurlu, 2010). Dynamic imbalances have been studied by several researchers, who have reported the appearance of abnormal patterns of patellar alignment with changes in the activity of the medial and lateral stabilizers of the patellofemoral joint (Sacco, Konno, Rojas, Arnone, Passaro, Marques et al., 2006;Tang et al., 2001; Santos, Bessa, Lins, Marinho, Silva, & Brasileiro, 2008). A reduction in vastus medialis muscle activity relative to the vastus lateralis along with a delayed onset of the vastus medialis relative to the vastus lateralis may contribute to abnormal tracking of the patella (Cowan et al., 2001; Grabiner, Koh, & Draganich, 1994; Bolgla et al., 2008). In addition to the findings of delayed activation of the vastus medialis and vastus lateralis, Brindle et al., (2003) reported a delay in gluteus medius activation relative to the vastus medialis and vastus lateralis and concluded that altered gluteus medius activity may adversely affect knee function (Bolgla et al., 2008).

Hip Strength

In line with the kinetic chain theory that dysfunction of a joint can contribute to injuries in other joints, especially those distal to the affected joint; proximal factors including hip muscle weakness have been projected to contribute to patellofemoral malalignment and the development of patellofemoral dysfunction (Fulkerson, 2002; Thijs et al., 2011). With absence of sufficient proximal strength, the femur may adduct or internally rotate and result in increased lateral patellar contact pressure (Ireland, Willson, Ballantyne, & Davis, 2003; Powers, 2003; Thijs et al., 2011). Weakness of the hip external rotators is considered to cause an increase in hip internal rotation and knee valgus angles during dynamic tasks thereby increasing the lateral compressive forces at the patellofemoral joint (Ireland et al., 2003; Lee, Anzel, Bennett, Pang, & Kim, 1994; Powers, 2003; Boling et al., 2009). Piva, Fitzgerald, Irrgang, Jones, Hando, Browder, & Childs (2006) state that hip abductor and external rotator strength are commonly measured in individuals with PFP since these muscles help to maintain pelvic stability by eccentrically controlling femoral internal rotation during weight bearing activities. Weakness in the hip abductors and hip external rotators may result in increased femoral rotation and valgus knee moments thereby increasing the compressive forces at the patellofemoral joint (Piva et al., 2006).

Several studies report a decrease in hip muscle strength in individuals with patellofemoral dysfunction (Ireland et al., 2003; Robinson & Nee, 2007; Souza & Powers, 2009). Bolgla, Malone, Umberger, & Uhl (2008) investigated the association of hip strength and hip and knee kinematics. Their subjects performed a stair stepping task, which was representative as an activity associated with PFP. Although they did not find any differences in regards to hip internal rotation and hip adduction they did find a strength deficit and attribute it to the fact that the stair descent task may not have been challenging enough to elicit compensation in those in the PFP group. There was a strength deficit of 24% for hip external rotation and a 26% deficit in hip abduction for the PFP individuals compared to the control group. Their findings were similar to those found by Ireleand, Wilson, Ballantyne, & Davis (2003) who also investigated hip external rotator and hip abductor strength in females with PFP. Ireland et al. (2003) reported a 36% deficit in hip external rotator strength and a 26% deficit in hip abductor strength in their female subjects with PFP as compared to their control group.

Cichanowski, Schmitt, Johnson, & Niemuth (2007) found that their PFP group displayed weakness in their hip abductors and external rotators for the injured leg in comparison to the non-injured leg. They also found that the PFP group displayed overall hip weakness in five of six hip muscles tested over the control group. The only group that did not display a significant weakness was the hip adductors. Tyler, Nicholals, Mullaney, & McHugh (2006) found that individuals with unilateral PFP demonstrated a deficit in hip flexion (14%), and abduction (14%) strength on the involved side. Robinson & Nee (2007) reported a strength deficit in their subjects in hip abduction (27%), external rotation (30%) and extension (52%) compared to the weaker limb of their control subjects. Boling, Padua, & Creighton (2009) reported that the individuals with PFP were 21% weaker than the control group for peak eccentric hip abduction torque. They also reported that the PFP group was 23% weaker than the control group for both average concentric and eccentric hip external rotation torque. The PFP group demonstrated a strength deficit of 8 % for hip extension in comparison with the control group. Souza & Powers (2009) studied females with PFP and reported that those with PFP generated significantly less peak isometric hip abduction (1.39 ± 0.41 vs. 1.62 ± 0.26 Nm/kg of body mass) and extension (1.98 ± 0.50 vs. 2.35 ± 0.38 Nm/kg of body mass) torque compared to a control group. Willson & Davis (2009) found a strength deficit of 15 % for both hip abduction and hip external rotation along with a 29 % deficit in lateral trunk flexion force with no differences in knee extension or flexion strength. The findings of this study demonstrate that females with PFP may not exhibit overall lower extremity weakness but rather demonstrate weakness in specific actions, demonstrating a need to understand the role of hip and trunk function in the etiology and exacerbation of PFP.

Quadriceps Angle

In order to fully understand the influence of muscular strength on the patellofemoral joint, one must also understand the influence of lower extremity alignment on this joint. The quadriceps angle (Q-angle) has been theorized to play a role in patellofemoral pain. The Q-angle was first defined by Brattstrom (1964) as the angle formed by the line of pull of the quadriceps mechanism and that of the patella tendon as they intersect at the center of the patella (Fredericson & Yoon, 2006). It is formed by transecting lines between the anterior superior iliac spine (ASIS) and midpatella and between the tibial tubercle and midpatella (Callaghan & Baltzopoulos, 1992). The Q-angle is a measure of the patella's tendency to move laterally when the quadriceps muscles are contracted (Fredericson & Yoon, 2006). An increased Q-angle may predispose the patella to excessive lateral tracking and stress (Messier, Davis, Curl, Lowery, & Pack, 1991; Schulthies, Francis, Fisher, & Van de Graaff, 1995; Bolgla et al., 2008). Despite this theory, other researchers have questioned the use of a Q-angle measurement due to the static nature of the measurement when comparing the behavior of the patella during dynamic tasks. Quadriceps contraction during weight bearing anchors the patella to the comparatively stable tibia, allowing the femur to move underneath the extensor mechanism (Powers, 2010). In contrast, the movement of the tibia during non-weight bearing knee extension allows the patella to move with the fixed femur (Powers, 2010). Recent evidence suggests that the patellofemoral joint kinematics may be different during weight bearing tasks compared to non-weight bearing tasks (Powers, 2010). Chen and Powers (2008) found that females with PFP demonstrated excessive "dynamic" Q-angles most notably during stair decent with an average of 39° in the PFP group compared to 24° in the control group (Powers, 2010). The increase in the lateral forces on the patella resulting from an increase in the dynamic Q-angle would be expected to increase the contact stress at the patellofemoral joint (Powers, 2010).

Foot Pronation

Tibial and femoral rotation along with the role of excessive foot pronation have been areas of specific concern in relation to malalignment of the lower extremity and its association with patellofemoral pain (Cheung et al., 2006). Patellofemoral pain has not only been associated with patellar malalignment locally but also distally with excessive and prolonged pronation of the foot during standing and the stance phase of walking (Messier, Davis, Curl, Lowery, & Pack, 1991; Callaghan & Baltzopoulos, 1994; Levinger, Gilleard, & Tibia, 2007; Bek, Kinikli, Callaghan, & Atay, 2010). Cheung et al. (2006) defined foot pronation as the combined three-dimensional movements of calcaneal eversion, abduction of the forefoot, and dorsiflexion of the foot. As the foot pronates at both the subtalar and navicular joints, the talus rotates and due to the tight articulation in the ankle mortise, the tibia also internally rotates (Williams et al., 2003). The knee flexion and internal tibial rotation that accompanies pronation of the subtalar joint play an important role in the absorbing shock when the heel comes in contact with the ground (Cheung et al., 2006). A normal amount of pronation provides a mean of decreasing peak forces experienced by the leg immediately following foot strike, however, excessive foot pronation can lead to an increase in internal rotation of the tibia and result in increased stresses on the bones and soft tissue structures (Clarke et al., 1983). Although pronation occurs during normal heel to toe gait patterns, excessive pronation has been linked with PFP (Cheung et al., 2006). The increased motions are thought to lead to abnormal patellofemoral joint alignment and result in patellofemoral pain (McClay & Manal, 1998).

Assessment of Foot Type

With the influence of foot pronation being linked with PFP, it is important to have a valid and reliable method of assessing the foot posture of those with PFP. Navicular drop is a common measure of arch height and an increase in navicular drop has been related to a pronated foot structure, yet it is limited since only one aspect of foot posture is measured (Redmond et al., 2005). While laboratory gait analysis remains the gold-standard, the resources needed to produce high-quality objective data are expensive, and the process of acquiring the data can be overly time consuming for routine patient assessment (Redmond et al., 2005).

The foot posture index (FPI) is a novel, foot specific outcome measure that was developed in order to quantify variation in the position of the foot easily and quickly in a clinical setting (Kennan, Redmond, Horton, & Conaghan, 2007). The FPI evaluates the multisegmental nature of foot posture in all three planes without the need for specialized equipment (Redmond, Crosbie, & Ouvrier, 2006; Barton, Levinger, Crossley, Webster, & Menz, 2011). It is comprised of a series of criterion-based observations that combine to provide a quantification of postural variation in three major regions of the foot (rearfoot, midfoot, forefoot) in the three cardinal planes of the body (Keenan et al., 2007). A five point Likert scale with scores ranging from – 2 to + 2 is used to score each measure. Final scores can range from -12 to + 12 with a normal foot being a score ranging from 0 to – 5, pronated foot ranging from + 6 to + 12, and a supinated foot ranging from – 6 to – 12 (Burns, Ryan, & Ouvrier, 2009; Redmond et al., 2005).

Barton, Bonanno, Levinger, & Menz (2010) found that the FPI can detect differences in those with and without PFP and possessed high intra- and inter-rater reliability in individuals with PFP. While the study by Barton et al. (2010) demonstrated that differences in individuals with PFP could be detected using the FPI, the relationship between the use of the FPI, dynamic measures, and PFP was still uncertain. Barton et al., (2011) evaluated the association of FPI score with kinematics of the rearfoot and forefoot during walking using a three-dimensional motion analysis system in individuals with and without PFP to further investigate the validity of the FPI in relation to dynamic function. A more pronated foot as measured by the FPI was associated with earlier peak rearfoot eversion and greater peak forefoot abduction relative to the laboratory in the PFP group (Barton et al., 2011). In addition to detecting differences in the pronated feet of those with PFP, differences were also detected in the control population with a pronated foot, displaying a greater rearfoot eversion range of motion relative to the laboratory (Barton et al., 2011). The finding of earlier peak rearfoot eversion associated with the pronated foot structure in the PFP group is consistent with the biomechanical model of PFP development (Barton et al., 2011).

Landing Task

Many athletic activities require the individual to perform single leg landings during participation. Single leg landings are common situations in sports that require sudden stops and change of direction (Schmitz, Kulas, Perrin, Riemann, & Shultz, 2007). These instances may occur when landing from a jump or simply running. While much research has investigated the lower extremity mechanics of bilateral landings, unilateral landings are considered more dangerous due to a decrease in the base of support and the increased demands on the musculature of only one lower extremity (Boden, Dean, Feagin, & Garrett, 2000; Weinhandl et al., 2010). Single leg landings may elicit different mechanical responses following a fatigue protocol then bilateral jump-landing tasks commonly used in studies investigating lower extremity biomechanics (Hollman et al., 2012). The forces that are imposed on the body during a landing must be attenuated predominately by the lower extremity (Coventry, O'Connor, Hart, Earl, & Ebersole, 2006). Despite a focus on the cause of knee injuries through applied forces in landing studies, it is important to consider the role of all lower extremity joints in controlling the body as the joints of the lower extremity act in concert to attenuate the transfer of mechanical energy absorption during the landing process (Prilutsky & Zatsiorsky, 1994; Schmitz et al., 2007). The musculoskeletal system plays a major role in attenuating the forces during landing from a height, and if these forces become too great for the body to adequately dissipate, the probability of injury increases (Dufek and Bates, 1990; Coventry et al., 2006). Microfractures, medial tibial stress syndrome, spinal injuries, and other degenerative changes in joint and articular cartilage have been suggested to be significantly influenced by the body's ability to attenuate shock from continual impacts (Light, McLellan, & Klenerman, 1980; McMahon, Valiant, & Frederick, 1987; Conventry et al., 2006). Injuries due to landing are prevalent in sports such as basketball, netball, volleyball, football, gymnastics, and aerobic dance (Dufek, Bates, Davis, & Malone, 1991; Conventry et al., 2006). The majority of previous research has utilized two-legged landings, while comparing their findings to many activities that that occur on a single leg such as running, cutting, and landing during play (Coventry et al., 2006). Due to this relative lack of research on single leg landings, it is unclear how joints of the lower extremity act to absorb single leg landings (Coventry et al., 2006).

Fatigue

Fatigue is an extrinsic factor affecting the musculoskeletal and neurologic systems (Chappell, Herman, Knight, Kirkendall, Garrett, & Yu, 2005). Muscle fatigue commonly occurs during strenuous dynamic physical activities and results in altered performance (James, Scheuermann, & Smith, 2010). Fatigue may disrupt afferent nerve impulses, which would impair conscious joint awareness, slow neural transmission and therefore decrease afferent signals needed to create compensatory contractions, and reduce joint control (Miller & Bird, 1976; Lundin, Feuerbach, & Grabiner, 1993; Gribble & Hertel, 2004; McMullen, Cosby, Hertel, Ingersoll, & Hart, 2011). Examining a motor task before and after localized muscle fatigue can provide insight into muscle's role in the performance of the task (Hollman, Hohl, Kraft, Strauss, & Traver, 2012). It is thought that a fatigued muscle will be less capable of protecting the body effectively from impact forces and thus the body will be predisposed to overuse impact-related injuries (Coventry et al., 2006). In running and rapid stop tasks, late onset of quadriceps and hamstring muscle activation and early occurrence of maximal knee flexion occur with fatigue (Chappell et al., 2005). It is thought that these biomechanical changes lead to decreased shock absorption and knee stabilizing during landing (Chappell et al., 2005). Dynamic stabilization in the knee joint tends to be affected by fatigue in the musculature acting on the knee joint (James et al., 2009). Participation in athletic activities while fatigued may further increase tendency for abnormal lower extremity mechanics and associated risk for PFP (Willson et al., 2008).

Reimer & Wikstrom (2010) note that either an isokinetic or functional fatigue protocol can be used to investigate the effects of muscular fatigue on neuromuscular control. Wikstrom, Powers, & Tillman (2004) demonstrated that both a functional and isokinetic fatigue protocol produced similar alterations in dynamic postural control in the same cohort of subjects (Reimer & Wikstrom, 2010). Miller & Bird (1976) indicate that isolating specific muscle groups during functional fatigue protocols would be problematic because of the contractile activity in other muscle groups (Reimer &Wikstrom, 2010). This demonstrates the importance of investigating the effects of both a generalized and localized fatigue protocol on the lower extremity kinematics and kinetics during a single leg drop landing.

