December 2021

# The Use of a Biopsychosocial Framework in Evaluating and Treating Patellofemoral Pain

Jennifer Thorpe
*University of Wisconsin-Milwaukee*

## Recommended Citation

Thorpe, Jennifer, "The Use of a Biopsychosocial Framework in Evaluating and Treating Patellofemoral Pain" (2021). *Theses and Dissertations*. 2842.
https://dc.uwm.edu/etd/2842

# THE USE OF A BIOPSYCHOSOCIAL FRAMEWORK IN EVALUATING AND TREATING PATELLOFEMORAL PAIN

by

Jennifer Lynn Thorpe

A Dissertation Submitted in

Partial Fulfillment of the

Requirements for the Degree of

Doctor of Philosophy

in Health Sciences

at

The University of Wisconsin-Milwaukee

December 2021

# ABSTRACT

# THE USE OF A BIOPSYCHOSOCIAL FRAMEWORK IN EVALUATING AND TREATING PATELLOFEMORAL PAIN

by

Jennifer Lynn Thorpe

The University of Wisconsin-Milwaukee, 2021
Under the Supervision of Professor Jennifer Earl-Boehm

Patellofemoral pain (PFP) is a chronic pain condition of the knee that afflicts approximately 25% of the population, and may lead to long-term complaints of pain and dysfunction. In the current literature, PFP is primarily studied using the framework of the pathomechanical model of biomechanical and muscular factors that increase patellofemoral joint loading. However, PFP may be better understood examining it through the Biopsychosocial Model of Sport Injury Rehabilitation (Brewer et al., 2002) as a conceptual framework to explore how injury characteristics, sociodemographic factors, and intermediate biopsychosocial outcomes may impact a patient's perceptions of pain and function. These relationships may also have in impact on treatment for PFP, as both the perception of pain and perception of function are commonly used as clinical outcomes to determine progress and prognosis. While there are several interventions that have been examined and implemented to treat patients with PFP, the long-term prognosis remains poor, with patients reporting symptoms months or even years after diagnosis. One treatment approach that is effective in both changing patient's perceptions of pain and function as well as their biomechanics is gait retraining. This approach, based on the concepts of motor learning, is commonly performed during running gait. Not all individuals with PFP are runners or may select not to run due to their knee pain. There is limited evidence to suggest that the concept of movement retraining applied to more universal tasks, such as a step-down, could yield similar results. Within the context of the Biopsychosocial Model (Brewer et al., 2002), the intervention chosen for the treatment intervention, along with delivery of that intervention by a trained health care professional, are components of the rehabilitation environment. The rehabilitation environment is one of many social and contextual factors within the Biopsychosocial Model (Brewer et al., 2002) that may impact the patient's perceptions of pain and function, as well as the intermediate rehabilitation outcomes. Therefore, using the Biopsychosocial Model (Brewer et al., 2002) as a conceptual framework, the purpose of this study was two-fold: 1) to better understand how selected injury characteristics (duration of symptoms and location of pain), sociodemographic factors (gender and age), and intermediate biopsychosocial outcomes (hip and knee strength and trunk, hip and knee biomechanics) relate to participant's perceptions of pain and function, and 2) to assess how a squat retraining intervention changes a participant's hip and knee strength, trunk, hip, and knee biomechanics, and perceptions of pain and function in individuals with PFP.

Three separate studies were conducted to achieve the study purpose. Study 1 consisted of a cross-sectional, U.S. population-based online survey shared via social media, email, and word of mouth to adults (18-45 years) with knee pain. Out of 400 respondents, 243 participants completed all four components of the survey, and 137 (105 females, 32 males, 30.80±8.68 years) were identified as having PFP. Duration of symptoms, location of pain, gender, age, perception of pain, and perception of function were assessed with the online survey. A multinomial logistic regression was utilized to create a model of the relationship between the independent variables and perception of pain score. A multiple linear regression was used to create a model for the relationship of the independent variables and perception of function score. Study 2 was a cross-sectional study conducted in a laboratory, with 40 participants (30 females, 10 males, 33.9±7.5 years) with PFP. Perceptions of pain and function, isometric hip and knee strength, and trunk, hip and knee 3-D kinematics and 2-D biomechanics during a step-down task were assessed. Pearson correlations were performed to determine if relationships existed among any of the variables. Separate multiple linear regressions were used to create a model of the relationship between all of the strength and biomechanical variables and perceived pain and function. Study 3 was a feasibility study consisting of 10 participants (9 females, 1 male, 36.30 ± 6.48 years) using a novel movement retraining intervention aimed at correcting knee alignment during a step-down. Wilcoxon Signed Rank tests and paired t-tests were performed to determine differences from baseline to post-intervention for perceived pain and function, hip and knee strength, and the biomechanical variables.

A summary of the results is presented here, with full statistics in each respective chapter. In Study 1, individuals who had PFP for a longer period of time, experienced widespread pain, and reported higher perceptions of pain also reported lower perceptions of function. Age and gender were not related to perceptions of pain or function in our sample. In Study 2, perception of pain was significantly correlated with perception of function and hip internal rotation (IR) angle, while perception of function score was significantly correlated with the perception of pain, hip abduction (ABD) strength, hip external rotation (ER) strength, knee extension (EXT) strength, and 2-D lateral trunk motion (LTM). For Study 3, perception of pain changed significantly from baseline to post-intervention and LTM significantly improved from baseline to post-intervention.

Results of this study support that symptom duration and painful locations are related to the perception of function in individuals with PFP. It emphasizes the need for early identification and treatment of PFP to minimize pain and preserve function early in the course of the overuse injury. We did not find a statistically significant predictive relationship between hip and knee strength and trunk, hip, and knee biomechanics and participant perceptions of pain and function in our sample. This suggests that there may not be a specific pattern of movement or muscle weakness that is uniform across individuals with PFP. Rather, the experience of PFP may be more individualized. The movement retraining intervention piloted in this study was effective at improving perceptions of pain, even though it did not lead to significant changes in strength or biomechanics, or perception of function. Taken together, these results provide preliminary support for the Biopsychosocial Model (Brewer et al., 2002) to be used as a framework to examine the overuse injury of PFP.

To my son Jackson –

never give up in the pursuit of your dreams.

# TABLE OF CONTENTS

# LIST OF FIGURES

# LIST OF TABLES

## ACKNOWLEDGEMENTS

There are many people I would like to thank for their role and support in this journey. First of all, I would like to thank Dr. Jennifer Earl-Boehm for your mentorship and guidance through this entire process. You are the person who recognized my early interest in research when I was un undergrad and encouraged me to continue my involvement in research, leading me to this path. You have been beyond supportive of me as I juggled my many roles during my doctoral work and I could not be more appreciative.

I also would like to thank my committee members – Dr. Monna Arvinen-Barrow, Dr. Wendy Huddleston, Dr. David Bazett-Jones, and Dr. Paola Dey. I appreciate all of your guidance, input, mentorship, and most importantly, believing in me when I didn’t believe in myself. Dr. Arvinen-Barrow, I sincerely appreciate your insights that helped me look beyond the biomechanics and into a more biopsychosocial viewpoint, as well as the extra time you spent with me on the proposal and theoretical framework of this study. Thank you, Dr. Huddleston, for your insights and guidance on motor learning and study design, as well as your encouragement. Dr. Bazett-Jones, I appreciate our conversations about biomechanics and your advice on study design and ways to include more technology in my methodology. I also appreciate all you did to help me when I started the doctoral program. Thank you Dr. Dey for your guidance, insights, and advice from afar. I truly appreciate each and every one of you and would not be where I am today without your guidance.

I would also like to thank Kemery Sigmund, Erin Lally, Madison Mach, Hayley Ericksen, and Renee Reckelberg for their support and for creating an engaging, supportive, and collaborative lab environment. I appreciate all the research conversations and overall vibe of our lab group. Erin, thank you for all of the assistance with data collection and post processing. I am going to miss the hours spent together in the lab. Kemery, there are no words to thank you for the constant support and I could not be more thankful that we get to cross this finish line together. I am looking forward to future research collaborations with you!

I would also like to acknowledge the Wisconsin Athletic Trainers' Association and the University of Wisconsin-Milwaukee College of Health Sciences for their funding of this research project.

Lastly, I would like to thank my family and friends, my support crew who have been behind me through this entire journey. To my parents, I thank you for your constant love and support, and encouraging me to reach for my goals in life. To my brother Jeff, sister-in-law Melissa, niece Riley, and nephews Charlie and Alex, thank you all for the love, support, and endless hugs. Thank you to my best friends Krissi, Michelle, Aimee, and Carrie for listening to me (even when you had no idea what I was talking about), helping me with recruitment, and your support throughout this journey. Thank you to my son, Jackson, for being patient with me when I had to work on "homework" on the weekends and at night, for asking me questions about my favorite bone, and the endless hugs and "I love you's" when I needed them the most. Lastly, thank you to my husband Billy for your endless love and support on this journey. Your encouragement of me and unfaltering faith in me truly means everything to me. I'm looking forward to spending more time with you and Jackson. Thank you.

# Chapter One: Introduction

## Background

Patellofemoral pain (PFP) is a chronic musculoskeletal condition characterized by retro- and peri-patellar pain with activities such as squatting, navigating stairs, jumping, running, and sitting with the knees flexed for an extended period of time (Crossley, Stefanik, et al., 2016). The onset of pain and symptoms associated with PFP is insidious and not the result of a specific acute trauma or direct tissue damage (Collins et al., 2018). PFP can interfere with the ability to engage in activities of daily living, physical activity, and occupational tasks (Smith, Moffatt, et al., 2018). If left untreated, long-term PFP may ultimately contribute to the development of patellofemoral osteoarthritis (Crossley, 2014).

In addition to the poor prognosis for this chronic musculoskeletal condition, the prevalence of PFP is relatively high. PFP accounts for 25-40% of all knee injuries evaluated by healthcare providers in clinical settings (Witvrouw et al., 2014). According to Glaviano et al. (2015), 2,188,753 individuals in the United States were diagnosed with PFP during the five-year period between 2007 and 2011. Smith, Selfe, et al., (2018) estimated the prevalence of PFP to be 22.7% in the general population. These estimates, however, are based on reports from medical professionals and do not include individuals who may elect not to seek medical attention for their symptoms, thus these numbers may be higher than reported in the previous literature.

The etiology of PFP is complex and multifaceted, yet previous researchers have adopted a primarily biomedical viewpoint to underpin their studies on the exact pathoetiological factors contributing to PFP. Powers et al. (2017) proposed a framework known as the pathomechanical model based on the existing evidence regarding PFP etiology. This model postulates that PFP is the result of elevated stress within the patellofemoral joint (PFJ), which is caused by a decrease in patellofemoral joint contact area and/or increased patellofemoral joint reaction forces (Powers et al., 2017). These two contributing factors at the patellofemoral joint are hypothesized to stem from an interaction of various biological factors, including altered biomechanics of the trunk (Bazett-Jones et al., 2013; Boling & Padua, 2013), hip (Hollman et al., 2014; Meira & Brumitt, 2011; Neal et al., 2016; Meira & Brumitt, 2011), and knee (Herrington, 2014; Huberti & Hayes, 1984; Nakagawa et al., 2012; Willson & Davis, 2008), weakness of the hip (Boling, Padua, & Creighton, 2009; Finnoff et al., 2011; Magalhães et al., 2010; Prins & van der Wurff, 2009) and knee musculature (Kaya et al., 2011; Lankhorst et al., 2012; Pappas & Wong-Tom, 2012), and lower extremity muscle tightness (Piva et al., 2005; Whyte et al., 2010; Rabin et al., 2014; Wyndow et al., 2016).

Within the pathomechanical model (Powers et al., 2017), the musculature of the hip is speculated to influence patellar position. More specifically, the hip external rotators and abductors are theorized to control transverse and frontal plane motion of the femur (Boling et al., 2009). Weakness of these muscles at the hip may lead to increased internal rotation of the femur, which could result in altered biomechanics during loading of the lower limb (Powers, 2010). More specifically, this may lead to increased knee abduction, hip adduction, hip internal rotation, and trunk flexion and rotation during single-limb loading tasks (Willson & Davis, 2008; Nakagawa et al., 2012, Herrington, 2014, Bazett-Jones et al., 2013). This altered movement pattern, known as dynamic malalignment, may contribute to patellar malalignment and maltracking and elevated loading at the PFJ (Powers et al., 2010). However, there are several studies that have failed to identify weakness of the hip musculature in this population (Thijs et al., 2011; Finnoff et al., 2011; Boling, Padua, Marshall et al., 2009; Herbst et al., 2015), as well as how weakness combined with altered biomechanical patterns relate to the proposed increase in PFJ stress.

Thus far, treatment interventions for PFP have primarily targeted mechanisms as outlined in the pathomechanical model (Powers et al., 2017) that are theorized to contribute to elevated patellofemoral joint stress. External supports such as taping (Salsich et al., 2002; Kurt et al., 2016), bracing (Petersen et al., 2016; Uboldi et al., 2018), and orthotics (Barton, Mentz, et al., 2011; Collins et al., 2008) have reported favorable outcomes regarding perceived pain and function in the short term but not in the long term. Exercise-based therapy is considered the gold standard treatment intervention for PFP (Collins et al., 2018) and focuses on increasing strength of the hip and knee musculature as a means of improving faulty hip and knee biomechanics. While this approach is effective in improving hip and knee muscle strength (Ferber et al., 2015) and in reducing knee abduction moment in females with PFP (Earl-Boehm & Hoch, 2011), it is unknown if the same results would be found in men with PFP. More importantly, similar to the use of external supports, exercise-therapy focused on hip and knee strengthening does not enhance the long-term prognosis for individuals with PFP (van Linschoten et al., 2009).

More recently, researchers have explored movement retraining as an adjunctive therapy focused on neuromuscular re-education of a functional task that causes pain in individuals with PFP. While most studies have focused on the use of this technique with running gait (Roper et al., 2016; Willy et al., 2012; Noehren et al., 2011), there is one feasibility study that suggests this same approach may be utilized with a different task, such as a step-down, that mimics a movement encountered in everyday life (Salsich et al., 2018). The additional of specific, externally-focused verbal cues directed at changing a movement pattern may help to correct hip and knee biomechanics associated with perceived pain in individuals with PFP.

Given the inconsistencies in the pathomechanical model, and the need to determine more effective rehabilitation strategies for patients with PFP, we propose examining this condition from a different perspective. Other musculoskeletal injuries, such as chronic low back pain (Waddell, 1987) and anterior cruciate ligament (ACL) injuries (Brewer et al., 2004) have adopted a biopsychosocial framework to inform rehabilitation research. In chronic low back pain, psychological factors such as fear avoidance (Saito & Nishida, 2015; Fujii et al., 2013; Panhale et al., 2016), catastrophizing (George & Beneciuk, 2015), and depression and anxiety (George & Beneciuk, 2015) have all been found to be related to rehabilitation outcomes. Within the ACL injury rehabilitation literature, the use of interventions focused on addressing psychological factors, such as the perception of pain and anxiety (Maddison, Prapavessis, & Clatworthy, 2006), have reported favorable outcomes, providing support that rehabilitation should be viewed as biopsychosocial in nature.

*A gap in PFP research is that a single theoretical framework that outlines the interrelationships among many biopsychosocial factors has not been used to conceptualize PFP etiology and rehabilitation.* The Biopsychosocial Model of Sport Injury Rehabilitation (Brewer, Andersen, & Van Raalte, 2002), is such a theoretical framework that shows the interrelationships between a multitude of factors that may influence an individual's injury experience and recovery. The model consists of a dynamic core including biological, psychological, and social and contextual factors that are all proposed to be interrelated (Brewer et al., 2002). The dynamic core of this model is influenced by injury characteristics and sociodemographic factors (Brewer et al., 2002). The psychological factors within this model are proposed to have a bidirectional relationship with intermediate biopsychosocial outcomes and sport injury rehabilitation outcomes (Brewer et al., 2002). Both biological factors and social and contextual factors influence the intermediate biopsychosocial outcomes (Brewer et al., 2002). Intermediate biopsychosocial outcomes also affect the overall sport injury rehabilitation outcomes as well (Brewer et al., 2002).

While researchers have acknowledged that PFP rehabilitation may be biopsychosocial in nature (Smith et al., 2018), there has yet to be a study that explicitly uses the Biopsychosocial Model as a framework for research. This Biopsychosocial Model (Brewer et al., 2002) may be useful to better understand the interrelationships among perception of pain and function (psychological factors), injury characteristics, sociodemographic factors, and intermediate biopsychosocial outcomes that have been implicated in PFP rehabilitation. It may also challenge current clinical practices such as considering pain severity and self-reported function as only clinical outcomes. By thinking of pain severity and self-reported function as the *participant's cognitions* about their knee pain and ability to function, the terms may be more appropriately defined as the participant's *perception of pain* and *perception of function* (Sternberg, 2007; Peacock & Watson, 2003). Thinking about perception of pain and perception of function in this way could provide additional support for treatment approaches aimed not only at addressing biological factors to enhance intermediate biopsychosocial outcomes, but also to include interventions focused on cognitions or psychological factors implicated in the rehabilitation process as well.

Many studies have examined factors that are identified in the Biopsychosocial Model (Brewer et al., 2002) individually, and provide the rationale for this approach. These factors include the duration of symptoms, pain location, gender, and age. One injury characteristic associated with a poorer prognosis in individuals with PFP is a longer duration of symptoms. Individuals who have experienced PFP symptoms for a longer period of time have been reported to report lower pain severity than those who had symptoms for a shorter period of time (Gerbino et al., 2006), suggesting that the perception of pain does in fact change as symptoms linger. Additionally, one study identified a statistically significant albeit weak correlation between symptom duration, body mass, and hip muscle strength, suggesting that those with a longer duration of symptoms had increased body mass and decreased hip muscle strength (Earl-Boehm et al., 2017). This supports the notion that individuals with PFP may elect to avoid painful activities, leading to a more sedentary lifestyle. Another study identified that participants who had their PFP symptoms for a longer period of time responded more favorably to exercise therapy (Lankhorst et al., 2015). This finding also supports that the length of time someone has experienced their symptoms may be impactful on how they appraise their condition.

Painful locations, an emerging injury characteristic in PFP research, is also implicated in the prognosis of this condition. Boudreau et al. (2017) identified that individuals who had experienced their PFP symptoms for five years or longer reported more widespread pain than those who experienced their pain for a shorter period of time. Additionally, those participants with a longer duration of symptoms also reported an ovate or “O” pattern of pain around the patella, in contrast to the “U” shaped pattern reported by those who had their pain for a shorter duration (Boudreau et al., 2018). It remains unknown how painful locations of the knee could influence perceptions of both pain and function in individuals with PFP.

A sociodemographic factor that has been studied relevant to the etiology of PFP is gender. The prevalence of PFP is more prevalent in females than in males (Boling et al., 2010) and the biological risk factors theorized to contribute to the development of PFP is thought to defer between males and females (Boling et al., 2019). However, these studies and previous PFP studies have identified participants based on their anatomical sex and not their gender identity. It remains unknown if gender identity would be related to perceptions of pain and function in this population.

Age is another sociodemographic factor from the Biopsychosocial Model (Brewer et al., 2002) that has only been partially explored in the PFP research. Lack et al. (2014) examined differences in response to various PFP interventions based on age, and reported that younger individuals responded more favorably to exercise therapy-based interventions while older individuals responded more favorably to interventions that included the use of a foot orthosis. The authors speculated that movement patterns may be more ingrained in older individuals, while younger individuals may have a greater capacity for neuromuscular adaptations and strength gains (Lack et al., 2014). Another study by Lankhorst et al. (2015) identified that age was not a significant predictor of treatment outcome in participants with PFP. These previous studies have focused primarily on patients under 30 years of age and do not account for middle aged adults who have PFP. Therefore, there is not a clear understanding of how age, especially including middle aged adults, is related to perceptions of pain and function in individuals with PFP.

The Biopsychosocial Model (Brewer et al., 2002) can also be used to explain how aspects of the delivery of the intervention, such as the use of tele-health and verbal and tactile cues can benefit movement retraining, which may help improve rehabilitation outcomes for individuals with PFP. These deliberate decisions regarding the delivery of the treatment intervention alter the rehabilitation environment, which as a social and contextual factor in the Biopsychosocial Model is related to not only to intermediate biopsychosocial outcomes, but also to psychological factors such as cognitions and affects surrounding the rehabilitation process (Brewer et al., 2002).

## Research Questions

What are (if any) the relationships between selected injury characteristics, sociodemographic factors, intermediate biopsychosocial outcomes, and participant's perception of pain and/or perception of function in individuals with PFP?

Does a squat retraining intervention change a participant's hip strength, hip and knee biomechanics, and perception of pain and perception of function in individuals with PFP?

## Purpose Statement

Using the Biopsychosocial Model of Sport Injury Rehabilitation (Brewer et al., 2002) as a conceptual framework, the purpose of this study is two-fold:

> 1) to better understand how selected injury characteristics (i.e., duration of symptoms and painful locations), sociodemographic factors (i.e., gender and age), and intermediate biopsychosocial outcomes (i.e., hip and knee strength, trunk, hip and knee biomechanics) relate to participant's perception of pain and/or perception of function in individuals with patellofemoral pain (PFP).
>
> 2) to assess how a squat retraining intervention changes a participant's hip and knee strength, trunk, hip and knee biomechanics and perception of pain and perception of function in individuals with PFP.

## Operational Definitions

**Duration of symptoms:** the length of time that an individual has experienced apparent features associated with PFP.

**Trunk, hip, and knee biomechanics:** both three-dimensional (3-D) and two-dimensional (2-D) joint angles associated with altered movement patterns in individuals with PFP, in particular 3-D measures of trunk flexion, hip adduction and hip internal rotation and 2-D measures of knee frontal plane projection angle and lateral trunk motion.

**Hip and knee strength:** quantifiable measure of isometric force produced by the hip abductor, hip extensor, hip external rotator, and knee extension muscle groups during a single maximal effort.

**Painful location(s):** the identification of the painful area of the knee(s) by the participant using a knee pain map. Painful location(s) can be further described as smaller or fewer locations indicating more localized pain and larger or more locations indicating more widespread pain.

**Perception of pain:** the individual's interpretation of pain sensation and attempt to attach meaning to the pain, encompassing both elements of pain perception and pain sensation.

**Perception of function:** an individual's interpretation of the subjective symptoms and functional limitations resulting from their condition (Kujala et al., 1993), influenced by both the perception of pain and the perceived level of exertion during functional tasks (Stratford & Kennedy, 2006).

### Specific Aims

1. To identify potential relationships among duration of symptoms, painful location(s), gender, age, and participant's perception of pain in individuals with PFP.
2. To identify potential relationships among duration of symptoms, painful location(s), gender, age, and participant's perception of function in individuals with PFP.
3. To identify potential relationships among hip and knee strength and participant's perception of function in individuals with PFP.

4. To identify potential relationships among trunk, hip, and knee biomechanics, and participant’s perception of pain in individuals with PFP.
5. To determine if an intervention to improve hip and knee biomechanics will change a participant’s hip and knee strength, trunk, hip and knee biomechanics, and perception of pain and perception of function in individuals with PFP.

## Hypotheses

1. $\mathbf{H_0}$: There will be no relationship between duration of symptoms, painful location(s), gender, age, and participant’s perception of pain in individuals with PFP.

   $\mathbf{H_1}$: There will be a relationship between duration of symptoms, painful location(s), gender, age, and participant’s perception of pain in individuals with PFP.

2. $\mathbf{H_0}$: There will be no relationship between duration of symptoms, painful location(s), gender, age, and participant’s perception of function in individuals with PFP.

   $\mathbf{H_1}$: There will be a relationship between duration of symptoms, painful location(s), gender, age, and participant’s perception of function in individuals with PFP.

3. $\mathbf{H_0}$: There will be no relationship between hip and knee strength, and participant’s perception of function in individuals with PFP.

   $\mathbf{H_1}$: There will be a relationship between hip and knee strength, and participant’s perception of function in individuals with PFP.

4. $\mathbf{H_0}$: There will be no relationship between trunk, hip and knee biomechanics, and participant’s perception of pain in individuals with PFP.

   $\mathbf{H_1}$: There will be a relationship between trunk, hip and knee biomechanics, and participant’s perception of pain in individuals with PFP.

5. **$H_0$:** The squat retraining intervention will not change hip and knee strength, trunk, hip and knee biomechanics, or the participant’s perception of pain and perception of function in individuals with PFP.

   **$H_1$:** The squat retraining intervention will improve hip and knee strength, trunk, hip and knee biomechanics, and the participant’s perception of pain and perception of function in individuals with PFP.

**Delimitations**

This study is focused on individuals between the ages of 18 and 45 who are suffering from patellofemoral pain (PFP) as opposed to other chronic, overuse conditions of the knee. Recruitment for this study will occur in a Midwestern metropolitan area using a community-based strategy. Potential participants will complete a computer/tablet-based survey to screen for eligibility for this study. Potential participants must be able to read and speak in English and use a computer or electronic device to complete the survey. Participants will be included based on their online survey response on the Survey instrument for Natural history, Aetiology and Prevalence of Patellofemoral pain Studies (SNAPPS; Dey et al., 2016) and based on responses to questions regarding exclusionary criteria, consistent with a diagnosis of PFP.

We selected duration of symptoms and location of pain as injury characteristics based on previous support in the PFP literature. For sociodemographic factors, we selected gender and age to determine their relationship with participant’s perceptions of pain and function. We recognize that biological and social and contextual factors may also influence the participant’s perceptions of pain and function but we will not examine those in this study. The muscles of interest for the strength variables are the hip abductors, hip extensors, hip external rotators, and knee extensors. For hip and knee biomechanics, we chose to examine trunk flexion, hip adduction and internal rotation collected from a three-dimensional (3-D) motion capture system. In addition, we included the two-dimensional (2-D) measures of knee frontal plane projection angle (kFPPA) and lateral trunk motion (LTM) as these are measures that clinicians often utilize to assess patient movement during dynamic tasks. The participant's perceptions of pain and function will be quantified using the self-report questionnaires.

## Limitations

Individuals with PFP will be identified based on the self-report of symptoms rather than a diagnosis from a medical professional. A potential participant's understanding of the questions, their memory and honesty about their symptoms may be a limitation. We also acknowledge that our relatively small sample size is a limitation. Another limitation is the intervention length. This intervention progresses over a 2- week period of time and immediate outcomes will be assessed. There will be no follow-up to the intervention, meaning that the findings can only be generalized to immediate outcomes. A final limitation is there the lack of a control group for this study, which means that the results regarding the squat retraining intervention cannot be compared to other interventions used for individuals with PFP.

## Assumptions

The study will adopt the assumption the participants will answer all questions on the surveys and instruments truthfully, and that the participants will perform their maximal effort on the strength tests. We also assume that for the 3-D motion capture, all body segments are assumed to be rigid bodies and that marker placement for the will be the same for the baseline testing and for the post-intervention testing. We also are assuming that our data for each of our outcome variables of interest will be normally distributed, allowing for parametric statistical analysis. Another assumption of this study is that our participants will follow the directions given during the intervention and will attend all scheduled sessions in their entirety.

# Chapter Two: Literature Review

The following literature review will present the pathomechanical model by Powers et al., (2017), which was developed to help explain the etiology of PFP based on predominantly biological factors. The current evidence regarding the factors within the model in participants with PFP will be critically evaluated. The current research regarding treatment interventions for PFP will be presented, leading to the rationale for incorporating movement retraining to improve perceived pain and function and intermediate rehabilitation outcomes, such as hip strength and hip and knee biomechanics. There is a wide range of terms used in the PFP literature to date to define the constructs of perception of pain and perception of function. The author's original terminology will be used throughout the review of the literature pertinent to the pathomechanical model (Powers et al., 2017). The Biopsychosocial Model of Sport Injury Rehabilitation (Brewer et al., 2002) will be presented and proposed as a conceptual framework to underpin future PFP studies, in an attempt to demonstrate that PFP is in fact biopsychosocial in nature. Research findings in two other musculoskeletal conditions – chronic low back pain and anterior cruciate ligament injury – will also be presented and analyzed to demonstrate how a biopsychosocial framework has been implemented in these areas of research. Existing evidence from the PFP literature that supports the use of a biopsychosocial model will also be appraised and synthesized to further illustrate the usefulness of this model to understanding the rehabilitation and recovery process in those with PFP.

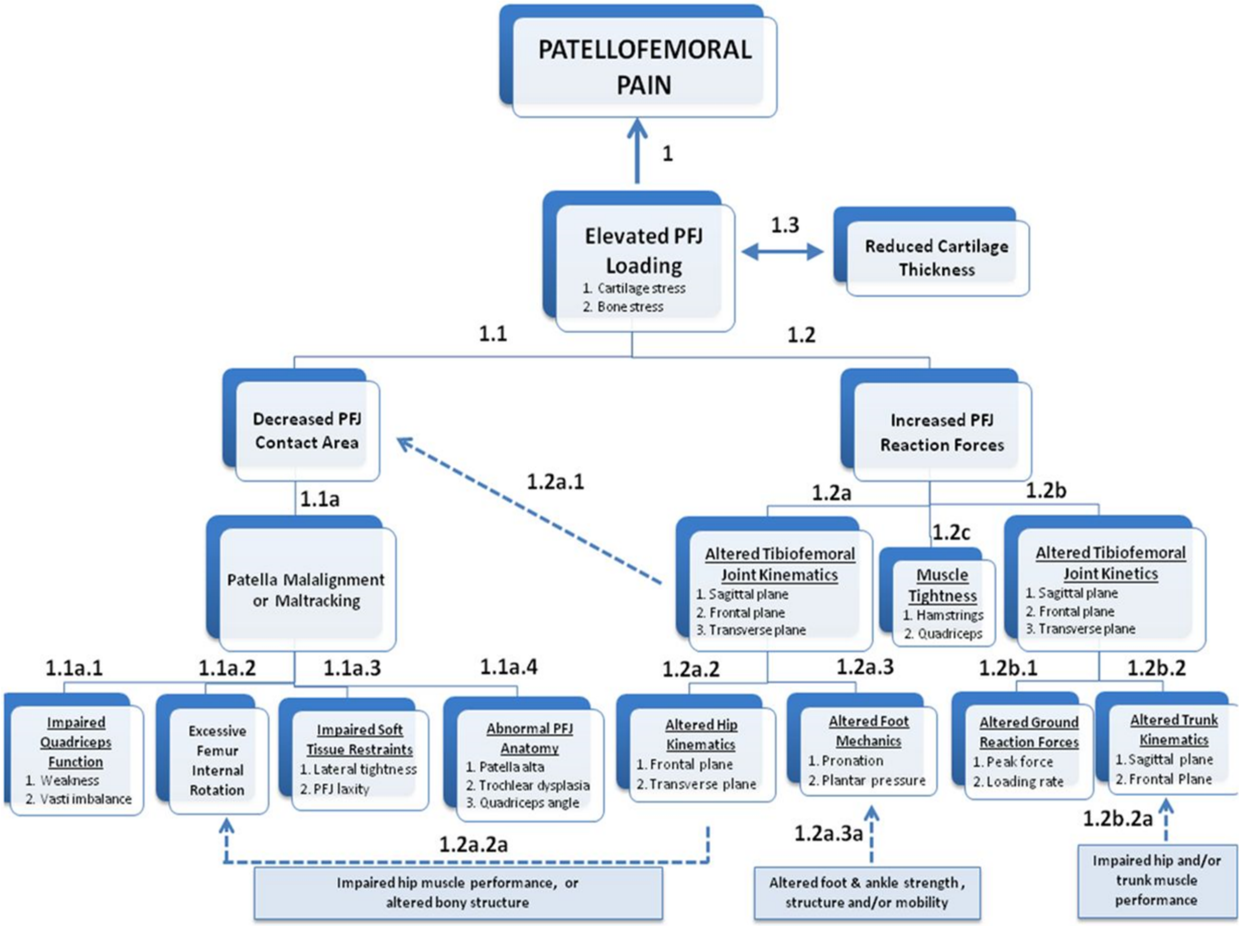
## The Etiology of Patellofemoral Pain: The Pathomechanical Model

The pathomechanical model of PFP (Powers et al., 2017) proposes that pain results from prolonged patellofemoral joint (PFJ) loading. One of the potential consequences of this prolonged loading of the patellofemoral joint is a reduction in the thickness of the cartilage of the

PFJ. The pathomechanical model (Figure 1) illustrates the interrelationships among various biological factors, based on previous literature, that are postulated to contribute to PFP. The model proposes that patellofemoral joint loading is influenced by two main biomechanical mechanisms: decreased PFJ contact area and increased PFJ reaction forces, both of which are influenced by a range of anatomical and biomechanical factors (Powers et al., 2017).

**Figure 1**

*Pathomechanical Model of Patellofemoral Pain (Powers et al., 2017)*



Source: Reproduced from [Evidence-based framework for a pathomechanical model of patellofemoral pain: 2017 patellofemoral pain consensus statement from the 4th International Patellofemoral Pain Research Retreat, Manchester, UK: part 3, Powers, C.M., Witvrouw, E., Davis, I.S., *et al.*, 51, 1713–1723, 2017] with permission from BMJ Publishing Group Ltd.

Decreased PFJ contact area is one of the main mechanisms speculated to contribute to elevated PFJ loading according to the pathomechanical model (Powers et al., 2017). The contact area of the PFJ can be influenced by the position of the patella relative to the trochlear groove (Salsich & Perman, 2013). Malalignment or maltracking of the patella has long been considered a contributor to the development of PFP, and within the pathomechanical model, it is illustrated as the main contributing factor for decreasing contact area of the patella (Powers et al., 2017). Another biomechanical factor that has been proposed to result in decreased PFJ contact area is altered kinematics of the tibiofemoral joint (Powers et al., 2017).

The pathomechanical model presents four biomechanical factors theorized to contribute to patellar malalignment or maltracking – impaired quadriceps function, excessive femur internal rotation, impaired soft tissue restraints, and abnormal PFJ anatomy (Powers et al., 2017). Impaired function of the quadriceps muscle group may influence the position of the patella relative to the trochlear groove, leading to excessive lateral displacement and tilt of the patella relative to the femur (Pal et al., 2011; Witrvouw et al., 2000; Van Tiggelen et al., 2009). Excessive internal rotation of the femur may also contribute to lateral displacement of the patella in females with PFP (Souza et al., 2010). This excessive internal rotation could be due in part to impaired performance of the hip musculature or alterations in the bony structure of the hip joint (Souza & Powers, 2007). Impaired soft tissue restraints, such as tightness of the iliotibial band or increased laxity of the ligamentous structures of the PFJ may also result in patellar malalignment and maltracking (Powers et al., 2017). Abnormal PFJ anatomy, such as patella alta (Pal et al., 2013) and lateral trochlear inclination (Teng et al., 2014) may also result in increased lateral patellar tilt and displacement.