Patient Outcome Assessments

An outcome assessment must be able to evaluate a change over time in an individual's status of either improvement or worsening (Deyo, 1984; Deyo, Diehr, & Patrick, 1991; Guyatt, Walter, & Norman, 1987; Guyatt, Deyo, Charlson, Levine, & Mitchell; 1989; Crossley, Bennell, Cowan, & Green, 2004). In addition to being valid and reliable, an outcome measure should have properties that allow detection of clinically relevant change (Crossley et al., 2004). The minimally clinically difference is important as it provides the clinician with meaningful information about the significance of differences obtained with the measure (Crossley et al., 2004).

Many outcome measures are self-administered and address pain and disability due to the individual's condition. The Numeric Rating Scale (NRS) is a standard instrument in studies dealing with chronic pain and ranges in score from zero to 10, with zero representing no pain and 10 representing worst possible pain (Farrar, Young Jr., LaMoreaux, Werth, & Poole, 2001). A clinically significant reduction in pain is considered when the NRS score decreases by two points or 30% (Selfe et al., 2008). Selfe et al. (2008) considered a pain rating of 3.23 or below clinically relevant as patients with knee osteoarthritis in this study considered themselves well at this pain rating and below. This pain rating value may be of particular interest to those dealing with individuals with PFP as PFP has demonstrated an association with patellofemoral osteoarthritis (Utting et al., 2005). The NRS has demonstrated both validity and reliability (Selfe et al., 2008). As pain is a major complaint in those with PFP, having a quick, valid, and reliable tool to use in the assessment of pain is important to the clinician and can provide valuable feedback as to how an intervention has affected pain.

While the NRS can provide insight into an individual's pain, it limits the clinician in only representing the pain at the time of administration of the instrument. The Global Rating of Change (GRoc) approaches an individual's global rating of change from baseline and allows the patient to demonstrate their improvement or deterioration over time. The GRoc scale asks the patient to assess their current health status, recall that status at a previous time-point, and then calculates the difference between the two (Norman, Stratford, & Regehr, 1997;Kamper, Maher, & Mackay, 2009). The face validity of the GRoc is high (Fisher, Stewart, Bloch, Loring, Laurent, & Holman, 1999) along with the correlations for these measures (r=0.72 and r=0.90), (Stratford, Binkley, Solomon, Gill, & Finch, 1994;Watson, Propps, Ratner, Zeigler, Horton, & Smith, 2005) indicating that the gradation along the scale represents a change that is meaningful to the patient (Kamper et al., 2009). The 11 point scale scores range from negative five, indicating very much worse, to positive five, indicating completely recovered, with the scores being discreet numbers, a change of two points or more is considered a clinically meaningful change (Kamper et al., 2009). The GRoc has the advantages of clinical relevance, adequate reproducibility, and sensitivity to change and is easy to understand by the patient and the administrator, as it is a quick and simple way of outlining self-assessed clinical progress in both the research and clinical settings (Kamper et al., 2009).

Knowledge of the patient's perceived level of pain and how it may have improved or deteriorated over time, may provide the clinician with valuable information, yet it may not provide information on the patient's perceived function. Understanding the patient's level of function allows the clinician to have a better understanding of how their condition is affecting their quality of life and the role the intervention has played. The

Anterior Knee Pain Scale (AKPS) also known as the Kujala, is a 13-item questionnaire related to various level of current knee function (Crossley et al., 2004). The categories within each item are weighted and responses are totaled to provide an overall score that ranges from zero to one hundred, in which 100 represents no disability and a score of 70 represents a moderate disability (Crossley et al., 2004). Clinically significant change is represented by an increase or decrease in the score by eight points (Crossley et al., 2004). The Kujala demonstrates high internal consistency of knee specific patient outcomes with a Cronbach α >0.80 and has also demonstrated good test-retest reliability with a coefficient of 0.86 (Paxton, Fithian, Stone, & Silva, 2003). Crossley et al. (2004) concluded that the Kujala can be used with confidence in the clinical setting, due to the fact that the change in scores is greater than the error associated with the measures and reflects real change that can be attributed to the intervention and provides meaningful information to the patient.

Summary

Despite our increasing knowledge of PFP, there are still gaps in the literature that must be addressed to continue to improve our recognition, treatment, and outcomes for individuals with PFP. Investigating single leg drop landings in both the fatigued and non-fatigued state will allow us to gain an understanding of how the lower extremity is attenuating the forces acting upon it and how the movement pattern of those with PFP may be altered. Also it is important to understand how knee pain in an individual with PFP affects their function. With increased knowledge of another piece of the PFP puzzle, improved recognition, management, and outcomes may be available to the clinician.

Chapter III

Project I

Lower Extremity Biomechanics in Individuals With and Without Patellofemoral Pain During a Single Leg Drop Landing

Title: Lower extremity biomechanics in individuals with and without patellofemoral pain during a single leg drop landing.

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Introduction

Patellofemoral joint pain is one of the most common afflictions of the active population (Almeida, Trone, & Leone,1999; Hutchinson & Ireland, 1995;. Brindle, Mattacola, McCrory, 2003). Nearly 10% of all sports injury clinic visits by physically active individuals and up to 40% of clinical visits for knee problems are attributed to patellofemoral pain (Kannus, Aho, Jarvinen, & Nittymaki,1987; Waryasz, & McDermott, 2008; Myer, Ford, Barber Foss, Goodman, Ceasar, Rauh, Divine & Hewett, 2010). Individuals who suffer from patellofemoral pain (PFP) present with insidious and diffuse pain in the anterior aspect of the knee that is aggravated during ascending or descending stairs, squatting, and prolonged sitting (Heintjes, Berger, Bierna-Zeinstra, Bernsen, Verhaar, & Koes, 2003; Nakagawa, Muniz, Baldon, Maciel, Amorim, & Serrao, 2011). In addition, walking, running, ascending and descending slopes and kneeling have also been found to aggravate symptoms of PFP (Gross & Foxworth, 2003;Barton, Munteanu, Menz, & Crossley, 2010). The prevalence of this condition is high since it can occur in individuals with a wide range of physical activity levels and the symptoms often cause disability with exercise participation and activities of daily living (Earl & Hoch, 2011) Despite having a clear picture of what activities aggravate the symptoms of PFP, the specific cause of PFP is unknown as there could be multiple contributing factors (Earl & Hoch, 2011).

Biomechanical and musculoskeletal factors both proximal and distal to the patellofemoral joint have been attributed to being causative factors of PFP. A myriad of factors that may contribute to abnormal patella tracking include quadriceps weakness, vastus medialis and vastus lateralis muscle imbalances, excessive knee soft tissue tightness, an increased quadriceps angle (Q-angle), hip weakness, and altered foot kinematics (Bolga & Boling, 2011). In addition, abnormal motions of the tibia and femur in the transverse and frontal planes are believed to have an effect on patellofemoral joint mechanics and therefore PFP (Powers, 2003). Clinicians must be aware of the stresses on the patellofemoral joint during activities both in a weight bearing and non-weight bearing state to gain a better understanding of how they may exacerbate the symptoms of PFP. Steinkamp, Dillingham, Markel, Hill, & Kaufman (1993) state that patellofemoral joint stress is less from 45 to 0 degrees of knee flexion during weight bearing exercise and less from 90 to 45 degrees of knee flexion during non-weight bearing exercise (Bolga & Boling, 2011).

Many athletic activities require the individual to perform single leg landings during participation, which require sudden stops and change of direction (Schmitz, Kulas, Perrin, Riemann, & Shultz, 2007). These instances may occur when landing from a jump or simply running. While researchers have investigated the lower extremity mechanics of bilateral landings, unilateral landings are considered more dangerous due to a decrease in the base of support and the increased demands on the musculature of only one lower extremity (Boden, Dean, Feagin, & Garrett, 2000; Weinhandl, Joshi, & O'Connor, 2010). The musculoskeletal system plays a major role in attenuating the forces during landing from a height, and if these forces become too great for the body to adequately dissipate, the probability of injury increases (Dufek & Bates, 1990; Coventry, O'Connor, Hart, Earl, & Ebersole, 2006). Due to this relative lack of research on single leg landings, it is unclear how joints of the lower extremity act to absorb single leg landings (Coventry et al., 2006). Examining the biomechanics of the lower extremity during a single leg drop landing may provide the clinician with an understanding of the landing pattern employed by individuals both with and without PFP. Therefore, the purpose of this study was to determine if lower extremity biomechanics were different in individuals with PFP compared to healthy individuals during a single leg landing.

METHODS

Subjects

Twenty-two physically active individuals ages 18-30 (11 PFP: ht=169.72±7cm, mass=67.08±15.81kg, Kujala: 70.72±8.67; 11 Control: ht=170.22±7.24 cm, mass=67.27±12.63 kg.) participated in the study. Subjects were included in the PFP group if they had anterior knee pain for a minimum of three weeks that was of insidious onset and not as a result of an injury, and pain that was present during one or more of the following tasks; repetitive knee flexion associated with weight-bearing activities such as running, jumping, squatting, and climbing stairs. All subjects had no current lower extremity injury, or musculoskeletal or neurological condition that would affect their ability to land on a single leg and maintain the position for two seconds. The subjects were considered physically active if they participated in aerobic physical activity for a minimum of 20 minutes on three days each week.[20] Subjects were excluded from the study if they failed to meet any of the inclusion criteria and/or they were sensitive or allergic to the adhesive on the tape used to keep markers on in the study, had a history of major orthopedic surgery to the lower extremity, or if they were pregnant. Prior to the start of the testing session, each subject read and signed the informed consent form that was approved by the University's Institutional Review Board (IRB).

Instrumentation

Data was collected at 200 Hz using an 8-camera Vicon motion analysis system (Vicon Motion Systems, Denver, CO), coupled with one Bertec force plate collected at 1000 Hz (Model FP4060-10, Bertec Corp., Columbus, OH). Three wooden boxes with a height of 20, 30, and 40 cm respectively were used to have standard drop heights for the subjects.

Testing Procedures

Subjects reported to the lab for one testing session, which lasted for approximately 90 minutes. Upon arriving at the lab, subjects read and signed an informed consent before participating in the study. The subjects filled out a general medical questionnaire prior to testing and the PFP subjects filled out the Kujala and a numeric rating scale (NRS) (Selfe, Bourguignon, & Taylor, 2008) for pain. Height, mass, age, and gender were recorded. Subject attire for the study included spandex shorts, no shirt (males), sports bra (females), and standard lab sneakers (Nike Air Max Glide, Nike Inc., Beaverton, OR). Forty-eight reflective markers were placed on the subject to track kinematic data of the lower extremity during the drop landings. Anatomical marker locations included the posterior superior iliac spine, iliac crest, anterior superior iliac spine, greater trochanter, medial femoral condyle of the knee joint, lateral femoral condyle of the knee joint, medial malleolus, lateral malleolus, base of the first metatarsal, and base of the fifth metatarsal (Weinhandl et al., 2010). Cluster marker plates with four reflective non-collinear markers were placed on the posterior trunk (between the scapulae), thigh, shank, and rearfoot of the subject (Weinhandl et al, 2010). The anatomical markers were adhered to the subject using double-sided tape, and the cluster marker plates of the lower extremity were applied by first putting on neoprene sleeves (McDavid USA, Woodridge, IL) on the thigh and shank, and adhered to the sleeves with velcro. The trunk cluster was applied by using a neoprene harness with adjustable velcro straps. The same researcher applied the reflective makers on the subjects.

A static calibration trial was collected for each subject prior to start of the dynamic drop landing tasks. Subjects were instructed to stand as still as possible on the force plate with their arms held out in front of them as to not occlude any of the markers (shoulders at 90^0 of flexion and elbows fully extended). The static calibration is necessary so that it can be referenced when calculating angles during the dynamic tasks. After the static calibration trial was complete all of the anatomical markers with the exception of the posterior superior iliac spine and anterior superior iliac spine were removed. The cluster markers plates remained on for all dynamic tasks. The drop landing task required the subject to stand atop the wooden box (20, 30, or 40 cm) placed 10 cm away from the force plate with their test leg in 90^0 of hip and knee flexion with their arms held across their chest. The drop heights were counterbalanced to account for possible sequencing effects and were randomly assigned to the subjects. The subject was then to drop down vertically onto the force plate and stick the landing. The subjects were allowed up to five practice trials to familiarize themselves with the task. Subjects then performed the drop-landing task until five acceptable trials were achieved from each drop landing height. The trial was considered acceptable if the subject meet the following requirements; (1) did not jump off the box, (2) landed on the test leg and maintained their balance for ~2 seconds, (3) landed on the force plate, and (4) did not allow their opposite leg to touch down prior to the 2 second balance maintenance period. Any trial that was ruled as unacceptable was immediately repeated. After completing the landings, the PFP subjects filled out the NRS.

Outcome Measures

The kinematic variables included rearfoot eversion(EV), ankle dorsiflexion(DF), knee flexion(KFL), knee abduction(KABD), knee internal rotation(KIR), hip flexion(HFL), hip adduction(HADD), and hip internal rotation(HIR) (degrees) at initial contact(IC) and maximum knee flexion(MaxKF). The kinetic variables included rearfoot inversion(INV) moment, ankle plantarflexion(PF) moment, knee extension(KEXT) moment, knee adduction(KADD) moment, knee external rotation(KER) moment, hip extension(HEXT) moment, hip abduction(HABD) moment, and hip external rotation(HER) moment (Newton Meters (Nm at maximum knee flexion.

The NRS is an 11-point pain scale in which the patient rates the level of pain according to the pain description at each level. The total range of scores is from zero (no pain) to 10 (severe pain or also commonly referred to as the worst pain you have ever felt). The NRS has demonstrated both validity and reliability(Selfe et al., 2008). A clinically significant reduction in pain is considered when the NRS score decreases by two points or 30% (Selfe et al, 2008).

Data Analysis

The data was then transferred to Visual3D (C-Motion, Inc., Rockville, MD) to reconstruct the model and calculate both kinematic and kinetic variables from the marker and forceplate data. Raw three-dimensional marker coordinate and forceplate data were low-pass filtered using a fourth-order, zero lag, recursive Butterworth filter with cutoff frequencies of 12 and 50 Hz, respectively. A kinematic model of the trunk, pelvis, and bilateral thighs, lower legs and feet was created from the standing calibration trial. Joint angles were then calculated using a joint coordinate system approach (Weindhandl et al., 2010, Grood & Suntay, 1983). Hip joint centers were placed at 25% of the distance between the greater trochanter markers (Weinhandl et al. 2010). Knee joint centers were placed at the midpoint between the femoral epicondyle markers (Grood & Suntay, 1983) and ankle joint centers were placed at the midpoint between the malleoli markers (Wu, Siegler, Allard, Kirtley, Leardini, Rosenbaum, Whittle, D'Lima, Cristofolini, Witte, Schmid, Stokes, 2002). Body segment parameters were estimated from Dempster (1955), and joint kinetics were calculated using a Newton-Euler inverse dynamics approach (Bresler, B., & Frankel, 1950) and reported in the distal segment reference frame. A 2x3 ANOVA was performed for each kinetic and kinematic variable to determine if significance was present at the two time instances of IC and MaxKF. In the event of a significant main effect or interaction ($\alpha \leq .05$) Fisher's LSD post-hoc tests were performed on all pairwise comparisons. Dependent t-tests were used to calculate significance for the NRS. Statistical data was analyzed using PASW software (Version 20, IBM, Armonk, NY). A priori levels were set at 0.05 for analysis.