The other main biomechanical mechanism in the pathomechanical model contributing to elevated PFJ loading is increased PFJ reaction forces (Powers et al., 2017). Altered PFJ reaction forces are theorized to contribute to elevated loading and stress in the PFJ (Powers et al., 2017). There are three biomechanical factors presented in the model that contribute to increased PFJ reaction forces – altered tibiofemoral joint kinematics, muscle tightness, and altered tibiofemoral joint kinetics (Powers et al., 2017).

Altered tibiofemoral joint kinematics in the sagittal, frontal, and transverse planes may influence the position of the femur relative to the patella, leading to changes in PFJ reaction forces (Powers et al., 2017). Tibiofemoral joint kinematics may be influenced in part by altered hip kinematics due to both joints sharing a common segment, the femur (Powers, 2003). Increased hip adduction and hip internal rotation have been associated with knee abduction during a weight-bearing task (Hollman et al., 2014). The pathomechanical model suggests that impaired hip muscle performance or altered bony structure may influence hip kinematics, however the evidence supporting this relationship is inconsistent (Powers et al., 2017). Tibiofemoral joint kinematics may also be influenced by altered foot mechanics and plantar pressures (Powers et al., 2017). Excessive subtalar pronation may result in increased rotation of the tibia and femur, thereby influencing motion at the tibiofemoral joint (Powers, 2003). Altered foot and ankle strength, structure, and mobility are presented in the model as a potential contributor to altered foot mechanics. Rearfoot and forefoot varus (Powers et al., 1995), excessive navicular drop (Barton et al., 2010), and tightness of the gastrocnemius muscle (Piva et al., 2005) have been reported in participants with PFP, although not consistently.

Muscle tightness, specifically of the quadriceps and hamstring muscle groups, has been reported in individuals with PFP (Piva et al., 2005) and hypothesized to result in increased PFP reaction forces, thereby elevating PFJ stress (Whyte et al., 2010). Altered tibiofemoral joint kinetics is the third proposed contributor to increased PFJ reaction forces within the pathomechanical model (Powers et al., 2017). Alterations in tibiofemoral joint kinetics have been reported for all three planes of motion in individuals with PFP. Two biomechanical factors are presented in the pathomechanical model – altered ground reaction forces and altered trunk kinematics – as potential contributors to the alterations in tibiofemoral joint kinetics (Powers et al., 2017). The latter, altered trunk kinematics, may be in part due to impaired hip (Boling, Padua, & Creighton, 2009) and/or trunk muscle performance (Cowan et al., 2009).

The purpose of the pathomechanical model (Powers et al., 2017) is to establish potential interrelationships among biological factors identified from previous research in individuals with PFP. While the model is the most comprehensive, evidence-based etiological framework currently presented for PFP, there are several inconsistencies in findings that challenge various elements of the model. The following section provide a review of the existing evidence regarding the etiological factors presented in the pathomechanical model (Powers et al., 2017) and a discussion on the interrelationships between these factors relative to PFP.

### *Elevated Patellofemoral Joint Loading and Reduced Cartilage Thickness*

According to the pathomechanical model of patellofemoral pain (Powers et al., 2017), PFP is theorized to result from elevated loading of the PFJ, which may be the result of decreased PFJ contact area and increased PFJ reaction forces. While elevated PFJ stresses have been identified in several studies, there are also studies that have failed to find differences between those with PFP and healthy controls.

In a cross-sectional study, Brechter & Powers (2002a) calculated PFJ stress using modeling based on magnetic resonance imaging (MRI) assessment of PFJ contact area and walking gait analysis in participants with PFP compared to healthy controls. The participants (n=10) with PFP on average exhibited significantly greater PFJ stress than the control group while walking on a level surface. The authors attributed this increase in PFJ stress to decreased PFJ contact area. Farrokhi et al. (2011) reported similar findings in their study comparing patellofemoral joint stress between females with PFP and healthy controls. PFJ stress profiles were calculated for both groups using subject-specific finite element models of the PFJ 15 and 45 degrees of knee flexion. The females with PFP exhibited greater peak PFJ stress and shear stress of the patellar cartilage when compared to the control group. The authors concluded that these results suggest that elevated peak PFJ stress and shear stress of the patellar cartilage could lead to reduced patellar cartilage thickness over time.

Ho et al. (2014) calculated patella bone strain and articular cartilage thickness in females with and without PFP to determine if the PFP group exhibited elevated patellar bone strain than the control group. The secondary aim of this study was to determine if there was a relationship between patella cartilage thickness and patella bone strain. Similar to the study by Farrokhi et al. (2011), participant-specific finite element models of the PFJ were used to quantify the patella bone strain. Cartilage thickness was calculated by measurements from MRI images. The PFP group had increased patella bone strain than the control group. There was also a negative correlation between patella cartilage thickness and patella strain, suggesting that increases in bone strain may result from decreased cartilage thickness, supporting the conclusion made by Farrokhi et al. (2011).

In contrast, Besier et al. (2015) did not find differences in patellar cartilage stresses between those with PFP and a control group. Finite element models were created for 24 individuals with PFP and 16 control participants to estimate peak patellar stress during a stair climbing task, and while the PFP group did not significantly differ from the control group, it was noted that the females in this study exhibited greater peak cartilage stress than the male participants. The authors concluded that this finding could partially explain why PFP is more prevalent in females than in males, but stated that there are clearly other factors involved in this condition that contribute to pain. Wirtz et al. (2012) also did not identify differences in PFJ stress between female participants with PFP and healthy controls while running. PFJ stress was estimated using PFJ contact area and a sagittal plane modeling technique of the joint. These findings demonstrate the inconsistency in the literature regarding elevated PFJ stress and loading in individuals with PFP. It is possible that this finding is position-specific, as the latter two studies focused on stair-climbing and running, both of which involve greater degrees of knee flexion, which could partially explain the differences in findings. In the paper presenting the pathomechanical model by Powers et al. (2017), the authors also acknowledge the conflicting findings regarding this mechanism, and suggest that there is not enough evidence to fully support how elevated PFJ loading contributes to PFP.

### *Decreased Patellofemoral Joint Contact Area*

The pathomechanical model suggests that diminished PFJ contact area may contribute to elevated PFJ stress, however this relationship may be dependent upon knee flexion angle (Powers et al., 2017). When the knee is in full extension, there is minimal joint congruency as the patella has yet to engage with the trochlear groove of the femur (Hartigan et al., 2005). In this position, the only point of contact is between the inferior pole of the patella and the femur

(Hartigan et al., 2005). As the knee flexes, the patella glides onto the articular surface of the trochlea, increasing the contact area between the patella and femur. When the knee reaches 90 degrees of flexion, the patella contacts the lateral and medial facets of the femur within the condylar fossa. As the knee flexes further, reaching 130-135 degrees of flexion, the lateral facet of the patella is fully in contact with the trochlear groove, while the medial facet does not maintain contact with the femur (Hartigan et al., 2005). In individuals with PFP, it is hypothesized that maltracking or malalignment may contribute to the alteration of this contact pattern, leading to decreases in the contact area of the patella, which in turn may lead to elevations in PFJ stress. There are five studies to date that have examined PFJ contact area in individuals with PFP.

Brechter & Powers (2002b) conducted a cross-sectional study to determine if PFJ stress differs between individuals with PFP and healthy controls during two walking speeds. PFJ contact area was calculated using MRI images and modeling techniques, and three-dimensional (3-D) motion analysis was used to assess knee joint kinematics and kinetics during gait. All of these measures were then applied to a biomechanical model used to estimate PFJ stress during walking. The PFJ contact area was significantly reduced in the PFP group as compared to the control group for both walking speeds. The PFP group also demonstrated increased PFJ stress when compared to the control group, which the authors attributed to the decrease in contact area observed in the PFP group (Brechter & Powers, 2002b). The authors also discussed that PFJ contact area may also be influenced by both the angle of the knee joint during the gait cycle and individual anatomical factors that may influence the position of the patella relative to the femoral trochlea (Brechter & Powers, 2002b). These findings support the notion that diminished PFJ contact area is related to elevated PFJ stresses during walking in individuals with PFP.

The study presented earlier by Bretcher & Powers (2002a) comparing PFJ stress during stair ascent and descent between individuals with PFP and healthy controls also calculated PFJ contact area using MRI images. A trend toward decreased PFJ contact area was identified in the PFP group, but this difference was not statistically significant (Brechter & Powers, 2002a). The authors concluded that the 14% reduction in PFJ contact area observed in the PFP group may have helped offset the decrease in PFJ stress that would be expected as PFJ reaction force decreases (Bretcher & Powers, 2002a).

The study by Besier et al. (2015) presented earlier also failed to identify differences in PFJ contact area between those with PFP and healthy controls. PFJ contact area was both predicted finite element modeling and measured using weight-bearing MRI images in males and females with PFP and without PFP. These values were used to determine peak PFJ stress during a stair climb task at 60 degrees of knee flexion. Predicted PFJ contact area values were within 8% of the measured values from the MRI images, and were reported for both males and females with and without PFP. The predicted PFJ contact area observed for all female participants was approximately 33% less than the contact area for males, which the authors attributed to sex-specific differences in bony anatomy of the PFJ joint (Besier et al., 2015). There were no statistically significant differences observed in PFJ contact area between both PFP groups and the control groups. The authors suggested that the lack of difference between groups could be attributed to PFJ contact area being dependent on knee flexion angle, since the contact area of the PFJ increases as the knee flexes and the patella contacts the trochlear groove.

Salisch & Perman (2013) conducted a cross-sectional study to determine if PFJ contact area differed in participants with PFP compared to pain-free participants at 0, 20, and 40 degrees of knee flexion. Similar to methods used in the previous studies, MRI imaging was used to quantify PFJ contact area in a simulated weight-bearing position. Significantly decreased PFJ contact area was reported for the PFP group at 0 and 20 degrees of knee flexion when compared to the pain-free group, but not at 40 degrees of flexion. The authors also attributed this finding to the biomechanics of the PFJ, particularly the position of the patella within the trochlear groove as the knee flexion angle increases. These findings are similar to those of an earlier study by Salsich et al. (2002) who also reported decreased PFJ contact area in individuals with PFP compared to healthy controls at full knee extension. Salsich et al. (2002) also estimated contact area for the medial and lateral facets of the patella using a modeling protocol, and reported the difference in PFJ contact area between groups was entirely due to decreases in contact area of the lateral facet. There were no differences observed in either group for medial facet contact area. These findings regarding the contact area of the lateral facet provide support for the contribution of patellar maltracking and malalignment to diminished PFJ contact area in individuals with PFP.

These findings suggest that PFJ contact area may contribute to elevated PFJ loading in individuals with PFP, but this finding may be dependent on knee flexion angle. As knee flexion angle increases, the patella engages more closely with the trochlear groove, thereby increasing patellar contact area. When the knee is in a less flexed position, it is hypothesized that patellar maltracking or malalignment may occur in individuals with PFP, leading to decreases in contact area.

### ***Patellar Malalignment/Maltracking***

The pathomechanical model of PFP (Powers et al., 2017) illustrates the potential contribution of patellar malalignment or maltracking to decreased PFJ contact area. Patellar malalignment is identified as a positional deviation of the patella relative to any axis, most commonly presenting as a lateral tilt and displacement relative to the midpoint of the femur (Hartigan et al., 2005). In contrast, patellar maltracking refers to abnormal tracking of the patella relative to trochlear groove as the knee moves through range of motion, particularly near full extension (Hartigan et al., 2005). Similar to patellar malalignment, the patella most commonly tilts and glides towards the lateral aspect of the knee, leading to diminished contact area between the patella and femur, particularly at lesser degrees of knee flexion (Hartigan et al., 2005). This is supported by the conclusion from a systematic review and meta-analysis by Drew et al. (2016) of 40 moderate to high quality studies, identifying that lateral patellar displacement was more pronounced during knee extension in individuals with PFP. The following papers examine the potential influence of patellar malalignment and maltracking and diminished PFJ contact area in individuals with PFP.

Patellar malalignment appears to be exacerbated with contraction of the quadriceps in individuals with PFP. In a study by Biedert & Gruhl (1997), PFJ position during the first 60 degrees of knee flexion was compared between participants with PFP (n=49) and healthy controls (n=15) using computed tomography (CT) imaging. Images were obtained in the following positions: 0 degrees with maximal quadriceps muscle contraction, and 0, 30, and 60 degrees of knee flexion with the muscles in a relaxed position. A larger sulcus angle was observed during 0 degrees of flexion in the PFP group, suggesting greater lateral displacement and lateral tilt of the patella in the PFP group when compared to the control group. This malalignment was more pronounced during the contraction of the quadriceps. These differences were less prominent as the knee flexion angle increased.

Similar findings were reported in a study by Witoński & Góraj (1999) that used MRI imaging to estimate patellar tracking and malalignment in the knees of participants with PFP (n=12) compared to the knees of healthy participants (n=20). Images were obtained at 0, 10, 20, and 30 degrees of knee flexion in a supine position and used to calculate patellar tilt angle, sulcus angle, and congruence angle. From the resulting images, the authors identified five different patterns of malalignment. The most frequently observed pattern was excessive lateral tilt and displacement, represented by increased congruence angle and decreased patellar tilt angle. Contraction of the quadriceps muscle caused a significant increase in this pattern in the participants with PFP, particularly during the first 30 degrees of flexion. The results from this study and from Biedert & Gruhl (1997) also support the notion that patellar malalignment is more prevalent during lesser degrees of flexion, as the knee approaches full extension.

More recent studies have examined patellar maltracking by using advanced imaging techniques during performance of active motion of the knee joint. Draper et al. (2011) examined the differences in joint kinematics between upright, weight-bearing and supine, non-weight-bearing conditions in those participants who displayed maltracking of the patella and those who did not. Real-time MRI was used to provide images of the PFJ during dynamic knee extension in both the weight-bearing and non-weight-bearing positions for the 20 participants with PFP. In the participants who exhibited excessive lateral translation of the patella, the patella translated more laterally during the weight-bearing dynamic knee extension task. This excessive lateral translation was most evident between 25 and 30 degrees of knee flexion. These findings are consistent with those of an earlier study by Draper et al. (2009) that reported increased lateral translation of the patella during a weight-bearing task between 0 and 50 degrees of knee flexion and increased lateral tilt of the patella between 0 and 20 degrees of knee flexion in participants with PFP. These findings suggest that excessive lateral displacement of the patella during lesser degrees of flexion occurs in individuals with PFP.

In a cross-sectional design, Souza et al. (2010) compared PFJ kinematics between participants with PFP (n=15) and healthy participants (n=15) during a single-leg squat. MRI images were used to allow for measurements of lateral patellar tilt and displacement to be taken at 45, 30, 15, and 0 degrees of knee flexion during the task. Similar to the findings by Draper et al. (2011) and Draper et al. (2009), the PFP group exhibited significantly more lateral translation of the patella at all of the angles of the single-leg squat, and significantly greater lateral patellar tilt at the lesser degrees of knee flexion (30, 15, and 0 degrees) as compared to the control participants.

Esfandiarpour et al. (2018) compared patellar motion during a dynamic lunge task in participants with PFP (N=8) and healthy controls (n=10) using a 3-D modeling technique. A dual-orthogonal fluoroscope was used to obtain images of the PFJ during the lunge task, and CT scans of the PFJ in a fully extended, supine position were used to reconstruct 3-D models of the bony structures of the PFJ. The participants with PFP exhibited significantly greater lateral tilt of the patella in the fully extended position when compared to the pain-free participants. There was also significantly greater lateral patellar tilt observed for the PFP group at 45, 60, and 75 degrees of flexion based on the modeling technique. These results differ from the findings of Draper et al. (2009) regarding patellar tilt during a single-leg squat, and may suggest that patellar positioning may change dependent on the task being performed.

Despite the observation of patellar malalignment and maltracking in several studies, very little is known as to the extent to which lateral displacement and lateral tilt of the patella contributes to diminished PFJ contact area. In an observational cohort study, Salsich & Perman (2007) used a regression analysis to determine if patellar alignment and tibiofemoral rotation alignment could account for significant portions of variance in PFJ contact area. MRI images of the PFJ with the knee in full extension were obtained from both participants with PFP (n=21) and healthy participants (n=21). PFJ contact area, lateral patellar displacement, patellar tilt angle, tibiofemoral rotation angle, and patellar width were all measured from these images. After omitting lateral patellar displacement to avoid multicollinearity, patellar width and tibiofemoral rotation angle emerged as the best predictors for PFJ contact area in the PFP group, accounting for 46% of the variance. These findings dispute the relationship between patellar malalignment and diminished PFJ contact area supported by the studies above, however this study only examined these measurements in one position (full knee extension). It is plausible that the contributions of patellar displacement or tilt may have been more significant as the knee moved further into flexion.

The findings of another study also dispute the influence of patellar maltracking as a causative factor for pain in individuals with PFP.  Carlson et al. (2017) conducted a longitudinal study to evaluate changes in patellar maltracking patterns in adolescent females (n=6) with PFP from mid- to late adolescence. Dynamic MRI was utilized to calculate 3-D PFJ kinematics during active extension-flexion of the knee joint, but kinematics at 10 degrees of flexion were compared between mid-adolescence and late adolescence. Kujala Anterior Knee Pain Score (AKPS; Kujala et al., 1993) to assess the severity of symptoms on function, visual analog scale (VAS; Harrison et al., 1995) for pain severity, and number of hours spent participating in physical activity were also gathered at both visits. At the follow-up visit, all the participants reported an improvement in both AKPS and VAS scores. The participants also reported a decrease in the number of hours spent participating in impact physical activities. There were no differences observed in patellar maltracking between the two visits. Fifty-percent of the participants demonstrated excessive lateral displacement of the patella when compared to the position reported for healthy, age-matched controls during the baseline measurement, which was unchanged when assessed at the follow-up session. These findings suggest that improvements in pain and symptoms in this sample were the result of other factors, and not due to changes in patellofemoral tracking.