Results

Initial Contact

At IC (Table 1) there was a main effect for box height for DF(P=0.012) with decreases between 20cm and 30cm (P=0.027), and 20cm and 40cm (P=0.03), and for HABD (P=0.001) with increases between 20cm and 30cm (P=0.007), 20cm and 40cm (P=0.009).

Maximum Knee Flexion

At MaxKF (Table 2) there was a main effect for box height (p=0.001) at KFL with increases between 20cm and 30cm (P=0.001), 20cm and 40cm (P=0.001), 30cm and 40cm (P=0.005), and for HFL (P=0.002) with increases between 20cm and 40cm (P=0.002), and 30cm and 40cm (P=0.008). There was a main effect for group for KFL (PFP: -48.43±7.16°; Con: -56.43±7.16°)(P=0.017).

Significant differences were also noted for joint moments at MaxKF (Table 3). There was a main effect for box height for PF moment (P=0.001) with increases between 20cm and 30cm (P=0.001), 20cm and 40cm (P=0.001), 30cm and 40cm (P=0.001) and for HEXT moment (P=.0001) with increases between 20cm and 30cm (P=.015), 20cm and 40cm (P=.001), and 30cm and 40cm (P=.001).

There was a significant group by box height interaction for knee extension moment (P=0.001). Post-hoc analysis did not demonstrate any significant differences between any of the pairings (P>0.05). A significant group by box interaction was also present for hip extension moment (P=0.032). A significant difference was present at the 20cm height for group (P=0.02) with the PFP group displaying a higher hip extension moment (-1.17±.98 Nm) than the control group (-0.76±.98 Nm). Table 4 contains the means and standard deviations for ankle, knee, and hip moments interactions at maximum knee flexion. No other significant findings were present (P>0.05).

NRS

There was a significant difference for the NRS between baseline (2.04±2.17) and post landings (3.68±1.68) (t=-2.5,P=.031) for the PFP individuals.

Discussion

The purpose of this study was to investigate lower extremity biomechanics during a single leg drop landings from various heights in individuals with and without PFP. We hypothesized that individuals with PFP would have an increase in rearfoot EV, decrease in DF, decrease in KFL, increase in KABD, increase in KIR, decrease in HFL, increase in HADD, and increase in HIR angle at instances of IC and MaxKF compared to the control group. We further hypothesized that there would be a statistically significant increase in rearfoot INV moment, decrease in PF moment, decrease in KEXT moment, increase in KADD moment, increase in KER moment, decrease in HEXT moment, increase in HABD moment, and increase in HER moment in the PFP group compared to those in the healthy group during single leg drop landings at MaxKF.

Despite having limited research to compare our findings to, it has been suggested that individuals with PFP may adopt compensatory gait and motion strategies to reduce muscular demands and pain (Dillion, Updyke, & Allen, 1983; Herbert, Gravel, & Tremblay, 1994; Levinger & Gilleard, 2007). Our results indicate that those in the PFP group demonstrated less knee flexion then the control group overall at the point of MaxKF during the single leg drop landing. Previous researchers have speculated that decreased knee flexion angle on landing is a compensatory strategy to decrease the amount of contact pressure of the patella to decrease pain (Crossley, Cowan, Bennell, & McConnell, 2004; Nadeau, Gravel, Hebert, Arsenault, & Lepage, 1997; Powers, Heino, Rao, & Perry, 1999; Boling, Padua, Marshall, Guskiewicz, Pyne, & Beutler, 2009). Boling et al (2009) found that decreased knee flexion angle at initial contact and max knee flexion were risk factors for the development of PFP rather than a compensatory mechanism for it. Their subjects performed a double leg landing compared to our single leg drop landing which may have also influenced their landing strategy. It has been found that flexion motion at the knee played a critical role in force dissipation during a single leg landing for healthy individuals, providing further evidence that individuals with PFP may be more apt to alter their knee flexion to dissipate the forces from landings (McNitt-Gray, 1993).

Knee and hip flexion at Max KF increased for all participants as the box height increased. These findings are supported by previous research (McNitt-Gray, 1993) and suggest that this is a mechanism by which the individuals utilize to decrease the body's momentum through coordinated joint actions (Schmitz et al., 2007). While many studies employ double leg landings, it has been found that single leg landings are performed primarily in the sagittal plane, and therefore controlled flexion of joints is the likely mechanism by which impact forces are absorbed (Schmitz et al., 2007). Additionally we found that PF moment increased and hip extension moment increased as the box heights increased. In addition a box height by group interaction was present for knee flexion moment, while no main effects were found. This implies that the forces applied to the lower extremity during the single leg drop landing were attenuated by sagittal plane movements by all participants with the PFP group demonstrating altered force attenuation during landing at the knee joint compared to healthy individuals. This may provide some insight into the influence of the strength of the quadriceps in individuals with PFP as it has been noted in previous research that individuals who have decreased quadriceps strength may display decreased knee flexion angle due to the demand of dynamic task and large amount of eccentric force from the quadriceps (Boling et al., 2009). This altered pattern with involvement at every joint may provide us with further knowledge as how the joints of the lower extremity act in the distribution of forces during a single leg drop landing.

At IC there was a main effect present for box height for DF with a decrease in DF present as the height of the box for the drop landing increased. This demonstrates that all subjects were in a more plantarflexed position upon initial contact as the drop height increased indicating an altered preparation strategy as the height of the drop landing increases. Although there was no group difference in DF during initial contact, we felt it was an important aspect of the lower extremity to examine since one of the risk factors of developing PFP is limited DF range of motion as it has been attributed to a series of biomechanical compensations in response to the decreased ankle range of motion (Hargrave, Carcia, Gansneder, & Schultz, 2003). Macrum, Bell, Boling, Lewek, & Padua (2012) examined the effects of limiting DF during a double-leg squat and found that restricted DF produced decreased peak KFL, while increasing peak knee valgus angle, noting that these are changes similar to those exhibited by individuals with PFP.

Research has previously shown that individuals with PFP demonstrate increased HADD in landing tasks compared to healthy individuals (Levinger & Gilleard, 2007); however we found increases in HABD as the box height increased for both groups. In a previous study in which a single leg squat was performed, individuals with PFP demonstrated medial deviation of the thigh, which has been theorized to be a result of gluteus medius weakness resulting in adduction of the femur (Levinger & Gilleard, 2007). When investigating the hip kinematics during stair decent in individuals with PFP, subjects did not demonstrate increased HADD compared to healthy individuals leading the researchers to speculate that the task was not strenuous enough to elicit such a response or that the individuals with PFP had sufficient strength to maintain their lower extremity alignment (Bolga, Malone, Umberger, & Uhl, 2008). This may be true for our participants as well as they may have had enough strength to attenuate the forces at initial contact leading them not to go into HADD.

In conclusion, individuals with PFP demonstrate biomechanical differences in KFL angle at the instance of MaxKF during a single leg drop landing compared to healthy individuals. The PFP group demonstrated less KFL at MaxKF suggesting that they employ a stiffer landing pattern and may not attenuate the forces imposed on the LE as well as a healthy individual. The decrease in KFL may serve as a coping mechanism for the individuals with PFP to reduce pain during landing activities.

Table 1

Ankle, Knee, and Hip Angles (degrees) at the Instance of Initial Contact (Mean+SD)

	20 cm	30 cm	40 cm
Ankle Dorsiflexion*	-17.85±11.25	-21.05±8.43	-21.06±7.20
Ankle Inversion	3.35±8.65	4.11±9.27	3.45±9.49
Knee Flexion	-15.13±4.33	-14.08±4.69	-14.26±7.06
Knee Abduction	.93±4.95	.45±4.39	-4.22±4.24
Knee Internal Rotation	-3.70±7.85	-3.07±7.15	-2.62±6.97
Hip Flexion	16.83±21.42	15.30±20.79	14.90±22.08
Hip Abduction*	-6.42±10.8	-8.58±12.93	-9.39±14.44
Hip Internal Rotation	-2.46±7.10	-2.22±7.89	-1.97±7.98

* Main Effect for Box Height ($P \leq 0.05$)

Dorsiflexion (+), Plantarflexion (-), Eversion (-), Inversion (-), Knee Flexion (-), Knee Extension (+), Knee Abduction (-), Knee Adduction (+), Knee Internal Rotation (+), Knee External Rotation (-), Hip Flexion (+), Hip Extension (+), Hip Adduction (-), Hip Abduction (+), Hip Internal Rotation (-), Hip External Rotation (+), Trunk Flexion (-), Trunk Extension (+)

Table 2

Ankle, Knee, and Hip Angles (degrees) at the Instance of Maximum Knee Flexion (Mean+SD)

	20 cm	30 cm	40 cm
Ankle Dorsiflexion	15.39 ± 4.23	16.52 ± 4.47	16.65±4.66
Ankle Inversion	-4.31±8.47	-4.63±8.63	-4.95±9.33
Knee Flexion*+	-49.81±7.11	-52.13±6.24	-55.37±9.16
Knee Abduction	1.76±5.94	.78±5.33	1.33±5.3
Knee Internal Rotation	1.08+7.87	2.02+8.71	1.65+9.99
Hip Flexion*	23.13±25.14	23.8±23.21	28.02±25.31
Hip Abduction	-1.65±7.64	-2.19±6.64	-1.24±7.01
Hip Internal Rotation	-.48±7.63	-.81±8.05	.67±8.69

*Main Effect for Box Height ($P \leq 0.05$)

+Main Effect for Group ($P \leq 0.05$)

Dorsiflexion (+), Plantarflexion (-), Eversion (-), Inversion (-), Knee Flexion (-), Knee Extension (+), Knee Abduction (-), Knee Adduction (+), Knee Internal Rotation (+), Knee External Rotation (-), Hip Flexion (+), Hip Extension (+), Hip Adduction (-), Hip Abduction (+), Hip Internal Rotation (-), Hip External Rotation (+), Trunk Flexion (-), Trunk Extension (+)

Table 3
Ankle, Knee, and Hip Moments (Nm) at the Instance of Maximum Knee Flexion (Mean+SD)

	20 cm	30 cm	40 cm
Ankle Dorsiflexion*	-1.32+.31	-1.65+.25	-1.84+.28
Ankle Inversion	-.01+.21	.00+.26	.03+.24
Knee Flexion	1.92+.57	1.97+.49	2.03+.60
Knee Abduction	-.43+.81	-.42+.75	-.37+.77
Knee Internal Rotation	-.06+.11	-.07+.11	-.06+.13
Hip Flexion*	-.72+.71	-.95+.75	-1.23+.82
Hip Abduction	-.64+1.03	-.69+1.04	-.61+1.09
Hip Internal Rotation	.20+.28	.19+.27	.17+.27

* Main Effect for Box Height ($P \leq 0.05$)

Dorsiflexion (+), Plantarflexion (-), Eversion (-), Inversion (-), Knee Flexion (-), Knee Extension (+), Knee Abduction (-), Knee Adduction (+), Knee Internal Rotation (+), Knee External Rotation (-), Hip Flexion (+), Hip Extension (+), Hip Adduction (-), Hip Abduction (+), Hip Internal Rotation (-), Hip External Rotation (+), Trunk Flexion (-), Trunk Extension (+)

Chapter IV

Project II

Lower Extremity Biomechanics During a Single Leg Drop Landing In Individuals With Patellofemoral Pain: Pre and Post An Aerobic Exercise Treadmill Protocol

Title: Lower extremity biomechanics during a single leg drop landing in individuals with patellofemoral pain: pre and post an aerobic exercise treadmill protocol.

Authors: Stacey Gaven, Bonnie Van Lunen

To be submitted to: Journal of Science, Medicine, and Sport

Introduction

Patellofemoral pain (PFP) is of insidious onset and reported as peripatellar and/or retropatellar, ranges from mild to severe, and is often provoked by physical activity (Tumia & Maffulli, 2002; Cheung, Ng, & Chen, 2006). Physical activities such as climbing stairs, squatting, jumping, running, and/or sitting with the knees flexed for prolonged periods of time have been found to exacerbate pain in the peripatellar area of the knee (Earl & Hoch, 2011). Patellofemoral pain is a particularly regular symptom of patients seen at sports medicine practices with reported incidence ranging from two to 30% (Crossley, Bennell, Green, & McConnell, 2001). Biomechanical and musculoskeletal factors both proximal and distal to the patellofemoral joint have been attributed to being causative factors of PFP (Tumia & Maffulli, 2002).

Contrary to other knee dysfunctions (e.g., anterior cruciate ligament injury) that often have a specific onset and mechanism of injury, the specific cause of PFP is unknown (Bolga, Malone, Umberger, & Uhl, 2008). Abnormal patella tracking may lead to an increase in stress on the patellofemoral joint, which in turn causes pain. An array of factors that may contribute to abnormal patella tracking include quadriceps weakness, quadriceps muscle imbalances, excessive knee soft tissue tightness, an increased quadriceps angle (Q-angle), hip weakness, and altered foot kinematics (Bolga & Boling, 2011). Repetitive movements with malalignment during functional activities can overload the patellar retinaculum and retropatellar articular cartilage and cause pain (Baldon, Nakagawa, Muniz, Amorim, Maclei, & Serrao, 2009). While etiological factors encompassing the entire lower extremity have been associated with PFP, participation in athletic activities while fatigued may further influence abnormal biomechanics in individuals with this condition (Willson, Binder-MacLeod, & Davis, 2008).

While lower extremity mechanics of bilateral landings has been given attention in the literature, unilateral landings are considered more dangerous due to a decrease in the base of support and the increased demands on the musculature of only one lower extremity (Boden, Dean, Feagin, & Garrett, 2000; Weinhandl, Joshi, & O'Connor, 2010). Single leg landings may elicit different mechanical responses following a fatigue protocol then bilateral jump-landing tasks commonly used in studies investigating lower extremity biomechanics (Hollman, Hohl, Kraft, Strauss, & Traver, 2012). Participation in athletic activities while fatigued may further increase the tendency for abnormal lower extremity mechanics and associated risks for PFP (Willson et al., 2008). Individuals with PFP experience peripatellar pain during repetitive knee flexion associated with weight-bearing activities such as running, jumping, and climbing stairs (Willson et al., 2008), all of which involve single leg landings; therefore having an understanding of the biomechanics during single leg landings both pre and post an aerobic exercise protocol in individuals with PFP may help the clinician in the evaluation and treatment of these individuals. Therefore, the purpose of this study was to determine if lower extremity biomechanics during a single leg drop landing were different in individuals with PFP following an aerobic exercise protocol.

Methods

Eleven physically active individuals with PFP were included in the study [6 Female, 5 Male; Age: 22.18±3.28 years; Ht. 169.72±7 cm; Mass: 67.08±15.81 kg; Kujala: 70.72±8.67; Foot Posture Index (FPI): 7.09±2.26]. Participants were included if they had patellofemoral pain for a minimum of three weeks that was of insidious onset and not as a result of an injury and pain that was present during one or more of the following tasks; repetitive knee flexion associated with weight-bearing activities such as running, jumping, squatting, and climbing stairs. Participants had no current lower extremity injury other than their PFP, or musculoskeletal or neurological condition that would affect their ability to land on a single leg and maintain the position for two seconds. Participants were excluded from the study if they failed to meet any of the inclusion criteria and/or they were sensitive or allergic to the adhesive on the tape used to keep markers on, had a history of major orthopedic surgery to the lower extremity, or if they were pregnant. Prior to the start of the testing session, each participant read and signed the informed consent form that was approved by the University's Institutional Review Board.

An 8-camera Vicon motion analysis system (Vicon Motion Systems, Denver, CO), coupled with one Bertec force plate (Model FP4060-10, Bertec Corp., Columbus, OH) with kinetic and kinematic data collected at 200 and 1000 Hz, respectively. The Vicon motion analysis system was calibrated prior to the testing session and the force plates were zeroed out prior to the testing session and between participants. Three wooden boxes with a height of 20, 30, and 40 cm, respectively, were used to have standard drop heights for the participants. A Lifetime Fitness Treadmill Model 95T (Lifetime Fitness, Chanhassen, MN) was used for the aerobic exercise protocol. The Borg CR-10 was used to assess the participant's perceived rating of exertion (RPE).

Participants reported to the lab for one testing session, and read and signed an informed consent before participating in the study. The participant filled out the Kujala, Numeric Rating Scale (NRS), and general medical questionnaire prior to testing. Height and weight were recorded using a physician's scale with a height rod (Detecto Model #339, Webb City, MO). The participant's foot posture was then assessed using the Foot Posture Index (FPI). Participants were prepared for the three dimensional motion analysis by having fifty reflective markers bilaterally on the participant's lower extremities and one cluster plate on their posterior trunk. Anatomical marker locations included the posterior superior iliac spine, iliac crest, anterior superior iliac spine, greater trochanter, medial femoral condyle of the knee joint, lateral femoral condyle of the knee joint, medial malleolus, lateral malleolus, base of the first metatarsal, and base of the fifth metatarsal (Weinhandl et al, 2010). Cluster marker plates with four reflective non-collinear markers were placed on the posterior trunk (between the scapulae), thigh, shank, and rearfoot of the participant (Weinhandl et al., 2010). The anatomical markers were adhered to the participant using double-sided tape, and the cluster marker plates of the lower extremity were applied by first putting on neoprene sleeves (McDavid USA, Woodridge, IL) on the thigh and shank, and adhered to the sleeves with velcro. The trunk cluster was applied by using a neoprene harness with adjustable velcro straps. The same researcher applied the reflective makers on the participants. A static calibration trial was collected for each participant prior to start of the dynamic drop landing tasks. Participants were instructed to stand as still as possible on the force plate with their arms held out in front of them as to not occlude any of the markers (shoulders at 90^{O} of flexion and elbows fully extended). The static calibration is necessary so that it can be referenced when calculating angles during the dynamic tasks. After the static calibration trial was complete all of the anatomical markers with the exception of the posterior superior iliac spine and anterior superior iliac spine were removed. The cluster markers plates remained on for all dynamic tasks.

The single leg drop landing task required the participant to stand atop the wooden box (20, 30, or 40 cm) placed 10 cm away from the force plate with their test leg in ~90^{0} of hip and knee flexion with their arms held across their chest. The participant was then to drop down vertically onto the force plate and stick the landing on the test leg. The participants were allowed up to five practice trials to familiarize themselves with the task. Drop landing heights were counterbalanced for the researcher to account for the possible influence of increased pain after performing multiple drop landings. Participants then performed the single leg drop landing until five acceptable trials were achieved from each drop landing height. The trial was considered acceptable if the participant met the following requirements; (1) did not jump off the box, (2) landed on the test leg and maintained their balance for ~2 seconds, (3) landed on the force plate, and (4) did not allow their opposite leg to touch down prior to the 2 second balance maintenance period. Any trial that was ruled as unacceptable was immediately repeated.

After completing five acceptable trials at each height, the participant then completed an aerobic treadmill protocol. The treadmill protocol was performed by having the participant walk on a treadmill at 3.0 mph at 0% grade for three minutes to become acclimated to the treadmill. After the initial warm-up phase the speed of the treadmill was increased to 4.0 mph at 0% grade for 10 minutes. After completing that stage the speed of the treadmill was increased by .2 mph and 1% grade after the initial 2% grade increase every minute (Ott, Cosby, Grindstaff, & Hart, 2011). The participant's heart rate and perceived rating of exertion was obtained after the first three minutes of the treadmill protocol and every minute thereafter. The treadmill protocol continued until the participant indicated that their knee pain was an 8 or higher on the NRS or their perceived rating of exertion was a 10 on the CR-10 scale. Our participants performed the protocol on average of 19:24±3:29 mins. Immediately following the treadmill protocol, the participant then repeated five acceptable trials of single leg drop landings from each height. After completing the post fatigue landings, the participant filled out the NRS. All participants wore standard lab sneakers (Nike Air Max Glide, Nike Inc., Beaverton, OR) during testing.

Data was post processed with Vicon Nexus software (Vicon Motion Systems, Denver, CO) to identify and fill missing trajectories, remove frivolous trajectories, and to export the data as a .c3d file. The data was then transferred to Visual3D (C-Motion, Inc., Rockville, MD) to reconstruct the model and calculate both kinematic and kinetic variables from the marker and force plate data. Joint angles were calculated using a joint coordinate system approach (Grood & Suntay, 1983; Weinhandl et al., 2010). A 2x3 ANOVA was performed for each kinetic and kinematic variable to determine if significance was present at the two time instances of initial contact (IC) and maximum knee flexion (MaxKF). In the event of a significant main effect or interaction ($\alpha \leq .05$) Fisher's LSD post-hoc tests were performed on all pairwise comparisons. Dependent t-tests were used to calculated significance for the NRS. Statistical data were analyzed using PASW software (Version 20, IBM, Armonk, NY). A priori levels were set at .05 for analysis.

Results

At IC there was a main effect for box height for knee flexion (p=0.001) with differences between 20cm and 30cm(p=0.007), 20cm and 40cm (p=0.001), and for hip flexion (p=0.016) at box heights of 20cm and 40cm (p=0.001). A main effect for time for hip internal rotation at initial contact was present with pre-treadmill protocol (-3.16±7.97°) being higher than post-treadmill protocol (-4.85±9.59°) (p=0.035). Means and standard deviations for ankle, knee, and hip angles at initial contact are located in Table 1.

At MaxKF there was a main effect for knee flexion (p=0.002) for box height with differences between 20cm and 40cm (p=0.006), and 30cm and 40cm (p=0.001). There was also a main effect for time for knee flexion (p=0.49), with pre-treadmill protocol (-48.43±6.37°) values being lower than post-treadmill protocol (-50.78±6.96°) values. Means and standard deviations for ankle, knee, and hip angles at maximum knee flexion are located in Table 2.

A main effect for box height was present for ankle plantarflexion moment (p=0.001) with differences between 20cm and 30cm (p=0.002), 20cm and 40cm (p=0.001), and 30cm and 40cm(p=0.002), knee extension moment with differences between 20cm and 30cm (p=0.005), 20cm and 40cm (p=0.003), 30cm and 40cm (p=0.039) and hip extension moment with differences between 20cm and 40cm (p=0.001), 30cm and 40cm (p=0.026). Means and standard deviations for ankle, knee, and hip moments at maximum knee flexion are located in Table 3.

An interaction for box height x time (P=0.015) was present for ankle plantarflexion moment with differences between the pre and post treadmill protocol for the 20cm height (Pre:-1.41±.95Nm,Post:-1.56±.56Nm) (p=0.03) and 40cm height (Pre:-

1.97±.88Nm,Post-1.78±1.42Nm)(p=0.02). No other significant findings were present. There were no other significant time x box height interactions (p>0.05).

There was a significant difference in the NRS between baseline (2.04±2.17) and post landings (6.32±2.68) (p=0.0002).

Discussion

The purpose of this study was to investigate the lower extremity biomechanics following an aerobic exercise treadmill protocol in individuals with PFP. We hypothesized that after performing the aerobic exercise treadmill protocol that we would see an increase in rearfoot eversion, decrease in ankle dorsiflexion, decrease in knee flexion, increase in knee abduction, increase in knee internal rotation, decrease in hip flexion, increase in hip adduction, and increase in hip internal rotation angle at instances of IC and MaxKF. We further hypothesized that there would be a statistically significant increase in rearfoot eversion moment, decrease in ankle plantarflexion moment, decrease in knee extension moment, increase in knee adduction moment, increase in knee external rotation moment, decrease in hip extension moment, increase in hip abduction moment, and increase in hip external rotation moment after performing the aerobic exercise protocol at the instance of MaxKF. We further expected to have differences in the variables as the drop landing heights increased. Finally, we hypothesized that the participant's NRS score would increase after performing the post fatigue drop landings compared to their baseline score.

Our results demonstrate that individuals with PFP have altered landing patterns following an aerobic exercise protocol along with differences when landing from the different heights. At IC participants displayed a decrease in hip internal rotation from pre aerobic exercise protocol to post. Decreased femoral internal rotation has been proposed as being a compensatory mechanism to avoid large quadriceps angles and associated lateral retropatellar stress (Willson et al., 2008). It has been postulated that individuals with PFP may not be able to maintain this compensatory strategy when fatigued or when performing dynamic tasks with high external loads (Willson et al., 2008). Despite this theory, our participants maintained and even increased this movement strategy following the aerobic exercise protocol while performing single leg drop landings. As our participants reported an increase in pain following the post fatigue drop landings, this compensatory strategy may have been maintained by the participants to avoid the pain that has been associated with repetitive activities in which increased retropatellar stress is present (Willson et al., 2008). In addition at IC a main effect was present for box heights for both knee and hip flexion with decreases in knee and hip flexion as the box heights increased indicating a stiffer landing. Decreased knee flexion prevents knee valgus and landing with less knee flexion does not require as much eccentric muscular strength (Benjaminse, Habu, Sell, Abt, Fu, Myers, & Lephart, 2007). This can serve as a compensatory strategy for those with PFP as an increase in knee valgus and flexion increases the lateral compressive forces of the patella. As the landing height increases a decrease in hip and knee flexion at IC is expected as the body prepares to absorb the landing. Additionally, landing with decreased knee flexion at IC has been shown to be a prospective risk factor for developing PFP (Boling, Padua, Marshall, Guskiewicz, Pyne, & Beutler, 2009).

At MaxKF our participants demonstrated an increase in ankle plantarflexion moment, knee extension moment, and hip extension moment as the landing height increased. Additionally, a significant box height by time interaction was present for ankle plantarflexion moment. Previous single leg landing findings suggest that the landing is performed primarily in the saggital plane, making controlled flexion of the joints the likely mechanism by which impulse is applied (Schmitz, Kulas, Perrin, Riemann, & Shultz, 2007). The prevention of collapse during weight bearing can be accomplished by collaboration of muscles at all three joints of the lower limb, therefore to collapse the knee during weight bearing there must be also be a simultaneous collapse at the hip and ankle (Winter, 1980). With this finding present along the entire lower extremity kinetic chain, it demonstrates the coordination of the joints to dissipate forces accordingly and how the joints act in concert when performing a single leg landing task. A distal to proximal redistribution of extensor moments, suggests that the larger proximal muscles in the lower extremity to contribute more to resisting lower extremity collapse during landing (Madigan & Pidcoe, 2003) and this became more evident in our study as the landing height increased.

After performing the aerobic exercise protocol our participants displayed an increase in knee flexion at the instance of MaxKF. We hypothesized that we would see a decrease in knee flexion after performing the aerobic exercise protocol however found that our participants displayed increased knee flexion as has been seen in previous studies with healthy individuals. Our findings do agree with those of Madigan & Pidcoe (2003) who found an increase in the knee flexion in healthy male individuals while performing a single leg landing following a fatigue protocol. In addition an increase in knee flexion was noted in healthy recreationally active males following a squatting fatigue protocol during single leg landings, than the females during the fatigued state (Kernozek, Torry, &

Iwasaki, 2008). While the protocol of previous studies differed from ours, all studies had their participants fatiguing in a weight bearing position performing function tasks (Madigan & Pidcoe, 2003; Kernozek et al., 2008). This was done to provoke overall lower extremity muscle fatigue and not an isolated muscle fatigue in an effort to understand what may occur during participation in activities when fatigued. As neuromuscular fatigue is a performance factor that may influence lower extremity loads, and as a result may play a role in injury development, it is a complex, multifaceted phenomenon that is well known but difficult to quantify (Madigan & Pidcoe, 2003).

Individuals with PFP landed with more knee flexion during a single leg drop landing following an aerobic exercise protocol. The aerobic exercise protocol evoked a perceived perception of exhaustion in the participants and the single leg landing protocol increased the perceived pain of the participants. While our participants demonstrated differences in kinematics at both IC and MaxKF and kinetics at MaxKF for the different box heights, only knee flexion and hip internal rotation were affected by the exercise protocol. This demonstrates that our participants were able to maintain their landing strategies after fatiguing and that while our participants perceived themselves to be fatigued we may not have induced enough fatigue on the musculature to alter their landing pattern. A limitation to the study was that we did not quantify muscle fatigue in a quantifiable manner and did not have a control group to compare our participants landing patterns to. Future research should use a measurable method of quantifying muscle fatigue and compare individuals with PFP to healthy individuals to investigate if the landing patterns present maybe attributed to their PFP or the task.