While lateral displacement and tilt of the patellar have been identified in multiple studies, the relationship between patellar maltracking and malalignment and pain not clearly established. This could be attributed to methodological differences between the studies regarding the type of imaging and modeling techniques used. The findings do support that patellar malalignment and maltracking appear to be more prevalent at lesser degrees of knee flexion. As the pathomechanical model by Powers et al. (2017) suggests, there are several biomechanical factors that may contribute to the patellar malalignment and maltracking observed in individuals with PFP.

### ***Altered Tibiofemoral Joint Kinematics***

In the pathomechanical model of PFP, altered kinematics at the tibiofemoral joint in the sagittal, frontal, and sagittal planes can also influence the contact area of the PFJ (Powers et al., 2017). The evidence presented above regarding decreased PFJ contact area identified that lesser degrees of knee flexion are associated with decreased PFJ contact area (Bretcher & Powers, 2002b). Reduced knee flexion during dynamic, weight-bearing tasks such as walking and running could contribute to decreases in PFJ contact area, thereby increasing PFJ stresses (Powers et al., 2017).

Tibiofemoral joint kinematics in the frontal plane are also theorized to contribute to decreases in PFJ contact area. While this relationship has yet to be examined in vivo, there are two cadaveric studies that have looked at the influence of knee valgus on PFJ contact and pressures. (Bryant et al., 2014) applied small degrees (5 degrees) of knee valgus to cadaver knees and did not report a significant change in PFJ contact area. Huberti & Hayes (1984) tested cadaver knee joints at varying degrees of knee valgus to determine how this motion influenced normal patellofemoral contact forces. At 10 degrees of knee valgus, normal patellofemoral contact force increased by 45%, but this was not accompanied by a change in contact area. Based on these findings, it is unclear how frontal plane motion, particularly knee valgus, may contribute to decreased PFJ contact area.

Transverse plane motion, namely tibiofemoral rotation, has been implicated with regard to PFJ contact area in participants with PFP. Liao et al. (2015) reported that internal rotation of the femur in relation to the tibia is associated with decreases in PFJ contact area at 15 and 45 degrees of knee flexion. The pathomechanical model presents excessive internal rotation of the femur as a contributing factor to patellar malalignment and maltracking (Powers et al., 2017). Rotation of the tibia relative to the femur can also influence PFJ contact area. Lee et al. (2001) identified that while internal rotation of the tibia relative to the femur does not influence PFJ contact area, external rotation of the tibia relative to the femur may reduce PFJ contact area, leading to less area for PFJ reaction forces to be distributed.

Alterations in kinematics of the tibiofemoral joint are theorized to influence the amount of PFJ contact area over which PFJ reaction forces are able to be dispersed (Powers et al., 2003). While there is some evidence provided above in support of the relationship between tibiofemoral kinematics and PFJ contact area, it appears there may be a stronger relationship between altered tibiofemoral kinematics and PFJ reaction forces in individuals with PFP.

### *Impaired Quadriceps Function*

As the research regarding patellar malalignment and maltracking implied, lateral displacement of the patella appears to be exacerbated with active contraction of the quadriceps (Biedert & Gruhl, 1997; Witoński & Góraj, 1999). Weakness, atrophy, or impaired performance of the quadriceps muscles is postulated to contribute to patellar maltracking and malalignment in individuals with PFP (Powers et al., 2017). Several studies have identified quadriceps weakness in individuals with PFP when compared to healthy controls (Lankhorst et al., 2012; Kaya et al., 2011; Pappas & Wong-Tom, 2012). In a systematic review and meta-analysis, Lankhorst et al. (2012) examined 13 potential risk factors identified from 7 articles included in the review, and identified that knee extension strength, quantified by peak torque, was significantly lower in individuals with PFP than in healthy controls. Similarly, Kaya et al. (2011) reported significant differences in total volume and cross-sectional area of the quadriceps measured using MRI in the involved limb compared to the unaffected limb in participants with PFP. The authors also reported significantly reduced peak torque of the quadriceps muscle of the involved limb as compared to the unaffected limb. In a systematic review and meta-analysis of prospective predictors for the development of PFP (Pappas & Wong-Tom, 2012), only knee extension strength was identified as a predictor of PFP. These findings all support that among individuals with PFP, weakness of the quadriceps is commonly reported.

Another aspect of quadriceps function that has been examined in individuals with PFP and considered a potential contributor to patellar maltracking and alignment is altered function of the vastus medialis (VM) relative to the vastus lateralis (VL) (Grabiner et al., 1994). More specifically, atrophy of the VM has been speculated as a contributing factor to increased lateral patellar tilt and displacement (Halabchi et al., 2013; Witvrouw et al., 2005). A case-control study by Pattyn et al. (2011) compared VM and total quadriceps cross-sectional area in participants with PFP (n=46) with healthy participants (n=30) using MRI imaging. The cross-sectional area of VM was significantly smaller in the PFP group than in the control group, and while not statistically significant, a trend was noted for smaller cross-sectional area of the quadriceps in the PFP group compared to the control group. These findings support the presence of VMO atrophy in individuals with PFP, however it is unknown whether this is a contributing factor or a result of PFP.

However, another study failed to identify the presence of selective VM atrophy in individuals with PFP compared to healthy controls. Giles et al. (2015) performed a cross-sectional study to assess for quadriceps atrophy in participants with PFP, and to determine if the VM was selectively involved. Real-time ultrasound was used to measure the quadriceps muscle sizes of participants with PFP (n=35) and sex and age matched controls (n=35). Atrophy of all of the quadriceps muscles was identified in the involved limb for the participants who presented with unilateral PFP (n=22) as compared to the uninvolved knee. When compared to the control groups, atrophy of the quadriceps was not observed in the participants with PFP. These findings refute the theory that isolated atrophy of the VM is present in individuals with PFP.

Another aspect of muscle performance proposed to contribute to the etiology of PFP is delayed activation of the VM relative to the VL. Activation of the VM is believed to limit lateral displacement of the patella due to its location and attachment to the patella. As a result, it is speculated that a delay in the activation of the VM relative to the VL could contribute to increased lateral displacement of the patella in individuals with PFP (Fulkerson, 2002). Lorenz et al. (2012) utilized selective electrical stimulation of the VM and VL in individuals with PFP and healthy controls to measure how activation of selected quadriceps muscles influenced 3-D motion of the patella. Selected activation of the VM resulted in greater medial patellar rotation, while activation of the VL alone caused increased lateral patellar displacement in the PFP group than in the control group. These findings suggest that alterations in the function of the quadriceps muscles in individuals with PFP may contribute to patellar maltracking and malalignment, thereby influencing patellofemoral joint contact area. However, this study used selective stimulation of the quadriceps muscles, which may not be representative of actual muscle activity during voluntary movement.

The findings of a prospective cohort study conducted in a military population by Van Tiggelen et al. (2009) also support delayed VM activation as a risk factor for PFP. Surface electromyography (EMG) of VM and VL activity was collected during performance of a functional task (rocking back on the heels of the feet) in healthy, male recruits (n=79) prior to beginning 6-weeks of basic military training. Upon completion of the basic military training, the participants were reassessed. Thirty-two percent of the participants developed PFP over the course of the 6-week training, and exhibited a significant delay of the VM compared to those who did not develop PFP. This delayed activation of the VM was also identified prior to the start of military training in those who went on to develop PFP, suggesting that delayed onset of the VM could be a predisposing factor for PFP. Similar findings were reported in another prospective study using an athletic population (Witvrouw et al., 2000). Altered VM muscle reflex response time was significantly correlated with the incidence of PFP in an adolescent population of athletic males and females, further supporting delayed activation of the VM as a risk factor for PFP.

Pal et al. (2011) provided additional support for this theory with the findings from their case control study exploring the relationship between delayed activation of the VM and patellar maltracking in both participants with PFP and healthy participants. Surface EMG was utilized to assess onset of muscle activation for the VM and VL during walking and running, and MRI images of the knee while in a weight-bearing position were used to measure patellar tilt and bisect offset of the patella relative to the femur. Among the participants with PFP, only those who displayed both abnormal patellar tilt and bisect offset had significant correlations between delayed VM activation and patellar maltracking. There were no differences identified between mean VM activation delays in the control and PFP group as a whole. These findings suggest that the relationship between delayed VM activation and patellar maltracking are not universal, and only occur in a subgroup of individuals with PFP.

In contrast to the findings above, Cavazzuti et al. (2010) conducted a study to assess whether delayed muscle activation of the VM relative to the VL differed between participants with PFP and healthy controls during the following tasks: sit to stand, stand to sit, squat, step-up, and step-down. Surface EMG was used to identify the activation instants for each muscle, and from these instants, the delay in activation was calculated for each muscle for each task. There were no significant differences identified between the participants with PFP and control participants regarding delayed activation of the VM relative to the VL for any of the tasks. These findings dispute the presence of a delayed onset of activation of the VM in individuals with PFP.

Sheehan et al. (2012) calculated patellofemoral and tibiofemoral kinematics derived from velocity data collected using dynamic MRI in healthy individuals before and after a motor branch block to the VM, and concluded that while the diminished capacity of the VM to generate force produced kinematic changes similar to those seen in individuals with PFP, it did not account for the all of the changes contributing to lateral displacement of the patella. This argues against the proposal that impaired function VM is a significant contributing factor to lateral patellar displacement, further suggesting that the relationship between VM function and patellar displacement is unclear.

Collectively, while individuals with PFP commonly present with quadriceps weakness and in some cases, altered quadriceps function, it remains unclear if this a contributing factor to PFP or if this is a result of the experience of PFP. There is inconsistency in the research to support that this is contributor to patellar alignment, and therefore additional research is warranted to examine the relationship between quadriceps function and the development of PFP.

### ***Excessive Internal Rotation of the Femur***

As illustrated in the pathomechanical model and suggested in the section above regarding altered tibiofemoral joint kinematics, internal rotation of the femur is theorized to contribute to patellar maltracking and malalignment (Powers et al., 2017). Powers et al. (2003) compared patellofemoral joint kinematics during weight-bearing and non-weight-bearing knee extension in individuals with PFP (n=6). Lateral patellar displacement was more pronounced in non-weight bearing knee extension than during the weight-bearing condition, but no differences in lateral patellar tilt were identified between the two conditions. Internal rotation of the femur was significantly greater during the non-weight-bearing condition, particularly within the range of 18-0 degrees of extension. This suggests that the kinematics of the patellofemoral joint during non-weight-bearing could be described as the patella rotating on the femur, while in weight-bearing, the femur rotates under the patella (Powers et al., 2003).

This finding was corroborated in another study. Souza et al. (2010) conducted a cross-sectional design using MRI to compare PFJ kinematics, femoral rotation, and patella rotation between females with PFP (n=15) and healthy controls (n=15) during performance of a single-leg squat. Significantly greater lateral displacement of the patella at 45, 30, 15, and 0 degrees of knee flexion was observed in the participants with PFP compared to the control group. The PFP group also displayed significantly greater lateral patellar tilt at 30, 15, and 0 degrees of knee flexion. Significantly greater internal rotation of the femur at 45, 15, and 0 degrees of knee flexion were also reported for the PFP group compared to the control group. These results suggest that lateral patellar displacement and lateral patellar tilt appear to be related to excessive internal rotation of the femur during weight-bearing activities.

While these findings support the relationship between internal rotation of the femur and patellar alignment during weight-bearing tasks, additional studies are warranted to determine if this relationship holds true during other functional tasks, as well as in a larger sample of individuals with PFP.

### *Impaired Hip Muscle Performance, or Altered Bony Structure*

The musculature of the hip is speculated to have an influence on patellar position (Powers et al., 2017). The hip external rotators and abductors are theorized to control transverse and frontal plane motion of the femur (Boling et al., 2009). Weakness of the hip external rotations is hypothesized to lead to increases in internal rotation of the femur, which as described above, may contribute to patellar malalignment and maltracking and elevated loading of the PFJ (Powers, 2010).

Impaired hip muscle performance has been consistently reported in individuals with PFP (Powers et al., 2017). The proximal musculature surrounding the hip and pelvis acts to stabilize the pelvis and the femur, which in turn can directly influence the positioning of the knee and other structures within the kinetic chain of the lower extremity. This proximal musculature, namely the gluteus maximus, gluteus medius, and tensor fasciae latae muscles, play a significant role in control of the lower extremity during stance and functional movement. Compared to healthy individuals, patients with PFP often exhibit weakness of the hip musculature, namely for the motions of hip extension, hip abduction, and hip external rotation (Prins & van der Wurff, 2009). Similar findings were also reported in a cross-sectional study Magalhães et al. (2010) that compared hip strength in sedentary females with unilateral (n=21) and bilateral PFP (n=29) to healthy controls (n=50). The females with bilateral PFP presented with statistically weaker isometric strength for all 6 hip muscle groups tested (abduction, adduction, external rotation, internal rotation, flexion, and extension). Weakness of the hip abductors, external rotators, flexors, and extensors was identified in the involved limb of those with unilateral PFP as compared to the control group. When compared to the contralateral limb, only the hip abductors were significantly weaker. A systematic review and meta-analysis by Van Cant et al. (2014) also reported deficits in isometric hip abduction, extension, and external rotation strength in participants with PFP when compared to healthy controls. When the strength of the involved side was compared to the uninvolved side in the PFP participants, two of the included studies reported deficits in hip abduction, and one study reported deficits in hip extension and external rotation strength.

However, at least two prospective studies conducted runners have reported conflicting findings to those presented above (Thijs et al., 2011; Finnoff et al., 2011). A prospective cohort study (Thijs et al., 2011) measured isometric hip strength in healthy female runners (n=77) at the start of a 10-week beginner running program. The baseline hip strength was then compared between the runners who did develop PFP over the course of the training to those who did not. There was no statistical difference identified between groups for hip muscle strength. Another prospective cohort study (Finnoff et al., 2011) assessed the hip strength of high school running athletes (n=98) at the beginning of the season, and re-assessed strength if one of the participants developed PFP. The participants who developed PFP had a lower hip external-to-internal rotation strength ratio than the uninjured runners. The injured runners also exhibited a decrease in hip abduction and external rotation strength from pre-injury to post-injury. Regression analysis revealed that greater hip abduction strength and hip abduction-to-adduction strength ratio was related to an increase in PFP risk, and that greater hip external-to-internal rotation strength ratio was related to a decrease in PFP risk.

Two additional prospective studies reported that hip external rotation and hip abduction strength was stronger in individuals who went on to develop PFP (Boling, Padua, Marshall, et al., 2009; Herbst et al., 2015). A prospective cohort study (Boling, Padua, Marshall, et al., 2009) examined United States Naval Academy recruits (n=1,597) at the date of their enrollment and followed up over the duration of their training. The participants who developed PFP had increased hip external rotation strength compared to those who did not, which contrasts with the findings reported in the above prospective studies. Another prospective study (Herbst et al., 2015) compared isokinetic hip and knee strength in female adolescent basketball athletes (n=255) who went on to develop PFP versus those who did not. Isokinetic strength was measured for knee flexion and extension and hip abduction. The females that developed PFP exhibited greater normalized hip abduction strength than those who did not. Isokinetic knee strength did not differ between the groups. One consideration for the difference in findings specific to this study is the measurement of isokinetic strength versus isometric strength. The result of both studies suggests that the increased hip strength in those with PFP may be due to activation to counteract excessive internal rotation of the femur during dynamic tasks.

The retrospective study presented earlier (Piva et al., 2005) also reported no differences between males and females with PFP and age-matched healthy controls for hip external rotation and hip abduction strength. Similarly, a systematic review and meta-analysis by Rathleff et al. (2014) reported moderate to strong evidence from prospective studies to indicate that there is no association between isometric hip strength and the risk of developing PFP. Upon review of the included cross-sectional studies, the authors reported moderate evidence suggesting that participants with PFP have deficits in isometric hip strength compared to healthy controls. The results of this review demonstrate the inconsistency in findings regarding hip strength between prospective and cross-sectional studies. When considering the results of all of the above studies regarding hip strength, there is support to suggest that hip strength may not be associated with an increased risk of PFP, but instead may be a consequence of PFP.

Altered bony structure of the hip is also posited as a potential contributor to excessive internal rotation of the femur in the pathomechanical model of PFP (Powers et al., 2017). However, the evidence regarding this proposed relationship is sparse. Increased femoral anteversion and increased femoral neck inclination (coxa valga) are two bony abnormalities of the femur that have been proposed to influence kinematics (Powers et al., 2017). A cross-sectional study (Souza & Powers, 2009) did not report increased femoral anteversion, but did identify greater femoral inclination in women with PFP (n=19) compared to healthy controls. A stepwise regression identified hip extension strength, and not increased femoral inclination as a predictor for average hip internal rotation during running.

These findings suggest that weakness of the hip musculature may occur concurrently with excessive internal rotation of the femur. The findings above do not establish a direct relationship between hip muscle strength and excessive hip internal rotation. While altered bony structure was reported in participants with PFP for one study (Souza & Powers, 2009), there was not a relationship between this abnormality and internal rotation of the femur.