Practical Implications

- Individuals with PFP land with increased knee flexion during a single leg drop landing after performing an aerobic exercise protocol to perceived exhaustion
- Individuals with PFP attenuate forces differently when landing from different heights in the saggital plane of the entire lower extremity
- Single leg drop landings induce increased pain in individuals with PFP

Table 1

Ankle, Knee, and Hip Angles in Degrees at Initial Contact (Means+ SD)

	20cm	30cm	40cm
Ankle Dorsiflexion	-18.68±11.94	-20.87±10.51	-21.94±8.13
Rearfoot Eversion	1.76±6.63	1.52±7.03	1.61±6.73
Knee Flexion*	-14.03±4.3	-12.19±4.31	-11.84±4.8
Knee Internal Rotation	-2.17±7.63	-2.85±8.13	-2.69±9.95
Knee Abduction	-.52±5.3	-.8±4.81	-1.41±4.64
Hip Flexion*	17.8±29.1	16.5±28.52	14.76±29.18
Hip Adduction	-4.7±11.6	-6.1±13.9	-6.78±15.26
Hip Internal Rotation	-4.34±8.29	-4.1±8.62	-3.57±9.3

*Main Effect for Box Height ($P \leq 0.05$)

Dorsiflexion (+), Plantarflexion (-), Eversion (-), Inversion (-), Knee Flexion (-), Knee Extension (+), Knee Abduction (-), Knee Adduction (+), Knee Internal Rotation (+), Knee External Rotation (-), Hip Flexion (+), Hip Extension (+), Hip Adduction (-), Hip Abduction (+), Hip Internal Rotation (-), Hip External Rotation (+), Trunk Flexion (-), Trunk Extension (+)

Table 2

Ankle, Knee, and Hip Angles in Degrees at Maximum Knee Flexion (Means+SD)

	20 cm	30cm	40cm
Ankle Dorsiflexion	14.47±3.64	15.1±3.55	16.4±4.91
Rearfoot Eversion	-3.67±7.79	-4.28±7.96	-4.24±9.12
Knee Flexion*	-47.68±7.53	-48.33±5.31	-52.81±7.3
Knee Abduction	.77±5.8	.51±5.31	.32±5.94
Knee Internal Rotation	-.91±8.29	-1.2±9.85	-.89±10.28
Hip Flexion	27.55±31.51	27.51±29.84	30.04±30.98
Hip Abduction	-1.07±6.96	-1.27±5.67	-.80±7.59
Hip Internal Rotation	-1.30±8.85	-1.86±8.95	-.70±8.95

*Main Effect for Box Height ($p \leq 0.05$)

Dorsiflexion (+), Plantarflexion (-), Eversion (-), Inversion (-), Knee Flexion (-), Knee Extension (+), Knee Abduction (-), Knee Adduction (+), Knee Internal Rotation (+), Knee External Rotation (-), Hip Flexion (+), Hip Extension (+), Hip Adduction (-), Hip Abduction (+), Hip Internal Rotation (-), Hip External Rotation (+), Trunk Flexion (-), Trunk Extension (+)

Table 3

Ankle, Knee, and Hip Moments in Newton Meters (Nm) at Maximum Knee Flexion (Means+SD)

	20 cm	30 cm	40 cm
Ankle Plantarflexion*	-1.50±0.23	-1.73±0.23	-1.88±3.32
Rearfoot Inversion	-0.08±0.26	0.70±0.36	0.07±0.33
Knee Extension*	1.85±0.56	2.04±0.50	2.15±0.50
Knee Adduction	-0.30±0.83	-0.28±0.83	-0.24±0.80
Knee External Rotation	-0.06±0.10	-0.07±0.10	-0.05±0.13
Hip Extension*	-1.04±0.73	-1.11±0.86	-1.37±0.73
Hip Adduction	-0.62±1.16	-0.65±1.19	-0.56±1.23
Hip External Rotation	0.14±0.30	0.12±0.28	0.10±0.30

*Main Effect for Box Height ($p \leq 0.05$)

Dorsiflexion (+), Plantarflexion (-), Eversion (-), Inversion (-), Knee Flexion (-), Knee Extension (+), Knee Abduction (-), Knee Adduction (+), Knee Internal Rotation (+), Knee External Rotation (-), Hip Flexion (+), Hip Extension (+), Hip Adduction (-), Hip Abduction (+), Hip Internal Rotation (-), Hip External Rotation (+), Trunk Flexion (-), Trunk Extension (+)

Chapter V

Single Leg Landing Biomechanics in Individuals with Patellofemoral Pain Following an Isolated Hip Abduction Fatigue Protocol

Title: Single leg landing biomechanics in individuals with patellofemoral pain following an isolated hip abduction fatigue protocol.

Authors: Stacey Gaven, Michelle Boling, Daniel Russell, Bonnie Van Lunen

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Introduction

Patellofemoral pain (PFP) encompasses disorders in which pain and point tenderness are present in and around the patellofemoral joint (Boling, Padua, Marshall, Guskiewicz, Pyne, Beutler, 2009). The prevalence of this condition is high since it can occur in individuals with a wide range of physical activity levels and the symptoms often cause disability with exercise participation and activities of daily living (Earl & Hoch, 2011; Powers, 2003). The predominant symptom is pain in the anterior aspect of the knee that is of insidious onset and aggravated during weight-bearing activities such as running, squatting, kneeling, ascending and descending stairs, as well as prolonged sitting (Earl & Hoch, 2011; Levinger, & Gilleard, 2005; Willson, Binder-Macleod, & Davis, 2008).

Despite having a clear picture of what activities aggravate the symptoms of PFP, the specific cause of PFP is unknown as there could be multiple contributing factors (Earl & Hoch, 2011; Powers, 2003). A myriad of musculoskeletal and biomechanical factors both proximal and distal to the patellofemoral joint have been theorized to attribute to the development of PFP. The multifactoral nature of PFP does not limit the pathological presentation to just the knee joint and therefore, gaining an understanding of the entire lower extremity kinetic chain during activity may provide more insight on the possible influences of PFP. Altered trunk, hip, knee, and foot kinematics have been associated with PFP. Dynamic knee valgus, which occurs when the foot is fixed to the ground with an inward movement of the knee joint results in the tibia abducting and pronation of the foot, has been suggested as a contributing factor to PFP (Powers, 2003; Powers, 2010). Abnormal rearfoot position during the gait cycle has been associated with PFP despite abnormal subtalar pronation not being a universal finding in all individuals with PFP, and the connection as to whether abnormal rearfoot pronation is a cause or effect of PFP is unknown (Thijs, Van Tiggelen, Roosen, De Clercq, & Witvrouw, 2007; Boling et al., 2009; Bek, Kinikli, Callaghan, & Atay, 2011). Greater hip adduction due to increased contralateral drop may also increase hip abduction moments due to increased contralateral displacement of the trunk (Schroter, Guth, Overbeck, Rosenbaum, & Winklemann, 1999). Improved kinesthetic awareness of the hip and trunk during dynamic activities, may be effective in the treatment of those with PFP (Willson et al., 2008).

Although altered kinematics along the entire lower extremity have been attributed to PFP, recent research has focused on the hip's role (Earl & Hoch, 2011; Willson et al., 2008; Willson et al., 2008; Willson & Davis, 2008; Souza & Powers, 2009). Altered hip kinematics may contribute to PFP as the hip is the most proximal aspect in the lower extremity kinetic chain and shares a common segment with the knee (Powers, 2010). Excessive femoral adduction and internal rotation may increase the dynamic quadriceps angle and lead to greater lateral patellar contact (Powers, 2003). Researchers have postulated that hip adduction can contribute to dynamic valgus of the lower extremity, resulting in increased lateral forces acting on the patella (Powers, 2003;Souza & Powers, 2009). Although several studies have investigated hip kinematics in individuals with PFP there have been variations in the findings (Willson et al., 2008; Willson & Davis, 2008; Souza & Powers, 2009). Increased hip adduction was found in individuals with PFP when running and performing single leg squats compared to healthy individuals (Willson & Davis, 2008). Souza & Powers (2009) observed that individuals with PFP demonstrated increased hip internal rotation angles during a drop jump, running, and step down were averaged together and compared to healthy individuals. Willson et al. (2008) found that individuals with PFP displayed decreased hip internal rotation along with increased hip flexion and hip adduction compared to healthy individuals during single leg jumps. In addition, a shift to decreased hip flexion was observed in the individuals with PFP after performing an exertional protocol (Willson et al., 2008).

Many athletic activities require the individual to perform single leg landings during participation, such as landing from a jump or simply running. While the majority of previous research has investigated the lower extremity mechanics of bilateral landings, unilateral landings are considered more dangerous due to a decrease in the base of support and the increased demands on the musculature of only one lower extremity (Boden, Dean, Feagin, & Garrett, 2000; Weinhandl, Joshi, & O'Connor, 2010; Hollman, Hohl, Kraft, Struss, & Traver, 2012). Single leg landings may elicit different mechanical responses following a fatigue protocol as compared to bilateral jump-landing tasks commonly used in studies investigating lower extremity biomechanics (Hollman et al., 2012). It is thought that a fatigued muscle will be less capable of absorbing impact forces and thus the body will be predisposed the body to overuse impact-related injuries (Coventry, O'Connor, Hart, Earl, Ebersole, 2006). Participation in athletic activities while fatigued may further increase tendency for abnormal lower extremity mechanics and associated risk for PFP (Willson et al., 2008). It is thought that these biomechanical changes lead that due occur due to fatigue lead to decreased shock absorption and knee stabilizing during landing (Chappell, Herman, Knight, Kirkendall, Garrett, & Yu, 2005). Therefore, the purpose of this study was to determine if there are differences in lower extremity biomechanics during a single leg drop landing pre and post an isolated hip abduction fatigue protocol in individuals with PFP.

Methods

Twenty physically active individuals with PFP were included in this study (14 Female, 6 Male; Age: 24.52±5.79 years; Ht. 168.1±8.27 cm; Mass: 65.95±12.43 kg; Kujala: 71.55±12.1;FPI: 5.95±2.35). Participants were included in the study if they had PFP for a minimum of three weeks that was of insidious onset and not as a result of a traumatic injury, pain that is present during one or more of the following tasks; repetitive knee flexion associated with weight-bearing activities such as running, jumping, squatting, and climbing stairs. Participants were excluded if they presented with any of the following criteria; current lower extremity injury other than PFP, musculoskeletal or neurological condition affecting their ability to land on a single leg and maintain the position for two seconds, allergy to adhesive tape, history of lower extremity orthopedic surgery, and/or if they were pregnant. Prior to the start of the first testing session, each participant read and signed the informed consent form that was approved by the university's Institutional Review Board (IRB).

Instrumentation

An 8-camera Vicon motion analysis system (Vicon Motion Systems, Denver, CO), interfaced with a Bertec force plate (Model FP4060-10, Bertec Corp., Columbus, OH) were used to collect kinematic and kinetic data collected at 200 and 2000 Hz respectively. The Vicon motion analysis system was calibrated prior to each testing session and the force plates were zeroed out prior to the testing session and between participants. Three wooden boxes with a height of 20, 30, and 40 cm respectively were used to have standard drop heights for the participants. A portable fixed dynamometer

Evaluator (BTE Technologies, Hanover, MD) was used for the hip abduction fatigue protocol. The NRS is an 11-point pain scale in which the patient rates the level of pain according to the pain description at each level (Selfe, Bourguigon, & Taylor, 2008). The total range of scores is from zero (no pain) to 10 (severe pain or also commonly referred to as the worst pain you have ever felt) (Selfe et al., 2008).

Procedures

Participants reported to the lab for two testing sessions. On the first testing session, the participant filled out the Kujala, numeric rating scale (NRS), and a general medical questionnaire prior to testing. Height and weight were recorded using a physician's scale with a height rod (Detecto Model #339, Webb City, MO). The participant's foot posture was then assessed using the Foot Posture Index (FPI). Testing attire required the participants to wear spandex shorts, shirtless (males), sports bra (females), and all participants wore standard lab sneakers (Nike Air Max Glide, Nike Inc., Beaverton, OR) during testing. Participants were prepared for the three dimensional motion analysis by having fifty reflective markers secured bilaterally on the participant's lower extremities and one cluster plate on their posterior trunk. Anatomical marker locations included the posterior superior iliac spine, iliac crest, anterior superior iliac spine, greater trochanter, medial femoral condyle of the knee joint, lateral femoral condyle of the knee joint, medial malleolus, lateral malleolus, base of the first metatarsal, and base of the fifth metatarsal (Weinhandl et al., 2010). Cluster marker plates with four reflective non-collinear markers were placed on the posterior trunk (between the scapulas), thigh, shank, and rearfoot of the participant (Weinhandl et al., 2010). The anatomical markers were adhered to the participant using double sided tape, and the cluster marker plates of the lower extremity were applied by first putting on neoprene sleeves (McDavid USA, Woodridge, IL) on the thigh and shank, and adhered to the sleeves with velcro. The trunk cluster was applied by using a neoprene harness with adjustable velcro straps. The same researcher applied the reflective makers on the participants. A static calibration trial was collected for each participant prior to the start of the dynamic drop landing tasks. During the static calibration participants were instructed to stand as still as possible on the force plate with their arms held out in front of them as to not occlude any of the markers (shoulders at 90^{O} of flexion and elbows fully extended). The static calibration was used as a reference when calculating angles during the drop landing. After the static calibration trial was complete all of the anatomical markers with the exception of the posterior superior iliac spine and anterior superior iliac spine were removed. The cluster marker plates remained on for all dynamic tasks.

The single leg drop landing task required the participant to stand atop a wooden box (20, 30, or 40 cm) placed 10 cm away from the force plate with their test leg (symptomatic leg and in the case of bilateral PFP, the leg that was perceived as worse by the participant) in approximately 90° of hip and knee flexion with their arms held across their chest. The participant was instructed to drop down vertically onto the force plate and land on the test leg. The participants were allowed up to five practice trials to familiarize themselves with the task. Drop landing heights were counterbalanced to account for the possible influence of increased pain after performing multiple drop landings. Participants then performed the single leg drop landing tasks from various heights (20,30,40cm) until five acceptable trials were collected. The trial was considered acceptable if the participant met the following requirements; (1) did not jump vertically off the box, (2) landed on the test leg and maintained their balance for approximately 2 seconds, (3) entire foot of the test leg landed on the force plate, and (4) did not allow their opposite leg to touch down prior to the 2 second balance maintenance period. Any trial that was ruled as unacceptable was immediately repeated. After performing the single leg drop landings, the participant filled out the NRS.

Prior to the beginning of the fatigue protocol, the participant's baseline maximum voluntary isometric contraction (MVIC) for hip abduction was obtained by having the participant perform three, five second MVICs and calculated by averaging the peak force for each of the three trials (Carcia, Eggen, & Shultz, 2005). The fatigue protocol was performed by having the participant in a standardized standing posture with the load cell of the portable fixed dynamometer (BTE Technologies, Hanover, MD) attached to the test leg using an ankle strap (Kollack, Onate, & Van Lunen, 2010). Participants performed maximal isometric contraction against the load cell for 15 seconds, with a five second rest (Carcia et al., 2005). After completing three repetitions on the test leg, the load cell was then attached to the opposite leg and the participant then performed maximal isometric contraction against the load cell for 15 seconds, with a five second rest. This protocol was repeated until the participant's inability to achieve 50% of their hip abduction baseline force for 2 consecutive trials on their test leg (Carcia et al., 2005). Immediately following the fatigue protocol, the participant then performed five acceptable trials of single leg drop landings from each height. After completing the post fatigue drop landings, the participant filled out the NRS. During one testing session the participant only performed the single leg drop landings and during the other testing session the participant performed the isolated hip abduction fatigue protocol and then the single leg drop landings. The testing session order was randomized and all participants who performed the fatigue protocol on their initial testing session had at least 48 hours before coming in for their second testing session.