### ***Impaired Soft Tissue Restraints***

The pathomechanical model demonstrates a potential relationship between impaired soft tissue restraints, particularly the iliotibial band (ITB), lateral retinaculum, and ligamentous structures of the PFJ and patellar maltracking and malalignment (Powers et al., 2017). The ITB originates proximally from the tensor fascia latae and gluteus maximus muscles, continues down the lateral aspect of the femur, and attaches distally to the linea aspera of the femur and Gerdy's tubercle on the tibia (Lobenhoffer et al., 1987). The iliopatellar band of the ITB attaches to the lateral border of the patella, constituting a key part of the lateral retinaculum of the knee (Terry et al., 1986). Due to this anatomical position and mechanical line of pull of the ITB, it has been postulated that tightness of the ITB contributes to lateral displacement of the patella (Merican et al., 2009).

Excessive tightness of the (ITB) has been reported in individuals with PFP. A case-control study (Hudson & Darthuy, 2009) assessed ITB length using the Ober test in participants with PFP (n=12) compared to matched control participants (n=12). The PFP group presented with significantly tighter ITB on the involved limb when compared to the control group. Tightness of the ITB can affect patellar positioning, which has been identified in two different studies. Kang et al. (2014) reported that healthy participants (n=40) with ITB tightness had a significantly laterally positioned patellar at 20 degrees of hip adduction, and also had greater lateral patellar translation in hip adduction than patients without tightness. Similar results were reported in a cadaveric study (Merican et al., 2009) exploring the effects of increasing ITB tension on knee kinematics. An increase in ITB tension resulted in significantly greater lateral tilt and lateral displacement of the patella, as well as external rotation of the tibia in a flexed position. While these findings support the relationship between ITB tension and patellar malalignment and maltracking in healthy individuals and cadavers, it is unknown if this result would be upheld in participants with PFP.

Another soft tissue impairment associated with PFP is generalized ligamentous laxity. In the prospective study described earlier (Witvrouw et al., 2000), hypermobility of the patella was identified as a risk factor for PFP in an athletic population. However, a case control study (Ota et al., 2008) that compared medial and lateral patellar mobility between females with PFP (n=22) and those without (n=22) did not identify differences between groups. Patellar mobility in this study was measured using a modified patellofemoral arthrometer, which differs from Witvrouw et al. (2000) who used a measurement rod to measure the maximal position of patellar displacement both medially and laterally. These findings suggest that while hypermobility of the patella may be a risk factor for developing PFP, it has not been identified in individuals who have been diagnosed with PFP.

Based on the current evidence regarding impaired soft tissue restraints as a factor contributing to patellar malalignment and maltracking, there is a need for further research to establish a definitive relationship between the two in participants with PFP. Cadaveric studies do support the influence that tightness of the ITB has on patellar positioning, but it is unclear if this relationship is maintained in vivo.

### ***Abnormal Patellofemoral Joint Anatomy***

The final factor presented in the pathomechanical model that can influence patellar maltracking and malalignment is abnormal patellofemoral joint anatomy (Powers et al., 2017). The ratio of patellar tendon length to patellar length, known as the Insall-Salvati index, is typically approximately 1:1 (Insall et al., 1972). Increased length of the patellar tendon results in an abnormally high position of the patella relative to the femoral sulcus, resulting in patella alta (Hartigan et al., 2005). Previous research has correlated patella alta with incongruence of the PFJ (Møller et al., 1986). Due to this incongruence of the PFJ, it is suggested that patella alta contributes to patellar malalignment and maltracking. In the study presented earlier by Pal et al. (2012), patellar maltracking was more prevalent in participants with PFP who presented with patella alta (67%) than those with normal patella height (16%) using MRI images of the PFJ while in a weight-bearing position. This finding was consistent for each of the four methods used to quantify patellar height, supporting the relationship between patella alta and patellar maltracking.

Anatomical differences in trochlear geometry may also contribute to patellar malalignment and maltracking. The study by Teng et al. (2014) examined MRI images of the patellofemoral joint during 25% weight-bearing of body weight at 0, 20, 40, and 60 degrees of knee flexion to determine whether patellar height and/or trochlear geometry predict patellar alignment. The height of the patella was the best predictor of lateral patellar tilt at 0 degrees of knee flexion and lateral trochlea inclination angle was the best predictor of patellar lateral displacement at 20, 40, and 60 degrees of knee flexion. These findings suggest that along with patella alta, lateral trochlear inclination is implicated in patellar alignment during weight-bearing tasks (Teng et al., 2014). These findings support the relationship of abnormal PFJ anatomy to patellar malalignment and maltracking in participants with PFP, and implicates these anatomical differences in the etiology of PFP.

### *Increased Patellofemoral Joint Reaction Forces*

In addition to decreased PFJ contact area, the pathomechanical model suggests that increased PFJ reaction forces may also contribute to elevated loading of the patellofemoral joint (Powers et al., 2017). PFJ reaction force can be influenced by both the force generated by contraction of the quadriceps and angle of the knee joint (Hartigan et al., 2005). As the knee progresses into flexion, the angle of pull between the quadriceps tendon and patellar tendon decreases, leading to increased PFJ reaction force and compression through the PFJ (Hartigan et al., 2005). Functional, weight-bearing tasks can also produce increased PFJ reaction forces. During the stance phase of gait at approximately 20 degrees of knee flexion, PFJ reaction forces can reach approximately 25-50% of body weight, and up to six times body weight during running (Hartigan et al., 2005). It is postulated PFJ reaction forces differ in individuals with PFP compared to healthy controls. The following studies provide evidence to support this difference in PFJ reaction forces in individuals with PFP.

Chen & Powers (2014) estimated PFJ reaction forces during walking and stair ambulation in females with and without patellofemoral pain (n=40) to determine if there were any differences between groups. MRI images of the PFJ, VM, and patellar tendon were obtained for both groups, and kinematics, kinetics, and EMG activity of the hamstrings and gastrocnemius muscles was collected during performance of the functional tasks. From the biomechanical analysis of each functional task, an optimization routine was applied to calculate the VM and patellar tendon forces. These variables were entered into the model algorithm to determine the 3-

D PFJ reaction forces for each functional task. Compared to the control group, the participants with PFP exhibited lower peak resultant PFJ reaction forces during walking and navigating stairs. The PFP group also demonstrated a higher lateral component of PFJ reaction forces than the control group. This suggests that individuals with PFP may alter their movement strategy to reduce joint loading of the patellofemoral joint during weight-bearing activities, but this modification in movement did not influence the lateral forces of the patella.

The cross-sectional study (Brechter & Powers, 2002b) presented earlier identified similar results comparing PFJ reaction forces in individuals with PFP (n=10) compared to healthy controls during self-selected and fast-paced walking. During the self-selected walking condition, peak PFJ reaction force was significantly less than the control group. There were no significant differences between groups for the peak PFJ reaction force during the fast-paced walking condition. The authors also attributed this finding to an alteration in movement strategy, namely a quadriceps avoidance gait pattern, in an attempt to reduce muscular forces acting to increase stress in the PFJ (Brechter & Powers, 2002b). In another study by the same authors (Brechter & Powers, 2002a), PFJ reaction force as well as knee extensor moment were reduced in participants with PFP during stair ambulation, again supporting the suggestion that individuals with PFP may alter their movement strategy in an attempt to reduce PFJ stresses.

One limitation of the above studies is the use of stationary MRI images of the PFJ in the modeling of PFJ reaction forces. Thomeer et al. (2017) employed a novel modeling technique for PFJ reaction force utilizing dynamic MRI images of the PFJ during active flexion and extension of the knee joint from 0 to 40 degrees. Using this approach, an increased mean normalized PFJ reaction force of 14.9% was identified in the PFP group (n=33) compared to the control group (n=38). These findings are in contrast with those reported above, but can be attributed to differences in modeling techniques. However, the results from the above studies all support the theory that PFJ reaction forces do differ in those with PFP from pain-free individuals, suggesting that PFJ reaction forces are implicated in the etiology of PFP. Further research is necessary to better understand how PFJ reaction forces influence PFJ stresses and loading, particularly in individuals experiencing PFP.

### *Altered Tibiofemoral Joint Kinematics*

Within the pathomechanical model, alterations in tibiofemoral joint kinematics is proposed to influence not only PFJ contact area, but also PFJ reaction forces (Powers et al., 2017). Altered tibiofemoral joint kinematics in the sagittal, frontal, and transverse planes are theorized to influence the resultant PFJ reaction force vector (Powers et al., 2003).

As described earlier, individuals with PFP tend to exhibit markedly lower degrees of knee flexion during dynamic, weight-bearing tasks such as walking (Powers et al., 1999), navigating stairs (Crossley et al., 2004; de Oliveira Silva et al., 2015), and running (Dierks et al., 2011).

A prospective study by Powers et al. (1999) assessed walking gait in patients with PFP (n=15) to determine if they demonstrated excessive loading of the lower limb as compared to healthy controls (n=10). Stride and gait characteristics, 3-D kinematics of the lower extremity, and loading rate was collected during self-selected walking pace and fast walking pace. The PFP group walked at a significantly slower velocity than the control group for both walking speeds. The PFP group also exhibited decreased knee flexion during the stance phase of the fast walking condition. Average peak loading rate was significantly less in the PFP group than in the control group for both walking speeds. These findings identified reduced knee flexion during walking gait in those with PFP, however this altered movement strategy was not related to increased loading of the lower limb.

Reduced knee flexion has also been reported during stair ambulation. Knee flexion and quadriceps muscle activity during stair ascent and descent was evaluated in a cross-sectional study (Crossley et al., 2004). Stance-phase knee flexion was assessed using two-dimensional (2-D) methods, and EMG activity of the VM and VL was collected in participants with PFP (n=48) and healthy controls (n=18). The PFP group was divided into groups based on the EMG activity of the VM and VL - one group with synchronous onset of activation, and the other with delayed onset of the VM relative to the VL. The PFP group as a whole demonstrated less peak knee flexion than the control group. When comparing the two PFP groups, the group with the delayed onset of the VM demonstrated reduced knee flexion during stair descent than the synchronous onset group and the control group. These findings support the altered knee flexion pattern in individuals with PFP, and suggests that the timing of activation of the VM and VL is related to this movement pattern.

Similar findings were reported in another study (de Oliveira Silva et al., 2015) that analyzed 3-D kinematics and kinetics during stair ambulation in individuals with PFP (n=29) and healthy controls (n=25). The PFP group demonstrated significantly less peak knee flexion, but in contrast to the findings by Crossley et al. (2004) during walking, the PFP group exhibited increased loading rates during the stair ambulation task when compared to the control group. These findings support the finding of reduced knee flexion in individuals with PFP, and associates this altered movement with increased loading of the lower extremity during stair ambulation.

Reduced knee flexion has also been reported during running in individuals with PFP. Dierks et al. (2011) investigated kinematics of the lower extremity in runners with PFP (n=20) and healthy controls (n=20) during a prolonged run. When compared to the control group, the PFP group exhibited less peak knee flexion. Consistent with the findings during walking and stair ambulation, these results support the reduction of knee flexion in individuals with PFP. This alteration in movement could potentially be a strategy to reduce pain.

Frontal plane motion of the tibiofemoral joint, specifically knee abduction or dynamic malalignment, has also been implicated as a contributor to patellofemoral joint reaction force (Powers et al., 2017). Powers et al. (2003) reported that dynamic malalignment during weight-bearing activities contributed to increases in the laterally directed component of the patellofemoral joint reaction force vector. Increased knee abduction has been reported in individuals with PFP during several functional weight-bearing tasks, such as squatting (Willson & Davis, 2008), stepping (Nakagawa et al., 2012), and landing from a hop (Herrington, 2014).

A case-control study by Willson & Davis (2008) utilized three different methods to assess dynamic malalignment in participants with PFP (n=20) and healthy controls (n=20) during three dynamic, weight-bearing tasks. Two-dimensional knee frontal plane projection angle (kFPPA) was measured using a digital camera during single-leg stance and single-leg squats. Three-dimensional kinematics of the lower extremity were measured during single-leg squats, running, and repetitive single-leg jumps. The kFPPA measures for the PFP group revealed greater dynamic malalignment than the control group during the single-leg squat task. The kFPPA angle during the single-leg squat task were also related to increases in hip adduction and knee external rotation across all three dynamic tasks. While dynamic malalignment was identified in those participants with PFP using kFPPA, these are not representative of 3-D joint rotations.

Frontal plane biomechanics were also examined in a cross-sectional study by Nakagawa et al. (2012) during a stepping task. Eighty recreationally active participants were evenly divided into four different groups: females with PFP, males with PFP, female controls, and male controls. Three-dimensional frontal plane kinematics for the trunk, pelvis, hip, and knee was assessed at varying degrees of knee flexion during performance of a stepping task. Both the female and male PFP groups demonstrated greater knee abduction for all of the knee flexion angles, which supports that both males and females with PFP are more likely to exhibit dynamic malalignment than healthy controls.

Herrington (2014) assessed 2-D kFPPA in females with unilateral PFP (n=12) and healthy controls (n=30) during a single-leg squat and hop landing task to assess for dynamic malalignment. The PFP group presented with significantly greater mean FPPA's for both tasks, further supporting the presence of dynamic malalignment during single-leg weight-bearing tasks in individuals with PFP.

Transverse plane motion of the patellofemoral joint is also speculated to contribute to increasing the laterally directed component of the patellofemoral joint reaction force vector and may lead to decreased contact area of the patella, particularly at 15 and 45 degrees of knee flexion (Liao et al., 2015). External rotation of the tibia relative to the femur may contribute to decreases in patellofemoral joint contact area, leading to an increase in stress of the patellofemoral joint (Lee at al., 2001). Internal rotation of the tibia relative to the femur has little influence on the patellofemoral contact area, therefore not influencing stress at the patellofemoral joint (Lee at al., 2001).

In the study discussed earlier by Willson and Davis (2008), females with PFP exhibited larger degrees of tibiofemoral external rotation during single-leg squats, running, and jumping than healthy controls. In contrast to these findings, Schwane et al. (2015) reported increased internal rotation of the tibiofemoral joint during a stair descent task in women with PFP (n=20) when compared to a control group (n=20). These findings suggest that there are differences among individuals with PFP regarding transverse plane motion at the knee, which could be due in part to motion of the femur during a weight-bearing task***Altered Hip Kinematics***

Kinematics at the hip can influence tibiofemoral joint kinematics due to the segment connecting the two joints – the femur (Powers et al., 2003). Hip adduction and knee abduction are highly correlated and together result in dynamic malalignment during weight-bearing tasks (Willson & Davis, 2008). This relationship is supported by the findings of Hollman et al. (2014). This study explored the relationships between 3-D hip and knee kinematics and dynamic malalignment during a single-leg squat in healthy female participants (n=41). A relationship was found between increased hip internal rotation and hip adduction with increased dynamic malalignment. Additionally, two systematic reviews (Meira & Brumitt, 2011; Neal et al., 2016) reported support for a relationship between hip adduction and PFP, further supporting the implication of this altered hip motion in the etiology of PFP.

The systematic review by Neal et al. (2016) reviewed 28 prospective, observational, and intervention studies that included clinical and biomechanical outcomes in runners with PFP. Limited evidence was found to support a moderate correlation between hip adduction, hip internal rotation, and contralateral pelvic drop and PFP in runners. In contrast, two papers (Barton, Levinger, et al., 2011; Powers et al., 2002) reported decreased hip internal rotation during walking gait in participants with PFP as compared to healthy controls. A case-control study (Barton, Levinger, et al., 2011) examined 3-D kinematics of the lower extremity during walking in individuals with PFP (n=26) and healthy controls (n=20) to identify differences between the two groups. The PFP group exhibited less peak hip internal rotation than the control group. Similarly, Powers et al. (2002) examined 3-D kinematics of the foot, tibia, and femur during a free-walking task in females with PFP (n=24) compared to healthy controls (n=17). No group differences were reported for foot pronation or tibia rotation magnitude or peak timing, but the PFP group did demonstrate significantly less internal rotation of the femur than the control group. This decrease in hip internal rotation may be a movement strategy adopted to reduce PFJ stress while walking. This difference in findings across studies could be attributed to differences in movement between running and walking or could suggest the adoption of a compensatory movement pattern to decrease PFJ stress and avoid pain.

Impaired hip muscle performance or altered bony structure, as reviewed earlier, also influence hip kinematics. As discussed earlier, the exact mechanism by which hip strength is related to hip kinematics is unclear, and very little evidence suggests that bony structural differences of the hip influence distal kinematics. It is possible that there are other factors, such as pain, that are implicated in this proposed relationship between hip strength and hip kinematics in those with PFP.

### *Altered Foot Mechanics*

Pronation of the subtalar joint may contribute to excessive rotation of the tibia, resulting in dysfunction at the patellofemoral joint, according to the pathomechanical model (Powers et al., 2017). A systematic review (Barton et al., 2009) including 24 case-control studies determined which kinematic gait characteristics were associated with PFP. Among the kinematic characteristics identified, rearfoot eversion was reportedly greater and delayed during both walking and running in those with PFP. However, in contrast, another systematic review (Dowling et al., 2014) only found limited to very limited support for rearfoot kinematic variables as a risk factor for several overuse conditions of the lower extremity, including PFP. Barton et al. (2012) evaluated 3-D kinematics of the lower extremity during over-ground walking in individuals with PFP (n=26) and those without (n=20). Rearfoot eversion was related to both tibial internal rotation and hip adduction in the PFP group, suggesting that mechanics at the foot segment is related to proximal biomechanics.

The findings presented above regarding altered foot mechanics within the pathomechanical model are inconsistent and further research is warranted to better establish the potential relationship between foot mechanics and tibiofemoral joint kinematics.