Data Analysis

Data was post processed with Vicon Nexus software (Vicon Motion Systems, Denver, CO). The data was then transferred to Visual3D (C-Motion, Inc., Rockville, MD) to reconstruct the model and calculate kinematic variables from the marker and forceplate data. Raw three-dimensional marker coordinate and forceplate data were low-pass filtered using a fourth-order, zero lag, recursive Butterworth filter with cutoff frequencies of 12 and 50 Hz, respectively. A kinematic model of the trunk, pelvis, and bilateral thighs, lower legs and feet was created from the standing calibration trial. Joint angles were then calculated using a joint coordinate system approach (Grood & Suntay, 1983; Weinhandl et al, 2010). Hip joint centers were placed at 25% of the distance between the greater trochanter markers (Weinhandl et al, 2010). Knee joint centers were placed at the midpoint between the femoral epicondyle markers (Grood & Suntay, 1983) and ankle joint centers were placed at the midpoint between the malleoli markers (Wu, Siegler, Allard, Kirtley, Leardini, Rosenbaum, Whittle, D'Lima, Cristofolini, Witte, Schmid, & Stokes, 2002). Body segment parameters were estimated from Dempster (1955) and joint kinetics were calculated using a Newton-Euler inverse dynamics approach (Bresler & Frankel, 1950) and reported in the distal segment reference frame. A 2 (time: pre-fatigue and post-fatigue) x 3 (box height: 20, 30, 40cm) repeated measures ANOVA was performed for each kinetic (ankle plantarflexion, rearfoot inversion, knee extension, knee external rotation, knee adduction, hip extension, hip external rotation, hip abduction moments) and kinematic (ankle dorsiflexion, rearfoot eversion, knee flexion, knee internal rotation, knee abduction, hip flexion, hip internal rotation, hip adduction, trunk flexion angles) variable to determine if significance was present at the two time instances of initial contact (IC) and maximum knee flexion (MaxKF). In the event of a significant main effect or interaction ($\alpha \leq .05$) Fisher's LSD post-hoc tests were performed on all pairwise comparisons. Dependent t-tests were used to calculated significance for the NRS from baseline to post landings for each testing session. Cohen's d effect size was performed for all kinematic and kinetic variables pre and post fatigue at all three heights (20, 30, 40cm) and at both time instances (IC, MaxKF). Statistical data was analyzed using PASW software (Version 20, IBM, Armonk, NY). A priori levels were set at .05 for all statistical analyses.

Results

At IC there was a main effect for box height for knee flexion (P=0.004) with decreases between 20cm and 30cm(P=0.006) and 20cm and 40cm(P=0.007), for knee adduction(P=0.001) with an decrease between 20cm and 40cm(P=0.001) and 30cm and 40cm(P=0.002), for knee external rotation (P=0.003) with decreases between 20cm and 40cm(P=0.004) and 30cm and 40cm(P=0.001). A main effect for box height was present for hip flexion (P=0.0001) with decreases between 20cm and 30cm(P=0.0001), 20cm and 40cm(P=0.0001), and 30cm and 40cm(P=0.002), for hip abduction (P=0.0001) with increases between 20cm and 30cm(P=0.0001), 20cm and 40cm(P=0.0001), and 30cm and 40cm(P=0.0001), and for hip external rotation (P=0.006) with increases between 20cm and 30cm(P=0.015) and 30cm and 40cm(P=0.023). A main effect for box height was also present for trunk flexion (P=0.0001) with increases between 20cm and

30cm(*P*=0.002) and 20cm and 40cm(*P*=0.001). Means and standard deviations for ankle, knee, hip, and trunk angles at IC are presented in Table 1.

At MaxKF there was a main effect present for box height for ankle dorsiflexion (*P*=0.0001) with increases between 20cm and 30cm(*P*=0.014) and 20cm and 40cm(*P*=0.0001), for knee flexion (*P*=0.001) with increases between 20cm and 30cm(*P*=0.003) and 20cm and 40cm(*P*=0.0001), and for trunk flexion (*P*=0.0001) with increases between 20cm and 30cm(*P*=0.01), 20cm and 40cm(*P*=0.0001), and 30cm and 40cm(*P*=0.002). Means and standard deviations for ankle, knee, hip, and trunk angles at MaxKF are presented in Table 2.

A main effect for box height was present for ankle plantarflexion moment (*P*=0.0001) with increases between 20cm and 30cm(*P*=0.0001), 20cm and 40cm(*P*=0.0001), and 30cm and 40cm(*P*=0.0001), for knee external rotation moment (*P*=0.033) however, post hocs revealed no differences in heights. A main effect for box height was present for hip flexion moment (*P*=0.005) with increases between 20cm and 40cm(*P*=0.005) and 30cm and 40cm(*P*=0.027). A main effect for time was present for hip internal rotation moment (*P*=0.047) with pre fatigue (0.25±0.12Nm) demonstrating a lower internal rotation moment than post fatigue (0.28±0.10Nm). Means and standard deviations for ankle, knee, and hip moments at MaxKF are presented in Table 3.

A significant difference was present for the NRS during both testing sessions. In the testing session consisting of only the single leg drop landings there was an increase in the NRS from baseline (1.43±1.49) and post landings (3.07±1.87) (P=0.0001). In the testing session consisting of the isolated hip abduction fatigue protocol and single leg drop landings, the NRS increased from baseline (1.55±1.64) to post landings (3.03±1.95) (P=0.002). No other significant findings were present.

Discussion

The purpose of this study was to examine the differences in LE biomechanics during single leg drop landings in individuals with PFP pre and post an isolated hip abduction fatigue protocol. We hypothesized that after performing the fatigue protocol our participants would demonstrate an increase in rearfoot eversion, decrease in ankle dorsiflexion, decrease in knee flexion, increase in knee abduction, increase in knee internal rotation, decrease in hip flexion, increase in hip adduction, and increase in hip internal rotation angle at IC and MaxKF. We further hypothesized that there would be an increase in rearfoot inversion moment, decrease in ankle plantarflexion moment, decrease in knee extension moment, increase in knee adduction moment, increase in knee external rotation moment, decrease in hip extension moment, increase in hip abduction moment, and increase in hip external rotation moment after performing the fatigue protocol. In addition we hypothesized that after completing the single leg drop landings that the NRS scores of the participants would increase compared to their baseline score. Our results demonstrated an increase in hip internal rotation moment when performing single leg drop landings following an isolated hip abduction fatigue protocol in individuals with PFP. While many main effects were present for box height at IC and MaxKF no other main effects for time were present suggesting that our participants maintained their landing strategy even after performing an isolated hip abduction fatigue protocol.

The primary actions of the gluteus medius are hip abduction and external rotation. Weakness and fatigue of this muscle may result in greater adduction and femoral internal rotation (Powers, 2003; Dierks, Davis, & Hamill, 2010). Although we did not see an increase in hip adduction or internal rotation angle in our participants following the fatigue protocol our results demonstrated an increase in hip internal rotation moment post fatigue suggesting that participants may have been working harder to control hip external rotation during landing. While we demonstrated statistical significance (*P*=0.047) for hip internal rotation moment the differences between pre (0.25±0.12Nm) and post (0.28±0.10Nm) were small and it's clinical significance should be observed with caution. Despite the small difference, it remains that an increase in hip internal rotation moment was observed among all participants following the fatigue protocol.

Current research encompassing a two-legged paradigm or one landing height suggests that individuals with PFP may adopt compensatory movement strategies to reduce muscular demands and pain (Dillion, Updyke, & Allen, 1983; Herbert, Gravel, & Tremblay, 1994; Levinger & Gilleard, 2007). Our results demonstrated decreases in knee and hip flexion for a unilateral landing as the box height increased at IC. Previous single leg landing studies (Weinhandl et al., 2010; Pappas, Hagins, Sheikhzadeh, Nordin, & Rose, 2007) in healthy individuals demonstrated knee flexion angles ranging from -12.9 ± 5.6° to -15.1 ± 7.7° at landing heights ranging from 30cm to 44cm at initial contact, with our PFP individuals demonstrating a decrease in knee flexion comparatively of -11.01±3.15° (30cm) and -12.87±7.57° (40cm). It has been found that flexion motion at the knee played a critical role in force dissipation during a single leg landing for healthy individuals, providing further evidence that individuals with PFP may be more apt to alter their knee flexion to dissipate the forces from landings (Hargrave et al., 2003). As the landing height increases a decrease in hip and knee flexion at IC is expected as the body prepares to absorb the landing. It has also been noted that increases in IC angles were accompanied by significantly less sagittal hip and knee range of motion (Weinhandl et al., 2010). Additionally, landing with decreased knee flexion at IC has been shown to be a prospective risk factor for developing PFP (Boling et al, 2009).

An increase in knee abduction, internal rotation, and hip adduction were also present at IC as the box height increased. Our participants displayed 0.76±3.34° of knee abduction compared to 0.96 ± 5.0° that was reported by Pappas et al (2007) at the 40cm drop landing height yet our participants displayed more hip adduction (-15.75±4.13°) at IC than Pappas et al (2007) (-8.4 ± 6.0°). Increases in knee abduction and internal rotation has been linked to a more valgus position of the knee joint, along with increased hip adduction, which may result in dysfunctional lower extremity alignment and has been linked to the development of PFP (Earl & Vetter, 2007). Since our participants are already identified as having PFP, we can't speculate if this alteration in their landing pattern was present before their PFP or was adopted as a result of the condition. Furthermore at IC a decrease in hip internal rotation main effect for box height was present, which may have served as a coping mechanism for those with PFP as increased hip internal rotation has been linked to an increase in quadriceps angle that may increase retropatellar stress (Willson & Davis, 2008). Additionally, the decrease in trunk flexion may have been demonstrated at IC as trunk muscle weakness may increase retropatellar stress and promote symptoms of PFP (Willson et al., 2008).

At MaxKF, decreases in ankle dorsiflexion and increases in knee and trunk flexion were found as the box height increased. Along with these changes in joint angles, ankle plantarflexion moment and hip flexion moment increased with box height increase.

Previous single leg landing findings suggest that the primary movement during landing is in the sagittal plane, making controlled flexion of the joints the likely mechanism by which force is applied (Schmitz et al, 2007). The prevention of collapse during weight bearing can be accomplished by contraction of muscles at the hip, knee, and ankle (Winter, 1980). A distal to proximal redistribution of extensor moments, suggest that the larger proximal muscles in the lower extremity contribute more to resisting lower extremity collapse during landing (Madigan & Pidcoe, 2003) and this became more evident in our study as the landing height increased. In addition the increase in trunk flexion as the box height increased could shift the ground reaction force vector anteriorly, closer to the knee joint, in turn decreasing the demands on the knee extensors and increasing the demand on the hip extensors (Willson et al., 2008). Willson et al. (2008) theorized that this may be a mechanism that females with PFP utilize to decrease the knee extension moment, retropatellar stress, and pain.

When further exploring our findings, we found moderate effect sizes at different instances and box heights that our fatigue protocol had an influence on some variables especially those in the sagittal plane. During IC knee flexion angle at 30cm (-11.01±3.15) increased post fatigue (-13.92±7.11) (d=0.53); along with hip flexion (6.89±8.24) increased post fatigue (10.46±6.55) (d=-0.50); and trunk flexion (1.55±5.31) decreased post fatigue (4.28±4.42) (d=-0.56) demonstrating that when fatigued individuals may change the way they prepare to attenuate forces during a single leg drop landing. In addition hip adduction at the 40cm drop height at initial contact demonstrated an increase from pre-fatigue (-13.68±3.10) to post fatigue (-15.72±3.61) (d=0.61). An increase in hip adduction has been detected in females with PFP during single leg squats, running, and jumping (Willson & Davis, 2008). At the instance of MaxKF, ankle plantarflexion moment demonstrated a decrease from pre-fatigue (-1.69±0.46) to (-1.33±0.19) post fatigue (d=-1.02), while the opposite occurred at the 40cm height with an increase from pre-fatigue (-1.57±0.23) to post fatigue (-1.76±0.24) (d=0.81). These findings further support the notion that single leg landings are attenuated primarily in the sagittal plane (Schmitz et al., 2007). These additional findings may help us better understand why more post fatigue differences were not found in our study.

We may not have seen significant differences following the implementation of the isolated hip abductor fatigue protocol since individuals may not produce fatigue in an isolated fashion but rather are affected by the fatigue of multiple muscle groups during activity (Carcia et al, 2005). Our participants may have been able to recruit enough muscle strength from surrounding musculature to overcome the fatigue of the hip abductors to maintain their landing patterns following isolated hip abductor fatigue. While previous research in individuals with PFP have noted a decrease in hip abductor strength, our participants may have already had a strength deficit present for which we did not assess for and may already have adopted landing strategies to overcome those strength deficits (Willson & Davis, 2008; Pappas et al, 2007; Ireland, Willson, Ballantyne, & Davis, 2003; Cichanowski, Schmitt, Johnson, & Niemuth, 2007; Tyler, Nicholas, Mullaney, & McHugh, 2006; Robinson & Nee, 2007). As previous research has noted, single leg landings are performed primarily in the sagittal plane, and therefore controlled flexion of joints is the likely mechanism by which impact forces are absorbed (Schmitz et al., 2007). Our hip abduction fatigue protocol may not have produced differences in our participants landing patterns as they may have controlled the impact forces of their landings in the sagittal plane whereas the fatigue protocol utilized in this study focused on musculature that controls frontal plane motion at the hip joint. Furthermore, our fatigue protocol was adopted from Carcia et al. (2005) in which 50% of the MVIC was the threshold they set for their participants to attain to terminate the protocol to indicate fatigue. Post analysis in their study revealed that their participants only achieved 30% of their MVIC and not the intended 50% yet they still displayed an increase in knee abduction during a bilateral drop landing (Carcia et al., 2005). Our study carried out the fatigue protocol to 50% of our participants MVIC which may not have been sufficient enough to induce changes in their post fatigue landings.

Conclusion

In conclusion, individuals with PFP only demonstrated a difference in hip internal rotation moment following an isolated hip abduction protocol while performing single leg drop landings. Although our participants demonstrated differences in kinematics at both IC and MaxKF and kinetics at MaxKF for the different box heights, only hip internal rotation moment was affected by the isolated hip abduction fatigue protocol. This indicates that our participants were able to maintain their landing strategies despite performing a fatiguing protocol. A limitation to this study is that we did not have a control group to compare our participants landing patterns to. Future research should include a quantifiable way to measure muscle activity to both ensure that the fatigue protocol was effective in producing muscle contraction changes and to gain an understanding of how the muscles function during the single leg drop landing which may provide more insight into the muscle recruitment of those with PFP.

Key Points

Findings: After performing an isolated isometric hip abduction protocol to 50% of their MVIC, individuals with PFP did not demonstrate alterations to their landing strategies post fatigue. Although a statistically significant decrease was found for hip internal rotation moment post fatigue, the difference was small and may not have much clinical relevance.

Implications: Based on our results, individuals with PFP may be able to compensate after performing an isolated hip abduction fatigue when performing a single leg drop landing.

Caution: The data from this study is based on individuals with PFP and it should not be generalized to other healthy or injured populations.