### *Altered Foot and Ankle Strength, Structure and/or Mobility*

According to the pathomechanical model, impairments relative to foot and ankle strength, structure and mobility consistent with excessive foot pronation may be identified in individuals with PFP (Powers et al., 2017). Rearfoot posture was measured in a study by Levinger & Gilleard (2004) using 2-D and 3-D measurements in females with PFP (n=13) and healthy controls (n=14) to determine if differences existed between the groups. The PFP group demonstrated significantly greater rearfoot eversion and subtalar varus than the control group.

However, the systematic review by Lankhorst et al. (2012) did not identify rearfoot posture as a risk factor for PFP. This could be due to differences in instrumentation and measurement of rearfoot posture. Further research is warranted to determine if rearfoot posture is in fact related to altered foot mechanics and thereby altered tibiofemoral joint kinematics.

Navicular drop is another foot posture that has been associated with the development of PFP (Barton et al., 2010; Boling, Padua, Marshall, et al., 2009). The case-control study presented earlier by (Barton et al., 2010) identified that the PFP group (n=20) had a more pronated foot than the control group (n=20). The authors also concluded that foot posture index, normalized navicular drop, and calcaneal angle relative to subtalar joint neutral are all reliable measurements that are sensitive to differences between those with PFP and those without. The prospective risk factor study also presented earlier (Boling, Padua, Marshall, et al., 2009) identified increased navicular drop was a risk factor for PFP in military cadets.

Decreased ankle dorsiflexion is also related with dynamic malalignment during dynamic weight-bearing tasks. Wyndow et al. (2016) used 2-D analysis during a lateral-step down task in healthy participants (n=30) to measure dynamic malalignment using the FPPA. Foot mobility and ankle joint dorsiflexion were also assessed to determine if there was a relationship with dynamic malalignment. Higher midfoot width mobility, lower midfoot height mobility and lower ankle joint dorsiflexion were significantly associated with greater peak FPPA. Similar findings were reported by a cross-sectional study (Rabin et al., 2014) that assessed the relationship between a range of physical measures and visually assessed quality of movement during performance of a lateral step-down test in Israeli soldiers with PFP, rating the movement as "good" or "moderate". The physical measures assessed included weight-bearing and non-weight-bearing ankle dorsiflexion range of motion (ROM). The participants who were rated as “moderate” for the quality of movement exhibited less weight-bearing and non-weight-bearing dorsiflexion ROM than those rated as “good” quality of movement.

The results from these studies demonstrate some support for the relationship of rearfoot eversion (Levinger & Gilleard, 2004) and navicular drop (Barton et al., 2009) to PFP, however these findings are not consistently reported. Ankle dorsiflexion is associated with dynamic malalignment in individuals with PFP (Rabin et al., 2014). Collectively, these results suggest that impairments at the foot and ankle, occurring concurrently with other proximal factors, may have a more direct influence in the pathomechanics associated with PFP.

### *Muscle Tightness*

Tightness of the quadriceps and hamstring musculature is another factor proposed to lead to increases in patellofemoral joint reaction forces in the pathomechanical model (Powers et al., 2017). Piva et al. (2005) reported that when compared to age- and gender-matched controls, individuals with PFP demonstrated significantly less flexibility of the gastrocnemius, soleus, quadriceps, and hamstring muscles. Whyte et al. (2010) examined the relationship between hamstring length and patellofemoral joint stress during a squat in males with hamstring tightness (n=8) and those without (n=8). Biomechanical modeling was used to calculate medial, lateral, and total patellofemoral joint stress using MRI images of patellofemoral joint contact area and patellofemoral reaction force during a squat. The group with hamstring tightness exhibited significantly greater total and lateral patellofemoral joint stress at 60 degrees of flexion during the performance of a squat than those without hamstring tightness. The authors attributed this result to the significant increase in patellofemoral joint reaction force and lower medial patellofemoral joint contact area at 60 degrees of flexion. These findings support the relationships presented in the pathomechanical model between muscle tightness and increased patellofemoral joint reaction forces.

### *Altered Tibiofemoral Joint Kinetics*

In the consensus paper that introduces the pathomechanical model, Powers et al. (2017) states that altered tibiofemoral joint kinetics occur in all three planes, but that alterations within the sagittal plane can influence the magnitude of the patellofemoral joint reaction force. In the article presented earlier by Chen and Powers (2014), individuals with PFP exhibited lower knee extensor moments than healthy controls during weight-bearing tasks such as walking, running, and navigating stairs. This could contribute to increases in patellofemoral joint reaction force as presented in the earlier section.

Altered knee kinetics have been reported in individuals with PFP during tasks such as walking (Paoloni et al., 2010) and navigating stairs (Aminaka et al., 2011). Kinematic and kinetic evaluation of walking gait was assessed in a study by Paoloni et al. (2010) in participants with PFP (n=9) and healthy age- and gender-matched controls (n=9). The PFP group demonstrated increased knee abductor moment and knee external rotator moment during the loading phase of gait and decreased knee extensor moment during both the loading phase and the terminal stance phase of gait. Similar findings were reported for a stair ambulation task (Aminaka et al., 2011). Participants with PFP (n=20) displayed an increased peak knee abduction moment during stair ascent and increased knee abduction moment impulse for both stair ascent and descent than the control group (n=20). The altered tibiofemoral joint kinetics observed in individuals with PFP are believed to contribute to increases in patellofemoral joint reaction stress.

### *Altered Ground Reaction Forces*

Ground reaction forces are also reportedly different in individuals with PFP than in healthy individuals. One study described earlier (Powers et al., 1999) measured ground reaction forces during walking at a self-selected pace and fast-paced walking in participants with PFP (n=15) compared to healthy controls (n=10). The PFP group exhibited markedly lower ground reaction forces than the control group during both walking conditions. In contrast, another study (de Oliveira Silva et al., 2015) reported increased vertical ground reaction forces during a stair ambulation task in recreational athletes with PFP (n=29) compared to healthy controls (n=25). While it is evident that ground reaction forces differ in individuals with PFP from healthy controls, the exact mechanism as to how this may relate to loading at the PFJ is unknown. It is also unclear is this is a contributing factor versus a consequence of PFP.

### *Altered Trunk Kinematics*

Altered kinematics of the trunk and pelvis can influence the joint reaction forces of the patellofemoral joint (Powers, 2010). Motion occurring at the trunk is capable of influencing the knee extensor moment during dynamic tasks, which as previously identified, can increase the patellofemoral joint reaction force vector (Powers et al., 2017). A common compensatory motion at the trunk during a single limb weight bearing task such as a single leg squat is an ipsilateral trunk lean (Boling & Padua, 2013). This compensation causes the center of mass to shift towards the stance limb, resulting in an increase of internal knee abductor moment in weight-bearing (Powers, 2010; Powers et al., 2017). Another compensatory trunk motion identified during running in females with PFP is increased forward trunk lean and anterior pelvic tilt (Bazett-Jones et al., 2013). Upon completion of an exhaustive run, the PFP participants (n=19) demonstrated increased anterior pelvic tilt compared to healthy controls (n=19). Trunk flexion was increased in both groups after the exhaustive run. It is possible that this compensation may shift the center of mass posteriorly, increasing the demand on the knee extensors and thereby increasing compressive forces on the patella (Bazett-Jones et al., 2013). This compensation and other compensatory movement patterns involving the trunk and pelvis may result from weakness of the hip musculature, namely the hip extensors (Bazett-Jones, et al., 2013). These findings support the relationship between motion at the pelvis and frontal plane motions at the knee joint.

In the presence of hip abductor weakness, an individual may drop the contralateral side of their pelvis during single leg stance, which would move the center of mass away from the stance leg, shifting the knee joint into a varus position (Powers, 2010). Another compensation considered to result from hip abductor weakness is elevation of the contralateral pelvis in an attempt to shift weight towards the stance leg, which would work to shift the center of mass closer to the center of the hip joint (Neumann, 2010). When this compensation occurs quickly, as in cutting or landing from a jump, the center of mass may shift too far laterally to the knee joint, resulting in a valgus moment (or dynamic malalignment) at the knee (Powers, 2010).

### ***Impaired Hip and/or Trunk Muscle Performance***

Impaired performance of the hip and trunk musculature is presented in the pathomechanical model (Powers et al., 2017) as a potential contributor to altered trunk kinematics in individuals with PFP. One study (Teng & Powers, 2016) identified differences between healthy runners with weakness of the hip extensors compared to those with greater hip extension strength. The runners with greater hip extension strength demonstrated a forward trunk lean while running, compared to the runners with decreased hip extension strength, who ran with a more upright trunk posture.

In the study described earlier by Boling & Padua (2013), 3-D kinematic analysis of trunk, hip, and knee motion during a jump-landing task was performed on individuals with PFP (n=15). In addition, concentric and eccentric strength was measured using an isokinetic dynamometer for hip abduction, hip external rotation, and hip extension. Weakness of the hip abductors was correlated to increases in frontal plane motion at the trunk, namely ipsilateral trunk lean. These findings support the relationship between weakness of the hip musculature and altered trunk kinematics in individuals with PFP.

Deficits in trunk side flexion strength have been reported in individuals with PFP (Cowan et al., 2009), however there is no evidence to support a relationship between weakness of the trunk musculature and trunk mechanics, particularly in those with PFP. Further research is needed to better establish the relationship between trunk strength and trunk kinematics in participants with PFP.

### ***Summary of the Pathomechanical Model Literature***

While the pathomechanical model does provide a framework to address the complex interactions among biomechanical factors implicated in the etiology of PFP, there are several inconsistencies in the evidence as presented. There are inconsistent findings regarding the presence of elevated PFJ loading and reduced cartilage thickness in individuals with PFP (Besier et al., 2015; Brechter & Powers, 2002a), and while there is evidence supporting that decreased PFJ contact area (Besier et al., 2015; Brechter & Powers, 2002a; Brechter & Powers, 2002b; Salsich & Perman, 2013) and increased PFJ reaction forces (Chen & Powers, 2014; Brechter &

Powers, 2002b) exist in individuals with PFP, the exact mechanism by which they cause elevated PFJ loading is not known.

There is evidence to support that individuals with PFP display patellar malalignment and maltracking (Biedert & Gruhl, 1997; Draper et al., 2009; Drew et al., 2016; Witoński & Góraj, 1999), altered tibiofemoral joint kinematics (Bryant et al., 2014; Huberti & Hayes, 1984; Liao et al., 2015), quadriceps weakness (Kaya et al., 2011; Lankhorst et al., 2012; Pappas & Wong-Tom, 2012), excessive internal rotation of the femur (Powers et al., 2003; Souza et al., 2010), and abnormal anatomy of the PFJ (Møller et al., 1986; Pal et al., 2013; Teng et al., 2014), it is unclear how each of these factors may contribute decreased PFJ contact area in individuals with PFP. Several other factors within the model postulated to influence PFJ contact area, such as impaired performance of the VM relative to the VL (Cavazzuti et al., 2010; Pal et al., 2011; Sheehan et al., 2012), impaired hip muscle function and altered bony structure (Boling, Padua, & Creighton, 2009; Finnoff et al., 2011; Herbst et al., 2015; Magalhães et al., 2010; Prins & van der Wurff, 2009; Thijs et al., 2011; Van Cant et al.,2014), and impaired soft tissue restraints (Hudson & Darthuy, 2009; Kang et al., 2014; Merican et al., 2009; Ota et al., 2008; E. Witvrouw et al., 2000) have been inconsistently reported within the PFP literature.

Among the factors presented as contributors to increased PFJ reaction forces, there is evidence to support that altered tibiofemoral joint (Herrington, 2014; Nakagawa et al., 2012; Willson & Davis, 2008) and hip kinematics (Hollman et al., 2014; Meira & Brumitt, 2011; Neal et al., 2016), increased navicular drop (Barton et al., 2010; Boling, Padua, Marshall, et al., 2009), decreased ankle dorsiflexion (Rabin et al., 2014; Wyndow et al., 2016), muscle tightness (Piva et al., 2005; Whyte et al., 2010), altered tibiofemoral joint kinetics (Aminaka et al., 2011; Paoloni et al., 2010), and altered trunk kinematics (Bazett-Jones et al., 2013; Boling & Padua, 2013) are reported in individuals with PFP. Inconsistent findings have been reported regarding altered foot mobility (Lankhorst et al., 2012; Levinger & Gilleard, 2004), altered ground reaction forces (de Oliveira Silva et al., 2015; Powers et al., 1999), and trunk muscle performance (Cowan et al., 2009) in individuals with PFP.

These inconsistencies lead to an unclear consensus regarding the exact mechanisms leading to the increase in PFJ loading, which presents challenges in regards to developing treatment interventions aimed at producing favorable prognosis and treatment outcomes (Collins et al., 2018; Powers et al., 2017). As presented in the next section, treatment interventions for PFP are focused on addressing biological factors presented in the pathomechanical model (Powers et al., 2017). As stated above, several inconsistencies exist regarding not only the presence of these etiological factors in individuals with PFP, but also regarding the exact mechanisms by which they result in the pain and symptoms associated with PFP.

## Treatment Interventions

There are several treatment interventions that have been implemented and tested for effectiveness in individuals with PFP. These interventions primarily focus on changing the perception of pain and function by correcting a biological factor believed to contribute to the decreased PFJ contact area and increased PFJ reaction forces, as proposed within the pathomechanical model proposed by Powers et al. (2017). Common treatment approaches include the use of external supports, such as braces, taping, or orthotics, and exercise-based therapy, including muscle strengthening and movement retraining. Other strategies that have been utilized in treatment to help enhance treatment outcomes include patient education and biofeedback. While some of these treatment approaches have yielded favorable outcomes for a subset of individuals in regards to pain and function, there are also findings to suggest that the current approaches are not as effective in the long-term for reducing pain and increasing function for individuals with PFP (Collins et al., 2018). The following will review and critique the existing treatment interventions within the PFP rehabilitation literature.

### ***External Supports***

One of the more traditional treatment approaches for PFP is the use of external supports, such as braces, taping, and orthotics as a means of correcting an anatomical malalignment theorized to contribute to the development of PFP. In a recent prospective randomized controlled trial published by Uboldi et al., (2018), the use of an elastomeric knee brace in addition to an exercise-based rehabilitation intervention was compared to exercise therapy alone. While both groups progressively improved for both pain and self-reported function over the course of the rehabilitation period, the group that utilized the brace reported significantly less pain at 6- and 12-months post intervention than the exercise therapy control group. The participants who used the brace also reported returning to sport activity more quickly and a high percent (75%) of these participants reported satisfaction with the intervention utilizing the brace. The authors concluded that the brace may have reduced pain by enhancing proprioceptive input and reducing medial tracking of the patella, which is theorized in the pathomechanical model to contribute to the increase in patellofemoral joint stress (Powers et al., 2017). These findings are consistent with those of a randomized clinical trial by Petersen et al. (2016) who also noted significant improvements in pain as well as self-reported function at 6- and 12-weeks into rehabilitation while utilizing a brace. After 1 year of follow-up, however, the positive effect of the brace was diminished, suggesting that bracing is more effective in the short-term as opposed to the long-term in individuals with PFP.

The effects of a knee brace in addition to an exercise-based intervention were also investigated in a study by Sinclair et al. (2016). Male and female participants (n=20) with PFP completed an exercise-based intervention in addition to the use of a brace for 2 weeks. Pain was assessed using the Knee Injury and Osteoarthritis Outcome Score (KOOS) (Roos & Lohmander, 2003) and 3-D lower extremity kinematics and patellofemoral loading was measured for three functional tasks: jogging, cutting, and a single-leg hop. When compared to baseline measures, significant reductions in peak patellofemoral loading were identified for the jogging and cutting tasks and in peak knee abduction moment for all three functional tasks while wearing the brace. There were also significant improvements in KOOS subscale scores for symptoms, pain, sport, function and daily living, and quality of life. Similar to the papers by Uboldi et al. (2018) and Petersen et al. (2016), the authors concluded that the improvement in scores was due to the brace's influence on the pathomechanics of the patellofemoral joint.

The application of kinesio-tape has also been utilized clinically to manage the symptoms of PFP. Kinesio-tape is theorized to enhance proprioceptive input, realign fascial tissues, and assist in the extradition of edema towards lymph nodes (Kase et al., 2003). Kurt et al. (2016) conducted a single-blind randomized controlled trial to assess the short-term effects of kinesio-tape on joint position sense, muscle strength, kinesiophobia, pain, and function in participants with PFP. Baseline measures were gathered for muscle strength and joint position sense using an isokinetic dynamometer, pain using the VAS (Harrison et al., 1995), kinesiophobia with the Tampa Scale of Kinesiophobia (TSK) (Miller et al., 1991), and self-reported function using the AKPS (Kujala et al., 1993). Participants were randomly assigned to either the kinesio-tape group or a placebo tape group and all measurements were repeated 2 days after tape application. There were no significant differences noted between baseline and post-tape measures for muscle strength. The kinesio-tape group demonstrated significant improvements in joint position sense, pain, and self-reported function and reductions in kinesiophobia after tape application, and these improvements were significantly greater than those of the placebo tape group. The authors attributed the success of the kinesio-tape group to the tape's influence on patellar alignment, once again relying on a pathomechanical model of PFP (Powers et al., 2017).

Another external support option is the use of foot orthoses to correct distal foot mechanics theorized to contribute to the development of PFP, as highlighted in the pathomechanical model (Powers et al., 2017). A prospective cohort study (Barton, Menz, et al., 2011) evaluated the effects of foot orthoses on functional performance, pain, and self-reported function in participants with PFP (n=60). Functional performance was assessed by performance of a single-leg squat, pain was measured using the VAS (Harrison et al., 1995), and self-reported function was quantified using the AKPS (Kujala et al., 1993) and the lower extremity functional scale (LEFS; Binkley et al., 1999) at baseline and after 12 weeks of wearing the foot orthoses. After 12 weeks, there were significant improvements in functional performance, pain, and self-reported function. The improvements in pain and self-reported function appeared to plateau as the intervention continued on. These findings support the use of foot orthoses to improve pain and function in individuals with PFP, however, the effects on self-reported pain and function may diminish over time.

Foot orthoses were provided in conjunction with exercise-based therapy in a prospective randomized clinical trial in 179 participants with PFP (Collins et al., 2008). The participants were randomly assigned to one of four treatment groups: foot orthoses, flat inserts, exercise-based therapy, or foot orthoses plus exercise-based therapy. The participants attended six sessions over the course of six weeks to complete the assigned intervention. Outcome measures for this study included the VAS for pain severity (Harrison et al., 1995) and the AKPS (Kujala et al., 1993) and functional index questionnaire (Chesworth et al., 1989) for self-reported function. The outcome measures were assessed at baseline and at six, 12, and 52 weeks. Foot orthoses were more effective at reducing pain and improving self-reported function than flat inserts in the short term, particularly at 6 weeks. There were no significant differences between the foot orthoses and exercise-based therapy groups or the exercise-based therapy group and the foot orthoses plus exercise-based therapy group. All of the groups experienced clinically meaningful improvements in primary outcomes over the 52 weeks of the study. These findings suggest that foot orthoses are more beneficial than flat inserts for individuals with PFP, and result in similar improvements as exercise-based therapy. The addition of foot orthoses to an exercise-based treatment intervention does not improve outcomes.

While the evidence presented above does provide minimal support for the use of external support in the treatment of PFP, it appears that these treatment approaches alone may work to reduce pain and improve function in the short-term. However, the long-term benefits of external supports are largely unknown, suggesting that while these interventions may help to reduce pain, there is a need to combine these supports with other interventions.

### ***Exercise-based Interventions***

In the 2018 consensus statement on exercise therapy and physical interventions to treat patellofemoral pain from the 5th International Patellofemoral Pain Research Retreat, an expert panel recommended the use of exercise therapy “to reduce pain in the short, medium, and long terms and to improve function in the medium and long terms,” (Collins et al., 2018). This recommendation was based on review of several studies examining the efficacy of exercise-based interventions. Exercise-based interventions typically are aimed at strengthening the musculature of the hip and/or knee. The expert panel also recommended that the evidence supports the use of exercise-based interventions that target both the hip and knee “to reduce pain and improve function in the short, medium, and long term,” and that this approach is preferred over interventions aimed at the knee alone (Collins et al., 2018). The following section will present the evidence regarding the use of exercise-based interventions aimed at strengthening the musculature of the hip and knee.

In a randomized-controlled clinical trial by Ferber et al. (2015), treatment outcomes were compared between participants with PFP who completed a hip and core-focused rehabilitation program and those who completed a rehabilitation program focused on the knee. Pain and self-reported function were assessed weekly using the VAS (Harrison et al., 1995) and AKPS (Kujala et al., 1993), respectively. Isometric muscle strength and core endurance were measured at baseline and at 6-weeks. While pain and function scores improved for both groups over the course of the intervention, the hip and core group experienced an earlier reduction in pain and greater improvements in isometric hip abductor and hip extensor strength than the knee group.

Another publication from the same multicenter randomized controlled trial (Bolgla et al., 2016) compared the hip and core-focused intervention and the knee-focused intervention in a sample of females and males with PFP. VAS (Harrison et al., 1995) scores for pain, AKPS (Kujala et al., 1993) scores for self-reported function, and hip and knee isometric strength were assessed before and after completion of the assigned intervention. VAS scores and AKPS scores were statistically analyzed to determine the change in score needed to group participants as successful outcomes and unsuccessful outcomes. As a whole, pain and self-reported function improved independent of gender or intervention applied. Among those with a successful outcome, improvements were identified for isometrics hip abductor, hip extensor, and knee extensor strength. A trend was identified for males improve their isometric hip external rotation strength (15.4%) more than females (5.0%). Within the unsuccessful outcome group, there were minimal changes in isometric strength reported. The authors concluded that perhaps exercises targeting the hip external rotators may be more beneficial for males than females. In these two studies, the focus of the intervention was on improving strength of the knee and hip, which are factors included in the pathomechanical model (Powers et al., 2017). There were differences noted between genders in the results from the hip/core and knee strengthening interventions.

Şahin, Ayhan, Borman, & Atasoy (2016) conducted a randomized controlled trial to compare an intervention incorporating both hip and knee-focused exercises with an intervention focused on knee-exercises alone. The outcome measures for this study included pain, measured using the VAS (Harrison et al., 1995) and self-reported function, assessed using the AKPS (Kujala et al., 1993). Objective function was assessed based on performance of a hop test, single-leg squat test, and step down, and knee extension, hip flexion, hip abduction, and hip external rotation strength was measured using an isokinetic dynamometer. While both groups reported reductions in pain and improvements in function at 6- and 12-months follow-up, the hip and knee exercise group demonstrated more significant improvements in pain and both self-reported and objective function than the knee exercise group. At the 6-month follow-up, both groups demonstrated improvements in hip abduction and hip external rotation strength, with the hip and knee group experiencing a greater improvement than the knee exercise group. However, when comparing strength in the two groups at 12-months follow-up, there was a slight decrease in strength for both groups, with no differences noted between groups for hip abduction strength. While these findings support the incorporation of hip-focused strengthening exercises in interventions for individuals with PFP, they also suggest that improvements in pain and self-reported function may occur independently of improvements in muscular strength. This also suggests that focusing solely on a biological factor, such as impaired muscle function, may not yield the most optimal patient outcomes in the long-term.

In a paper published by van Linschoten et al. (2009), the authors provide support for the use of a supervised exercise therapy intervention over a usual care approach for individuals with PFP. This randomized controlled trial evaluated the effectiveness of an exercise-based intervention that included exercises to improve strength of the quadriceps, adductor, and gluteal muscles compared to simply resting from painful activities. The outcomes of interest were self-reported recovery, reported using a 7-point Likert scale, pain and rest and with activity, assessed using a numerical rating scale (Downie et al., 1978), and self-reported function based on the AKPS score (Kujala et al., 1993). All outcome measures were collected at baseline, at 3 months, and 12 months post-intervention. At the 3-month follow-up, participants in the exercise therapy group reported greater reductions in pain at rest and with activity and greater improvements in function than the resting group. At 12 months post-intervention, the exercise therapy group continued to report greater reductions in pain with rest and activity than the resting group, but not in regards to function. A higher percentage of participants in the exercise therapy group reported recovery at 3 months (41.9%) and 12 months (62.1%) than the resting group (35.0% and 50.8%, respectively). The participants for the exercise therapy group did report improvements in pain and self-reported function initially, but at 12-months post intervention, the participants in the exercise therapy group did not differ from the resting.

Another targeted outcome for exercise-based interventions for PFP is to improve faulty movement patterns that are theorized to contribute to the increased loading at the patellofemoral joint. Claudon et al. (2012) examined the effect of an exercise-based intervention focused on stretching and strengthening the quadriceps and hamstring muscle groups. The AKPS (Kujala et al., 1993) was used to assess self-reported symptoms and pain. During baseline assessment of walking kinetics, a reduction in knee extension moment and increase in trunk forward bending was identified in participants with PFP compared to healthy controls. This movement strategy is hypothesized to be a compensation to reduce patellofemoral reaction force and pain. Of the 21 participants who completed the intervention and reported for the post-intervention testing, 17 reported a significant reduction in pain. Knee extension moment was increased in participants post-intervention and was believed to be a result from the reduction in pain.

Earl-Boehm & Hoch (2011) assessed changes in hip strength, core endurance, biomechanics of the lower extremity, and patient reported outcomes following an exercise-based intervention. Females with PFP (n=19) completed an 8-week exercise-based rehabilitation intervention aimed at strengthening the hip and core and improving dynamic malalignment. Pain severity was assessed using the VAS (Harrison et al., 1995) and self-reported function was measured using the AKPS (Kujala et al., 1993) at baseline and post-intervention. Isometric hip strength, core endurance, and 3-D kinematic and kinetic analysis of running gait were also conducted at baseline and post-intervention. Following the intervention, significant improvements were observed for pain severity, self-reported function, lateral core endurance, isometric hip abduction and hip external rotation strength. In addition, there was a significant reduction in knee abduction moment during the stance phase of running observed post-intervention. These findings demonstrate improvements in both muscular strength and biomechanics following the implementation of an exercise-based intervention in females with PFP.

Pairot de Fontenay et al. (2018) conducted a cross sectional longitudinal study to determine if an exercise-based rehabilitation program was effective at improving hip kinematics, pain, and self-reported function in a sample of females (n=16) with PFP. Pain and self-reported function were quantified using the KOS-ADLS (Roos & Lohmander, 2003), and hip kinematics were measured during performance of a step-down task and a vertical drop jump task. Following the 8-week intervention progression, the participants reported significant improvements in KOS-ADLS scores, with 12 of the 16 reporting a clinically significant improvement in pain and self-reported function. Post-intervention there was a trend for a decrease in peak hip internal rotation and a significant decrease in hip adduction and hip internal rotation variability during performance of the step-down task. The improvement in self-reported function was not significantly correlated with the changes in hip kinematics. Similarly, the significant improvement in hip internal rotation variability during a drop vertical jump task was also not correlated with the change in pain or self-reported function. These findings suggest that a rehabilitation program may influence hip kinematics and pain and self-reported function, but that these changes may occur independent of one another.

There are other strategies that may be utilized in conjunction with exercise therapy to enhance outcomes for individuals with PFP. In a double-blinded randomized clinical controlled pilot trial, Yip & Ng (2006) examined the efficacy of EMG biofeedback supplementation to exercise-based therapy in the treatment of PFP. Participants (n=26) were randomly assigned to either the EMG and exercise group or the exercise-only group. The exercise-based intervention for both groups was 8-weeks long, during which the EMG and exercise group received visual EMG feedback of the quadriceps muscle activity during the exercises. Isokinetic strength of the knee extensors, patellar alignment, and pain severity was assessed at baseline, 4-weeks, and 8-

weeks. Both groups demonstrated improvements in knee extension peak torque, work output, and patellar alignment, and there was a trend of pain reduction as well. The EMG and exercise group demonstrated faster improvements in lateral patellar rotation and peak torque per body weight than the exercise-only group, however these differences were not statistically significant. These findings suggest that the addition of biofeedback in this situation did not produce significant changes in participant outcomes. This may be in part due to the specificity of the biofeedback to address quadriceps muscle activity.

While the evidence provides strong support that exercise therapy is the preferred treatment approach in regards to rehabilitation outcomes in individuals with PFP, there are several emerging treatment approaches that could enhance recovery for individuals with PFP. One of the more recent approaches is movement retraining which, when used in conjunction with exercise therapy, is showing promising results and clinical outcomes.

### ***Movement Retraining***

In an attempt to correct dynamic malalignment during functional weight-bearing tasks in individuals with PFP, interventions have been introduced to improve movement patterns during tasks such as walking, running, and step-downs. These interventions rely on specific strategies aimed at neuromuscular re-education of a specific movement to elicit motor learning and improve movement patterns, thereby improving patient recovery and outcomes. The following section will provide a synthesis of the research regarding movement retraining interventions specific to dynamic malalignment commonly observed in individuals with PFP.

Roper et al. (2016) conducted a randomized trial to determine whether a gait retraining intervention aimed at modifying foot strike patterns during running was effective at reducing pain and select biomechanical factors theorized to contribute to the development of PFP in runners. The participants (n=16) were randomly assigned to either the experimental or control group. Prior to beginning the intervention, baseline measures were collected, including a 3-D kinematic analysis of running gait and completion of the VAS (Harrison et al., 1995) for pain severity. These measures were repeated upon completion of the 2-week intervention, and at one-month post-treatment. The experimental group reported significantly reduced pain at the conclusion of the intervention and at the one-month follow-up as compared to the control group. The intervention also resulted in significant improvements in knee abduction and in ankle range of motion, specifically ankle flexion immediately following the intervention and at the one-month follow-up. These findings provide support for the use of gait retraining in runners to improve biomechanics as well as improving the participant's pain.

Willy et al. (2012) also investigated the effects of mirror gait retraining on pain, function, and hip kinematics and kinetics in female runners (n=10) with PFP. The participants completed 8 sessions consisting of mirror and verbal feedback aimed at correcting lower extremity alignment while running on a treadmill. Prior to beginning the intervention, the participants completed the VAS (Harrison et al., 1995) to measure pain severity and the LEFS (Binkley et al., 1999) to assess self-reported function. Three-dimensional kinematics and kinetics were gathered during running, single leg squats, and step descent. Participants who exhibited altered hip biomechanics (peak hip adduction greater than the one standard deviation above the laboratory's normative mean) while running were invited to participate in the gait retraining phase of the study. The gait retraining intervention was performed as eight sessions over the span of two weeks. The participants ran on a treadmill in front of a full-length mirror, and were provided scripted verbal cueing at the beginning of each session. As the intervention progressed, the running time was gradually increased and both the verbal cues and visual feedback were gradually removed during the final four training sessions. All baseline measures (kinematics, kinetics, VAS, and LEFS) were repeated post-intervention and at 1-month and 3-months post-intervention. Following completion of the intervention, the participants exhibited reduced peaks of hip adduction, contralateral pelvic drop, and hip abduction moment while running as compared to the baseline. These improvements in dynamic malalignment were also noted in during a single-leg squat and step-down when compared to baseline measures, suggesting skill transfer indicative of a higher level of motor learning. These improvements were maintained at both the 1-month and 3-month follow-up sessions as well, despite the participants no longer receiving any form of feedback. The participants also reported improvements in pain and function that persisted to the 3-month follow-up.

Noehren, Scholz, & Davis (2011) found similar results in their study using real-time kinematics feedback during treadmill running in a sample of ten runners with PFP. Baseline 3-D kinematic and kinetic analysis of running gait and single-leg squat performance was performed. The VAS (Harrison et al., 1995) and LEFS (Binkley et al., 1999) were completed to assess pain severity and self-reported function, respectively. Those participants who exhibited altered hip biomechanics as outlined in the study by Roper et al. (2016) were invited to complete the intervention. The intervention followed the same progression and gradual reduction in feedback as the study above (Roper et al., 2016). All baseline measures were repeated upon completion of the intervention and at one-month post-intervention. Following the gait retraining, significant reductions in hip adduction and contralateral pelvic drop were observed during running. Hip internal rotation decreased by 23% during running and hip adduction decreased by 18% during a single-leg squat following the intervention. Another key finding of this study was an 18% and

20% reduction in instantaneous and average vertical load rates, respectively. The participants also reported significant improvements in pain and self-reported function that were maintained at the one-month follow-up. Both of these studies provide support for the use of gait retraining as an effective intervention for improving hip biomechanics, pain, and self-reported function in the short-term for runners with PFP.

While these findings demonstrate the effects that a gait retraining intervention alone may have on recovery and outcomes associated with PFP, most clinicians will utilize other treatment approaches along with movement retraining to treat their patients. In a block randomized controlled trial by Willy & Davis (2011), 20 females with excessive hip adduction observed during a running gait analysis were randomly assigned to either the treatment group or the control group. The treatment group completed a 6-week intervention that included both hip strengthening exercises as well as a movement re-education program utilizing mirror and verbal feedback regarding proper mechanics during a single-leg squat. The control group did not complete an intervention and were instructed to maintain their current running distance. Isometric hip abduction and hip external rotation strength and 3-D kinematics and kinetics during running and a single-leg squat were assessed both before and after the intervention for both groups. The treatment group demonstrated significant increases in hip abduction and hip external rotation strength following the intervention, but no significant differences were noted in hip and knee kinematics during running. The treatment group did exhibit significant decreases in hip adduction, hip internal rotation, and contralateral pelvic drop during the single-leg squat. The control group did not display changes in hip strength or in running or single-leg squat kinematics at the end of the 6-weeks. Contrary to the findings of Roper et al. (2016), neuromuscular re-education and verbal feedback aimed at improving running gait did not lead to significant improvements in running biomechanics in this study. This study did not assess the participant's pain severity or self-reported function at baseline or post-intervention.

Esculier et al. (2018) conducted a single-blind randomized clinical trial to compare the effectiveness of three 8-week rehabilitation programs on symptoms and self-reported function in runners with PFP. The participants (n=69) were randomly assigned to one of the three following groups: 1.) an education-focused group, which received patient education on symptom management and training modifications; 2.) an exercise-focused group, which completed traditional strengthening exercises in addition to the education provided to the education-focused group; and 3.) a gait-retraining group that underwent gait retraining in addition to the patient education. The KOS-ADLS (Roos & Lohmander, 2003) was used to quantify self-reported symptoms and functional limitations and the VAS (Harrison et al., 1995) was used to assess pain at baseline and at 4, 8, and 20 weeks.  Isometric strength and kinematics and kinetics of the lower extremity during running were assessed at baseline and at 8 weeks. All three groups reported similar improvements in KOS-ADLS and VAS scores at 4-, 8- and 20-weeks compared to baseline measures. The exercise-focused group had increased knee extension strength following the intervention and the gait retraining group increased the step rate and decreased the average vertical loading rate following the intervention. Similar to the findings of Willy & Davis (2011), the resulting changes in movement strategies were specific to the neuromuscular re-education program and movement utilized. These findings highlight not only the importance of specificity when designing a movement retraining intervention, but also suggest the importance of patient education as part of an effective treatment approach for management of symptoms in individuals with PFP.