Table 1

Ankle, Knee, Hip, and Trunk Joint Angles in Degrees at Initial Contact (Means+SD)

	20cm	30cm	40cm
Ankle Dorsiflexion	-24.40±4.36	-24.55±4.43	-24.35±8.54
Rearfoot Eversion	7.28±4.08	7.38±4.3	6.9±4.87
Knee Flexion*	-13.26±4.29	-12.07±4.51	-11.64±4.22
Knee Abduction*	1.64±3.66	1.64±3.77	.76±3.34
Knee Internal Rotation*	-5.69±5.79	-5.12±6.75	-3.48±5.45
Hip Flexion*	10.36±5.76	8.07±6.61	6.57±7.15
Hip Adduction*	-10.63±2.99	-13.45±4.02	-15.75±4.13
Hip Internal Rotation*	-5.17±4.27	-6.71±4.19	-7.05±4.51
Trunk Flexion*	3.91±3.69	3.63±4.08	2.04±4.56

* Main Effect for Box Height

Dorsiflexion (+), Plantarflexion (-), Eversion (-), Inversion (-), Knee Flexion (-), Knee Extension (+), Knee Abduction (-), Knee Adduction (+), Knee Internal Rotation (+), Knee External Rotation (-), Hip Flexion (+), Hip Extension (+), Hip Adduction (-), Hip Abduction (+), Hip Internal Rotation (-), Hip External Rotation (+), Trunk Flexion (-), Trunk Extension (+)

Table 2

Ankle, Knee, Hip, and Trunk Joint Angles in Degrees at Maximum Knee Flexion (Means±SD)

	20cm	30cm	40cm
Ankle Dorsiflexion*	13.9±6.26	15.63±6.66	16.43±5.9
Rearfoot Eversion	-6.87±3.05	-7.16±2.87	-7.34±3.23
Knee Flexion*	-44.55±9.88	-47.13±10.37	-47.67±10.86
Knee Abduction	2.57±3.3	2.15±4.11	2.06±4.06
Knee Internal Rotation	4.24±3.2	5.09±3.97	4.4±4.66
Hip Flexion	15.06±8.4	15.31±10.33	16.27±11.98
Hip Abduction	-1.8±4.78	-2.49±5.54	-2.42±6.79
Hip Internal Rotation	-1.96±4.74	-2.36±5.09	-1.94±5.54
Trunk Flexion*	-5.34±4.96	-7.6±5.5	-10.68±5.99

*Main Effect for Box Ht. ($P \leq 0.05$)

Dorsiflexion (+), Plantarflexion (-), Eversion (-), Inversion (-), Knee Flexion (-), Knee Extension (+), Knee Abduction (-), Knee Adduction (+), Knee Internal Rotation (+), Knee External Rotation (-), Hip Flexion (+), Hip Extension (+), Hip Adduction (-), Hip Abduction (+), Hip Internal Rotation (-), Hip External Rotation (+), Trunk Flexion (-), Trunk Extension (+)

Table 3

Ankle, Knee, and Hip Moments in Newton-Meters(Nm) at Maximum Knee Flexion (Means+SD)

	20cm	30cm	40cm
Ankle Plantarflexion*	-1.28±.29	-1.51±.31	-1.72±.26
Rearfoot Eversion	-0.07±.08	-0.09±.08	-0.12±.13
Knee Extension	1.68±.49	1.71±.44	1.66±.53
Knee Adduction	-0.78±.17	-0.73±.17	-0.75±.13
Knee External Rotation*	-0.11±.04	-.11±0.04	-0.15±.08
Hip Extension*	-0.41±.44	-0.52±.58	-0.74±.71
Hip Adduction	-1.1±.22	-1.09±.26	-1.09±.31
Hip External Rotation*	0.26±.08	0.27±.08	0.26±.08

*Main Effect for Box Ht. ($P \leq 0.05$)

Dorsiflexion (+), Plantarflexion (-), Eversion (-), Inversion (-), Knee Flexion (-), Knee Extension (+), Knee Abduction (-), Knee Adduction (+), Knee Internal Rotation (+), Knee External Rotation (-), Hip Flexion (+), Hip Extension (+), Hip Adduction (-), Hip Abduction (+), Hip Internal Rotation (-), Hip External Rotation (+), Trunk Flexion (-), Trunk Extension (+)

Chapter VI

CONCLUSIONS

Overall, the three projects have provided some understanding into single leg drop landing characteristics of individuals with PFP. The fatigue protocols have provided some insight into how individuals with PFP may alter their landing biomechanics when they are in a fatigued state. In the first project, when compared to healthy individuals, those with PFP displayed a significant decrease in knee flexion at the instance of MaxKF. The decrease in knee flexion suggests that those with PFP employ a stiffer landing indicating that they may not be able to dissipate the forces as well as a healthy individual. The decrease in knee flexion may serve as a coping mechanism for individuals with PFP to reduce pain during landing activities. In project II, an increase in knee flexion was displayed in those with PFP after performing an aerobic exercise protocol, demonstrating that those with PFP may not be able to maintain their landing strategies specifically in regards to knee flexion after a global lower extremity fatiguing protocol. Project III, only displayed differences for hip external rotation moment with a decrease from pre to post fatigue in our isolated hip abduction fatigue protocol suggesting that individuals with PFP may not employ different landing strategies following an isolated hip abduction fatigue protocol.

These projects have illustrated that having PFP may influence landing patterns during a single leg drop landing. Furthermore, biomechanical factors may be influenced by fatigue and drop landing height. These changes can be seen as a compensatory strategy to attenuate the forces imposed on the lower extremity in different conditions.

Future studies should analyze quantifiable muscle fatigue and other landings tasks in individuals with PFP and compare their lower extremity biomechanics to healthy individuals to gain more insight into the differences those with PFP may exhibit during landings.

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Appendix I-Project I descriptive analysis (Means and SDs) of the kinematic variables at initial contact for the three box heights.

Ankle, Knee, and Hip Kinematics (Degrees) at IC (Means±SD)

	20cm		30cm		40cm	
	PFP	Control	PFP	Control	PFP	Control
Ankle Dorsiflexion	-17.63±14.35	-18.06±6.88	-21.12±11.00	-20.98±4.61	-22.44±8.63	-19.67±5.40
Rearfoot Eversion	0.55±8.82	6.14±8.48	0.29±9.55	7.93±8.98	-0.39±9.27	7.29±9.714
Knee Flexion	-13.94±4.41	-16.32±4.25	-12.32±4.87	-15.85±4.87	-11.98±4.98	-16.54±8.65
Knee Internal Rotation	-3.24±8.36	-4.16±7.30	-3.47±8.00	-3.06±6.19	-2.60±7.35	-2.64±6.56
Knee Abduction	-0.04±5.25	2.06±4.36	-0.66±4.96	0.90±3.74	-1.34±4.65	0.50±3.79
Hip Flexion	11.04±13.41	14.66±7.66	10.10±12.30	12.73±8.11	7.68±14.86	14.31±10.18
Hip Internal Rotation	-5.35±5.27	-1.28±6.61	-5.41±7.54	-1.02±7.54	-4.89±6.63	-0.90±7.07
Hip Adduction	-8.93±8.01	-8.80±9.16	-11.29±9.10	-11.96±10.65	-11.97±10.75	-13.44±11.48

Dorsiflexion (+), Plantarflexion (-), Eversion (-), Inversion (-), Knee Flexion (-), Knee Extension (+), Knee Abduction (-), Knee Adduction (+), Knee Internal Rotation (+), Knee External Rotation (-), Hip Flexion (+), Hip Extension (+), Hip Adduction (-), Hip Abduction (+), Hip Internal Rotation (-), Hip External Rotation (+), Trunk Flexion (-), Trunk Extension (+)

Appendix II-Project I descriptive analysis (Means and SDs) of the kinematic variables at maximum knee flexion for the three box heights.

Ankle, Knee, and Hip Kinematics (Degrees) at MaxKF (Means+SD)

	20cm		30cm		40cm	
	PFP	Control	PFP	Control	PFP	Control
Ankle Dorsiflexion	14.05±3.68	16.73±4.72	15.28±4.19	17.76±4.72	15.20±3.62	18.10±5.51
Rearfoot Eversion	-3.52±7.99	-5.11±8.93	-4.03±7.94	-5.22±8.95	-4.30±8.98	-5.72±9.67
Knee Flexion	-46.14±7.52	-53.47±6.68	-47.54±5.62	-56.72±6.81	-51.63±6.80	-59.11±11.02
Knee Internal Rotation	-1.10±8.05	3.25±7.68	-0.06±9.81	4.10±7.45	-0.09±11.07	3.90±8.77
Knee Abduction	1.14±6.34	2.38±5.40	-0.39±5.83	1.95±4.77	0.01±5.99	2.64±4.50
Hip Flexion	17.92±18.74	20.25±14.83	18.63±14.64	21.14±14.64	20.08±18.15	28.22±17.98
Hip Internal Rotation	-2.07±7.18	-0.24±7.04	-3.17±8.22	0.22±7.04	-1.97±8.78	1.83±7.57

Dorsiflexion (+), Plantarflexion (-), Eversion (-), Inversion (-), Knee Flexion (-), Knee Extension (+), Knee Abduction (-), Knee Adduction (+), Knee Internal Rotation (+), Knee External Rotation (-), Hip Flexion (+), Hip Extension (+), Hip Adduction (-), Hip Abduction (+), Hip Internal Rotation (-), Hip External Rotation (+), Trunk Flexion (-), Trunk Extension (+)

Appendix III-Project I descriptive analysis (Means and SDs) of the kinetic variables at maximum knee flexion for the three box heights.

Ankle, Knee, and Hip Kinetics (Nm) at MaxKF (Means+SD)

	20cm		30cm		40cm	
	PFP	Control	PFP	Control	PFP	Control
Ankle Plantarflexion	-1.44±0.29	-1.20±0.24	-1.73±0.27	-1.57±0.24	-1.97±0.26	-1.72±0.30
Rearfoot Inversion	0.003±0.26	-0.01±0.15	0.05±0.32	-0.04±0.18	0.09±0.29	-0.03±0.16
Knee Extension	1.81±0.65	2.03±0.48	1.92±0.53	2.01±0.44	2.18±0.57	1.88±0.62
Knee External Rotation	-0.06±0.12	-0.05±0.10	-0.07±0.11	-0.07±0.11	-0.05±0.14	-0.06±0.11
Knee Adduction	-0.28±0.83	-0.57±0.79	-0.27±0.79	-0.57±0.70	-0.20±0.88	-0.54±0.65
Hip Extension	-1.06±0.72	-0.39±0.70	-1.13±0.87	-0.78±0.61	-1.33±0.91	-1.12±0.72
Hip External Rotation	0.14±0.29	0.26±0.28	0.11±0.28	0.27±0.26	0.08±0.32	0.26±0.22
Hip Abduction	-0.62±1.21	-0.66±0.81	-0.66±1.21	-0.72±0.83	-0.52±1.36	-0.71±0.73

Dorsiflexion (+), Plantarflexion (-), Eversion (-), Inversion (-), Knee Flexion (-), Knee Extension (+), Knee Abduction (-), Knee Adduction (+), Knee Internal Rotation (+), Knee External Rotation (-), Hip Flexion (+), Hip Extension (+), Hip Adduction (-), Hip Abduction (+), Hip Internal Rotation (-), Hip External Rotation (+), Trunk Flexion (-), Trunk Extension (+)

Appendix IV-Project II descriptive analysis (Means and SDs) of the kinematic variables at initial contact for the three box heights.

Ankle, Knee, and Hip Kinematics (Degrees) at IC (Means+SD)

	20cm		30cm		40cm	
	Pre	Post	Pre	Post	Pre	Post
Ankle Dorsiflexion	-17.63±14.35	-19.60±11.02	-21.12±11.00	-20.62±10.20	-22.44±8.63	-21.45±7.94
Rearfoot Eversion	0.55±8.82	2.97±6.97	0.29±9.55	2.75±7.06	-0.39±9.27	3.62±6.84
Knee Flexion	-13.94±4.41	-14.13±4.53	-12.32±4.87	-12.07±4.45	-11.98±4.98	-11.70±4.82
Knee Internal Rotation	-3.24±8.36	-1.10±7.32	-3.47±8.00	-2.62±8.51	-2.60±7.35	-2.78±6.15
Knee Abduction	-0.04±5.25	-0.84±5.41	-0.66±4.96	-0.94±4.73	-1.34±4.65	-1.48±4.61
Hip Flexion	11.04±13.41	9.94±13.13	10.10±12.30	8.36±11.39	7.68±14.86	7.56±13.58
Hip Internal Rotation	-5.35±5.27	-7.20±6.66	-5.41±7.54	-7.10±6.71	-4.89±6.63	-6.81±6.89
Hip Adduction	-8.93±8.01	-6.08±10.74	-11.29±9.10	-7.92±13.10	-11.97±10.75	-8.97±13.83

Dorsiflexion (+), Plantarflexion (-), Eversion (-), Inversion (-), Knee Flexion (-), Knee Extension (+), Knee Abduction (-), Knee Adduction (+), Knee Internal Rotation (+), Knee External Rotation (-), Hip Flexion (+), Hip Extension (+), Hip Adduction (-), Hip Abduction (+), Hip Internal Rotation (-), Hip External Rotation (+), Trunk Flexion (-), Trunk Extension (+)

Appendix V-Project II descriptive analysis (Means and SDs) of the kinematic variables at maximum knee flexion for the three box heights.

Ankle, Knee, and Hip Kinematics (Degrees) at MaxKF (Means+SD)

	20cm		30cm		40cm	
	Pre	Post	Pre	Post	Pre	Post
Ankle Dorsiflexion	14.05±3.68	14.90±4.40	15.28±4.19	14.91±3.86	15.20±3.62	17.50±6.37
Rearfoot Eversion	-3.52±7.99	-3.82±7.66	-4.03±7.94	-4.53±8.16	-4.30±8.98	-4.29±9.61
Knee Flexion	-46.14±7.52	-49.22±8.02	-47.54±5.62	-49.12±6.07	-51.63±6.80	-53.99±8.59
Knee Internal Rotation	-1.10±8.05	-0.72±9.24	-0.06±9.81	-2.35±10.16	-0.09±11.07	-1.17±10.04
Knee Abduction	1.14±6.34	0.41±5.38	-0.39±5.83	1.41±5.11	0.01±5.99	0.63±6.14
Hip Flexion	17.92±18.74	21.42±19.07	18.63±14.64	20.26±15.27	20.08±18.15	24.45±18.61
Hip Internal Rotation	-2.07±7.18	-3.79±7.97	-3.17±8.22	-3.41±8.24	-1.97±8.78	-2.38±8.13
Hip Adduction	-2.21±7.41	-1.26±6.88	-2.37±6.13	-1.22±5.70	-2.08±7.11	-0.64±8.67

Dorsiflexion (+), Plantarflexion (-), Eversion (-), Inversion (-), Knee Flexion (-), Knee Extension (+), Knee Abduction (-), Knee Adduction (+), Knee Internal Rotation (+), Knee External Rotation (-), Hip Flexion (+), Hip Extension (+), Hip Adduction (-), Hip Abduction (+), Hip Internal Rotation (-), Hip External Rotation (+), Trunk Flexion (-), Trunk Extension (+)

Appendix VI-Project II descriptive analysis (Means and SDs) of the kinetic variables at maximum knee flexion for the three box heights.

Ankle, Knee, and Hip Kinetics (Nm) at MaxKF (Means+SD)

	20cm		30cm		40cm	
	Pre	Post	Pre	Post	Pre	Post
Ankle Plantarflexion	-1.44±0.29	-1.56±0.17	-1.73±0.27	-1.74±0.26	-1.97±0.26	-1.78±0.43
Rearfoot Inversion	0.003±0.26	-0.02±0.30	0.05±0.32	0.09±0.43	0.09±0.29	0.06±0.39
Knee Extension	1.81±0.65	1.90±0.50	1.92±0.53	2.17±0.46	2.18±0.57	2.12±0.44
Knee External Rotation	-0.06±0.12	-0.06±0.12	-0.07±0.11	-0.06±0.12	-0.05±0.14	-0.05±0.14
Knee Adduction	-0.28±0.83	-0.33±0.80	-0.27±0.79	-0.28±0.85	-0.20±0.88	-0.27±0.74
Hip Extension	-1.06±0.72	-1.02±0.80	-1.13±0.87	-1.08±0.87	-1.33±0.91	-1.42±0.62
Hip External Rotation	0.14±0.29	0.14±0.28	0.11±0.28	0.12±0.28	0.08±0.32	0.11±0.27
Hip Abduction	-0.62±1.21	-0.62±1.08	-0.66±1.21	-0.63±1.17	-0.52±1.36	-0.60±1.09

Dorsiflexion (+), Plantarflexion (-), Eversion (-), Inversion (-), Knee Flexion (-), Knee Extension (+), Knee Abduction (-), Knee Adduction (+), Knee Internal Rotation (+), Knee External Rotation (-), Hip Flexion (+), Hip Extension (+), Hip Adduction (-), Hip Abduction (+), Hip Internal Rotation (-), Hip External Rotation (+), Trunk Flexion (-), Trunk Extension (+)

Appendix VII-Project III descriptive analysis (Means and SDs) of the kinematic variables at initial contact for the three box heights.

Ankle, Knee, Hip, and Trunk Kinematics (Degrees) at IC (Means+SD)

	20cm		30cm		40cm	
	Pre	Post	Pre	Post	Pre	Post
Ankle Dorsiflexion	-24.34±5.78	-24.69±6.12	-24.11±12.41	-24.46±4.74	-24.24±5.80	-24.61±7.88
Rearfoot Eversion	8.09±4.33	7.62±4.55	7.17±4.93	6.48±4.58	7.15±4.65	6.65±5.38
Knee Flexion	-12.60±3.51	-11.27±3.70	-11.01±3.15	-13.92±7.11	-12.87±7.57	-12.28±7.27
Knee Internal Rotation	-6.24±5.75	-5.67±6.75	-3.44±5.87	-5.14±6.59	-4.57±7.34	-3.52±5.69
Knee Abduction	1.75±3.48	1.72±3.89	0.73±3.61	1.53±4.74	1.57±4.64	0.79±3.92
Hip Flexion	10.26±7.52	8.32±7.86	6.89±8.24	10.46±6.55	7.82±7.75	6.25±7.86
Hip Internal Rotation	-5.71±3.53	-6.90±3.81	-7.23±4.55	-4.63±6.68	-6.53±5.50	-6.88±5.88
Hip Adduction	-10.97±3.72	-13.23±5.66	-15.78±5.22	-10.48±2.96	-13.68±3.10	-15.72±3.61
Trunk Flexion	3.56±3.98	3.07±4.42	1.55±5.31	4.28±4.42	4.19±4.43	2.53±4.48

Dorsiflexion (+), Plantarflexion (-), Eversion (-), Inversion (-), Knee Flexion (-), Knee Extension (+), Knee Abduction (-), Knee Adduction (+), Knee Internal Rotation (+), Knee External Rotation (-), Hip Flexion (+), Hip Extension (+), Hip Adduction (-), Hip Abduction (+), Hip Internal Rotation (-), Hip External Rotation (+), Trunk Flexion (-), Trunk Extension (+)

Appendix VIII-Project III descriptive analysis (Means and SDs) of the kinematic variables at maximum knee flexion for the three box heights.

Ankle, Knee, Hip, and Trunk Kinematics (Degrees) at MaxKF (Means+SD)

	20cm		30cm		40cm	
	Pre	Post	Pre	Post	Pre	Post
Ankle Dorsiflexion	13.98±7.45	15.44±7.49	15.91±5.97	13.83±5.51	15.84±6.55	16.96±6.51
Rearfoot Eversion	-6.16±3.81	-6.75±3.73	-7.12±3.94	-7.58±2.82	-7.59±2.90	-7.58±4.31
Knee Flexion	-44.27±11.15	-46.81±10.73	-47.03±11.99	-44.83±9.84	-47.46±10.90	-48.31±10.42
Knee Internal Rotation	4.28±3.76	5.20±4.20	4.59±6.25	4.20±3.75	4.99±5.34	4.22±5.26
Knee Abduction	2.13±3.54	1.51±4.16	1.39±3.97	3.01±4.00	2.80±4.89	2.74±5.28
Hip Flexion	15.01±9.27	15.41±11.41	15.94±13.03	15.11±9.34	15.21±11.04	16.10±12.56
Hip Internal Rotation	-2.46±5.26	-2.68±5.56	-1.96±5.21	-1.47±5.80	-2.04±6.10	-1.93±6.49
Hip Adduction	-1.66±5.22	-2.94±7.00	-3.06±8.07	-1.95±4.83	-2.05±4.89	-1.78±6.19
Trunk Flexion	-5.26±4.62	-5.43±6.67	-8.24±5.57	-6.97±6.48	-10.52±6.13	-10.84±7.36

Dorsiflexion (+), Plantarflexion (-), Eversion (-), Inversion (-), Knee Flexion (-), Knee Extension (+), Knee Abduction (-), Knee Adduction (+), Knee Internal Rotation (+), Knee External Rotation (-), Hip Flexion (+), Hip Extension (+), Hip Adduction (-), Hip Abduction (+), Hip Internal Rotation (-), Hip External Rotation (+), Trunk Flexion (-), Trunk Extension (+)

Appendix IX-Project III descriptive analysis (Means and SDs) of the kinetic variables at maximum knee flexion for the three box heights.

Ankle, Knee, and Hip Kinetics (Nm) at MaxKF (Means+SD)

	20cm		30cm		40cm	
	Pre	Post	Pre	Post	Pre	Post
Ankle Plantarflexion	-1.25±0.49	-1.47±0.47	-1.69±0.46	-1.33±0.19	-1.57±0.23	-1.76±0.24
Rearfoot Inversion	-0.90±0.15	-0.07±0.16	-0.11±0.16	-0.06±0.08	-0.12±0.10	-0.13±0.14
Knee Extension	1.65±0.54	1.72±0.46	1.64±0.62	1.72±0.61	1.72±0.54	1.69±0.55
Knee External Rotation	-0.12±0.08	-0.11±0.07	-0.13±0.07	-0.12±0.07	-0.12±0.07	-0.18±0.19
Knee Adduction	-0.79±0.21	-0.71±0.24	-0.71±0.21	-0.79±0.24	-0.76±0.31	-0.80±0.22
Hip Extension	-0.38±0.46	-0.56±0.60	-0.68±0.80	-0.45±0.53	-0.49±0.68	-0.81±0.80
Hip External Rotation	0.26±0.14	0.26±0.13	0.24±0.13	0.28±0.11	0.28±0.10	0.29±0.12
Hip Abduction	-1.12±0.29	-1.09±0.30	-1.06±0.39	-1.09±0.26	-1.09±0.31	-1.13±0.35

Dorsiflexion (+), Plantarflexion (-), Eversion (-), Inversion (-), Knee Flexion (-), Knee Extension (+), Knee Abduction (-), Knee Adduction (+), Knee Internal Rotation (+), Knee External Rotation (-), Hip Flexion (+), Hip Extension (+), Hip Adduction (-), Hip Abduction (+), Hip Internal Rotation (-), Hip External Rotation (+), Trunk Flexion (-), Trunk Extension (+)

Appendix X-Project III effect sizes of the kinematic variables at initial contact for the 20cm box height

		Confidence Interval	
Criterion Variable	**Cohen's d-effect size**	**Lower**	**Upper**
Ankle Dorsiflexion	0.06	-0.56	0.68
Rearfoot Eversion	0.11	-0.51	0.73
Knee Flexion	-0.37	-0.99	0.26
Knee Internal Rotation	-0.09	-0.71	0.53
Knee Abduction	0.29	-0.34	0.91
Hip Flexion	0.25	-0.37	0.87
Hip Internal Rotation	0.32	-0.30	0.95
Hip Adduction	0.47	-0.16	1.10
Trunk Flexion	0.12	-0.50	0.74

Appendix-XI-Project III effect sizes of the kinematic variables at initial contact for the 30cm box height

		Confidence Interval	
Criterion Variable	**Cohen's d-effect size**	**Lower**	**Upper**
Ankle Dorsiflexion	-0.04	-0.66	0.58
Rearfoot Eversion	0.15	-0.48	0.77
Knee Flexion	0.53	-0.10	1.16
Knee Internal Rotation	0.27	-0.35	0.90
Knee Abduction	-0.19	-0.81	0.43
Hip Flexion	-0.50	-1.13	0.13
Hip Internal Rotation	-0.45	-1.08	0.17
Hip Adduction	-1.25	-1.93	-0.57
Trunk Flexion	-0.56	-1.19	0.07

Appendix XII-Project III effect sizes of the kinematic variables at initial contact for the 40cm box height.

		Confidence Interval	
Criterion Variable	**Cohen's d-effect size**	**Lower**	**Upper**
Ankle Dorsiflexion	0.05	-0.57	0.67
Rearfoot Eversion	0.10	-0.52	0.72
Knee Flexion	-0.08	-0.70	0.54
Knee Internal Rotation	-0.16	-0.78	0.46
Knee Abduction	0.18	-0.44	0.80
Hip Flexion	0.20	-0.42	0.82
Hip Internal Rotation	0.06	-0.56	0.68
Hip Adduction	0.61	-0.03	1.24
Trunk Flexion	0.37	-0.25	1.00

Appendix XIII-Project III effect sizes of the kinematic variables at maximum knee flexion for the 20cm box height.

		Confidence Interval	
Criterion Variable	**Cohen's d-effect size**	**Lower**	**Upper**
Ankle Dorsiflexion	-0.20	-0.82	0.43
Rearfoot Eversion	0.16	-0.46	0.78
Knee Flexion	0.23	-0.39	0.85
Knee Internal Rotation	-0.23	-0.85	0.39
Knee Abduction	0.16	-0.46	0.78
Hip Flexion	-0.04	-0.66	0.58
Hip Internal Rotation	0.04	-0.58	0.66
Hip Adduction	0.21	-0.41	0.83
Trunk Flexion	0.03	-0.59	0.67

Appendix XIV-Project III effect sizes of the kinematic variables at maximum knee flexion for the 30cm box height.

		Confidence Interval	
Criterion Variable	**Cohen's d-effect size**	**Lower**	**Upper**
Ankle Dorsiflexion	0.36	-0.26	0.99
Rearfoot Eversion	0.13	-0.49	0.75
Knee Flexion	-0.20	-0.82	0.42
Knee Internal Rotation	0.08	-0.54	0.70
Knee Abduction	-0.41	-1.03	0.22
Hip Flexion	0.07	-0.55	0.69
Hip Internal Rotation	-0.09	-0.71	0.53
Hip Adduction	-0.17	-0.79	0.45
Trunk Flexion	-0.26	-0.88	0.36

Appendix XV-Project III effect sizes of the kinematic variables at maximum knee flexion for the 40cm box height.

		Confidence Interval	
Criterion Variable	**Cohen's d-effect size**	**Lower**	**Upper**
Ankle Dorsiflexion	-0.17	-0.79	0.45
Rearfoot Eversion	0.00	-0.62	0.62
Knee Flexion	0.08	-0.54	0.70
Knee Internal Rotation	0.15	-0.48	0.77
Knee Abduction	0.01	-0.61	0.63
Hip Flexion	-0.08	-0.70	0.54
Hip Internal Rotation	-0.02	-0.64	0.60
Hip Adduction	-0.05	-0.67	0.57
Trunk Flexion	0.05	-0.57	0.67

Appendix XVI-Project III effect sizes of the kinetic variables at maximum knee flexion for the 20cm box height.

		Confidence Interval	
Criterion Variable	**Cohen's d-effect size**	**Lower**	**Upper**
Ankle Plantarflexion	0.46	-0.17	1.09
Rearfoot Inversion	-0.13	-0.75	0.49
Knee Extension	-0.14	-0.76	0.48
Knee External Rotation	-0.13	-0.75	0.49
Knee Adduction	-0.35	-0.98	0.27
Hip Extension	0.34	-0.29	0.96
Hip External Rotation	0.00	-0.62	0.62
Hip Abduction	-0.10	-0.72	0.52

Appendix XVII-Project III effect sizes of the kinetic variables at maximum knee flexion for the 30cm box height.

Criterion Variable	Cohen's d-effect size	Confidence Interval	
		Lower	Upper
Ankle Plantarflexion	-1.02	-1.68	-0.36
Rearfoot Inversion	-0.40	-1.02	0.23
Knee Extension	-0.13	-0.75	0.49
Knee External Rotation	-0.14	-0.76	0.48
Knee Adduction	0.35	-0.27	0.98
Hip Extension	-0.34	-0.96	0.29
Hip External Rotation	-0.33	-0.96	0.29
Hip Abduction	0.09	-0.53	0.71

Appendix XVIII-Project III effect sizes of the kinetic variables at maximum knee flexion for the 40cm box height

		Confidence Interval	
Criterion Variable	**Cohen's d-effect size**	**Lower**	**Upper**
Ankle Plantarflexion	0.81	0.16	1.45
Rearfoot Inversion	0.08	-0.54	0.70
Knee Extension	0.06	-0.56	0.67
Knee External Rotation	0.42	-0.21	1.05
Knee Adduction	0.15	-0.47	0.77
Hip Extension	0.43	-0.20	1.06
Hip External Rotation	-0.09	-0.71	0.53
Hip Abduction	0.12	-0.50	0.74

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- EXSC 322: Anatomical Kinesiology Lecture (Teaching Assistant)

Research Assistant, Neuromechanics Laboratory

- School of Physical Therapy and Athletic Training, Old Dominion University, Norfolk, VA, August 2012-May 2013
- Research Assistant to Dr. Matthew Hoch of the School of Physical Therapy and Athletic Training. Responsibilities include but not limited to recruitment, scheduling, testing, and post-processing of subjects for various research projects. Mentoring of Masters students during research project experience.