The findings from these studies support the use of gait retraining as an effective treatment approach to enhance outcomes for individuals with PFP. However, not all individuals with PFP are runners, and there is limited evidence existing regarding the use of movement retraining interventions focused on a more universal task that more closely mirrors an activity or motion encountered in daily life, such as a step down. The only study to examine movement retraining outside of running with individuals with PFP is a prospective, non-randomized, within-group, double baseline, and feasibility intervention study by Salsich et al. (2018). The purpose of this study was to determine whether a novel, task-specific retraining intervention focused on correcting pain-producing movement patterns would improve hip and knee kinematics, pain, and self-reported function in females with PFP who exhibited observable dynamic malalignment during a single-leg squat. Prior to completing the intervention, baseline measures were gathered for the participants (n=25). Three-dimensional kinematics and 2-D video analysis was conducted to quantify movement quality during a single-leg squat, stair ascent and descent, sit to stand, and stand to sit tasks. The kinematic variables of interest included hip adduction, hip internal rotation, and knee external rotation angles at the point of peak knee flexion. In addition, pain was measured using the VAS (Harrison et al., 1995) and self-reported function was assessed using the Patient-specific Functional Scale (PFS; Stratford et al., 1995). The participants then completed a 6-week intervention that consisted of supervised repetitive practice of four common pain-provoking activities: single-leg squats, double-leg squats, standing up and sitting down from a chair, and navigating stairs. The participants received individualized verbal, visual, and tactile feedback during the performance of each of the activities. There was an improvement following the intervention for hip adduction, hip internal rotation, and knee external rotation during the single-leg squat. In addition, the participants reported improvements in pain and self-reported function following the intervention. The participants also completed the Credibility-Expectancy questionnaire (Devilly & Borkovec, 2000) to determine their value of the intervention, and they reported viewing the intervention as “credible”. These findings lend support for movement retraining for a novel task to enhance outcomes for a wider range of individuals with PFP, however more research is warranted to examine this approach in a larger sample, and to determine if muscular strength could also be improved using this intervention.

### ***Prognosis & Outcomes***

While the short-term prognosis following the commonly utilized treatment interventions is generally favorable, the long-term outcomes are moderately effective at best. One study followed up with participants following 6 weeks of supervised exercise therapy and 3 months of self-monitored home exercises and identified that 41.9% of participants had reported recovery at 3 months and 62.1% at 12 months (van Linschoten et al., 2009). While these percentages were higher compared to the control group who simply rested and avoided painful activities, these values still indicate that less than 75% of individuals with PFP will feel that they have fully recovered in the long term. Additional studies have reported that four years after being diagnosed with PFP, 91-96% of patients reported continued pain or dysfunction (Price et al., 2000; Stathopulu & Baildum, 2003).

Several characteristics have been reported to contribute to the prognosis for patients with PFP, including longer duration of symptoms, increased age, gender, decreased function, bilateral pain, and greater differences in side-to-side knee extension strength (Lankhorst et al., 2015). Given the rising costs of healthcare, there is a need to better treat the symptoms associated with PFP to help patients return back to their regular daily activities and to avoid recurrent pain and dysfunction. Furthermore, the symptoms and pain associated with PFP may have debilitating effects on an individual's daily life. Symptoms may interfere with one's ability to perform activities of daily living, including simple tasks such as navigating stairs. As symptoms persist and become more chronic, they may also interfere with an individual's ability to perform work-related activities as well as physical activity. There are reports that as many as 74% of individuals with PFP report that their symptoms are severe enough to limit or stop their participation in physical activity (Heintjes et al., 2003). Higher self-reported levels of disability along with higher body mass indicies (BMI) have been observed in patients with PFP, providing support of this claim (Jensen et al., 2005). These statistics suggest that persistence of pain and symptoms from PFP can create other significant health concerns for patients if left untreated or mismanaged.

Additionally, a large percentage of individuals with PFP may have persistent or recurrent chronic pain years after being diagnosed with PFP (Stathopulu & Baildam, 2003). One study conducted a long-term follow up with patients diagnosed with PFP and reported that 91% of the respondents still complained of knee pain four to eighteen years after the initial clinical presentation of their symptoms (Stathopulu & Baildam, 2003). Forty-five percent of the respondents indicated that their knee pain affected their ability to perform activities of daily living (ADLs) and 36% reported that they were limited in their ability to participate in physical activity as a result of their pain (Stathopulu & Baildam, 2003). Fifty-four percent of the respondents relied on pain medication to manage their symptoms associated with PFP (Stathopulu & Baildam, 2003). These findings stress the need for additional research to not only better understand the etiology of PFP, but also to establish treatment interventions that will result in a better long-term prognosis.

### *Summary of Treatment Interventions Literature*

Within the PFP rehabilitation literature, several treatment interventions have been presented to address biological factors included in the pathomechanical model (Powers et al., 2017). Braces aimed at improving patellar malalignment and maltracking have been effective in reducing pain and improving self-reported function in individuals with PFP in the short-term (Uboldi et al., 2018) but not in the long term (Petersen et al., 2016). These studies also did not examine patellar position or biomechanics to support the hypothesis that the reduction in pain and improvement in self-function was due to improved patellofemoral joint tracking and position. When combined with exercise therapy, using a brace did lead to improvements in pain and self-reported function, as well as reductions in PFJ loading and peak knee abduction (Sinclair et al., 2016). However, it is unclear whether the reduction in PFJ loading and peak knee abduction was due to the exercises or the addition of the brace to the intervention.

Two other external supports have been researched in the PFP rehabilitation literature – kinesio-tape and foot orthoses. Kinesio-tape has been shown to improve joint position sense, pain and self-reported function, but did not improve muscle strength (Kurt et al., 2016). The use of foot orthoses led to improved functional performance, pain, and self-reported function after 12 weeks, but these improvements did not continue in the long-term (Barton, Menz, et al., 2011) and were not more effective than exercise-therapy based treatment interventions (Collins et al., 2008). These findings suggest that external supports may be beneficial in the short-term for improving pain and self-reported function in individuals with PFP, but should be considered in conjunction with another treatment approach, such as exercise-based therapy, to lead to improved outcomes and prognosis.

Exercise-based therapy is considered the gold standard for rehabilitation for PFP (Collins et al., 2018). Interventions aimed at improving hip and core strength are successful in improving not only strength but also pain and self-reported function for individuals with PFP (Ferber et al., 2015), but these outcomes may differ between males and females (Bolgla et al., 2016). There is also evidence supporting that improvements in pain and self-reported function may occur independent of improvements in muscle strength (Şahin et al., 2016), and that these improvements do not persist in the long-term (van Linschoten et al., 2009). These exercise-based treatment interventions have not been successful in changing biomechanics or dynamic malalignment in individuals with PFP.

Gait retraining is another treatment intervention that has recently gained popularity in the PFP rehabilitation literature. This treatment intervention is successful in improving biomechanics during running and decreasing pain (Roper et al., 2016), and can lead to higher level skill transfer to other tasks, such as single-leg squats and step-downs (Willy et al., 2012). When added to an exercise-based approach aimed at improving muscle strength, improvements in strength were observed, but not in biomechanics (Esculier et al., 2018). It is important, however to note that not all individuals with PFP are runners, and therefore it may be beneficial conduct movement retraining for a more novel task, such as a step-down. To date, only one study (Salsich et al., 2018) has used movement retraining for novel, every-day tasks and reported improvements in biomechanics, pain, and self-reported function. Further research is warranted to explore how movement retraining may be used to lead to improvements not only in pain, self-reported function, and biomechanics, but also muscle strength.

### *Knowledge Gap*

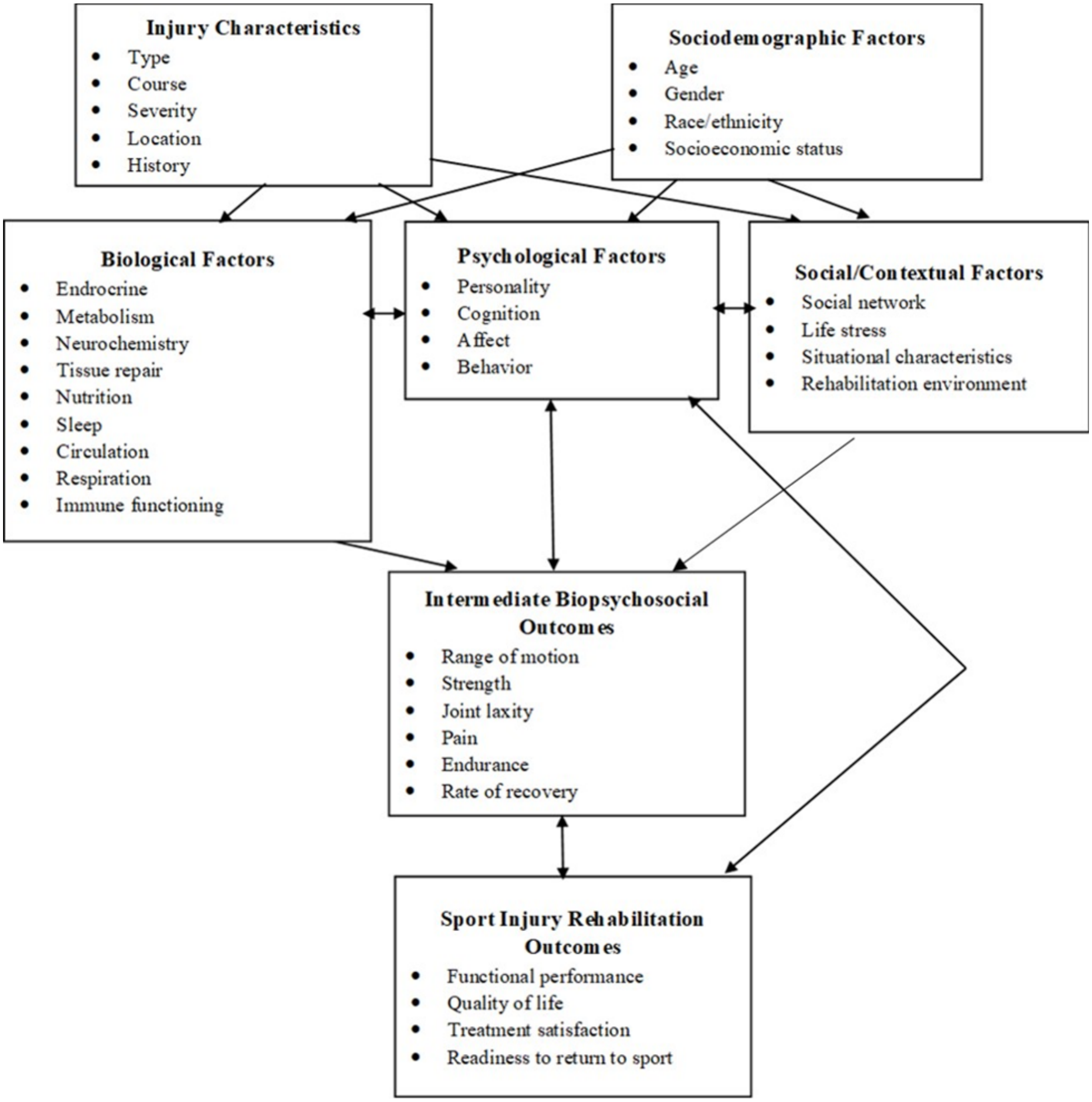
While the pathomechanical model clearly illustrates the interaction of the various risk factors and PFP, there are several areas where the findings are inconclusive or inconsistent. This model assumes that PFP is solely a product of a biological etiology. While the pathomechanical model hypothesizes the interrelationships among biological factors implicated in the etiology of PFP, treatment interventions that focus solely on addressing these biological factors often fail to result in favorable outcomes, particularly in the long-term. These findings suggest that other factors, such as psychological and social factors, may influence recovery from PFP. There is a gap in our knowledge of the interactions among the pathomechanical factors and psychological and social factors. Therefore, the use of a Biopsychosocial Model as a framework to examine PFP may be more appropriate to understand interrelationships between the multitude of factors contributing to the rehabilitation and recovery process. The next section will present the Biopsychosocial Model of Sport Injury Rehabilitation (Brewer et al., 2002), followed by a review of the existing literature to support the application of this model to the rehabilitation in PFP.

## The Biopsychosocial Model of Sport Injury Rehabilitation

Conceptual frameworks such as the Biopsychosocial Model of Sport Injury Rehabilitation provide a means of recognizing the myriad of factors that interact during rehabilitation and return to activity (Brewer et al., 2002; Podlog & Eklund, 2007). The Biopsychosocial Model of Sport Injury Rehabilitation (Figure 2) is a conceptual framework aimed to broaden the current scope of sport injury rehabilitation in the literature and to enrich understanding of the general relationships among biological, psychological, and social/contextual factors that may influence injury rehabilitation outcomes (Brewer et al., 2002; Podlog & Eklund, 2007).

**Figure 2**

*The Biopsychosocial Model of Sport Injury Rehabilitation (Brewer et al., 2002)*



Source: Reproduced from Brewer, B.W., Andersen, M.B., & Van Raalte, J.L. (2002). Psychological Aspects of Sport Injury Rehabilitation: Toward a Biopsychosocial Approach. In D.L. Mostofsky & L.D. Zaichkowsky (Eds.), *Medical and Psychological Aspects of Sport and Exercise* (pp. 41-54). Morgantown, WV, USA: Fitness Information Technology, Inc.

This model consists of seven dimensions: biological factors, psychological factors, social and contextual factors, injury characteristics, sociodemographic factors, intermediate biopsychosocial outcomes, and sport injury rehabilitation outcomes (Brewer et al., 2002; Santi & Pietrantoni, 2013). The model has been applied to the rehabilitation of several musculoskeletal injuries, including non-specific chronic low back pain (Saragiotto et al., 2016), anterior cruciate ligament (ACL) (Ardern et al., 2016), and ankle injury rehabilitation (Arvinen-Barrow et al., 2019).

At the core of the Biopsychosocial Model of Sport Injury Rehabilitation are biological, psychological, and social and contextual factors. Biological factors refer to processes and function of bodily systems affected by the physical damage resulting from injury, such as metabolic processes or neurochemistry changes (Brewer et al., 2002). Psychological factors include individual differences in personality as well as the cognitive, emotional, and behavioral variables associated with sport injury rehabilitation (Brewer et al., 2002). This model also includes the social and contextual factors of the rehabilitation environment, which recognizes that rehabilitation can be influenced by the context of the environment in which the rehabilitation occurs (Brewer et al., 2002). Psychological factors are positioned in the center of these three categories and are theorized to have reciprocal relationships with both biological factors and social and contextual factors (Brewer, 2010).

The biological, psychological, and social contextual factors are conceptualized to be influenced by injury characteristics and sociodemographic factors (Brewer, 2010). Characteristics of the injury may include the type of injury sustained, cause of injury, severity, location, and history of the current injury or past injuries (Brewer et al., 2002).

Sociodemographic factors provide the personal background against which sport injury rehabilitation takes place (Brewer et al., 2002). Factors such as age, gender, ethnicity, and socioeconomic status all fit within the sociodemographic factors (Brewer et al., 2002). For instance, the gender of an injured athlete could influence the rehabilitation process by the interaction of hormonal influences (biological factor), emotional reactions (psychological factor), and societal expectations based on gender (social and contextual factor) (Brewer et al., 2002).

The psychological factors are also proposed to have a bidirectional relationship with intermediate biopsychosocial outcomes and sport injury rehabilitation outcomes (Brewer et al., 2002). Intermediate biopsychosocial outcomes are also said to affect the overall sport injury rehabilitation outcomes (Brewer et al., 2002). These intermediate biopsychosocial outcomes include flexibility, muscular strength, endurance, joint laxity, pain, and rate of recovery (Brewer et al., 2002). Sport injury rehabilitation outcomes refer to the end point of the rehabilitation process and include measures of functional performance, quality of life, treatment satisfaction, and readiness to return to sport (Brewer et al., 2002). Biological and social and contextual factors are thought to influence intermediate biopsychosocial outcomes (Brewer et al., 2002). A bidirectional interaction between the intermediate biopsychosocial outcomes and sport injury rehabilitation outcomes illustrates the influence that each of these categories has on one another (Brewer et al., 2002).

Although the Biopsychosocial Model (Brewer et al., 2002) provides an excellent framework to conceptualize range of injury factors together, only a limited, explicit application of the model to musculoskeletal injury rehabilitation research exists. What follows is a brief review of existing literature as it relates to applicability of the biopsychosocial approach to chronic injury (i.e. non-specific chronic low back pain) and another knee injury (albeit acute, i.e., anterior cruciate ligament, ACL). The review will also demonstrate the explicit usefulness of the biopsychosocial model as a framework for musculoskeletal injury rehabilitation, by presenting existing evidence in support of such approach for lateral ankle sprain rehabilitation.

### ***Biopsychosocial Approach to Chronic Low Back Pain***

Chronic low back pain (LBP) is arguably one of the most studied conditions from a biopsychosocial perspective. Traditionally, the typical way to treat patients with chronic LBP was bed rest, based on the premise that spinal pain was an indication of an irritated structure that would only be exacerbated by movement or physical activity. This view was challenged by clinicians and researchers alike, and based on mounting evidence concluding bed rest resulted in disability in chronic LBP patients; Waddell (1987) proposed a biopsychosocial model as a means of understanding the multifaceted nature of LBP. The model postulates that disability resulting from chronic LBP is a psychosocial phenomenon rather than a medical phenomenon, influenced by the interaction of pain, attitudes and beliefs surrounding the experience of pain, psychological distress, illness behaviors, and the social environment (Waddell, 1987).

The biopsychosocial model (Waddell, 1987) suggests that at the core of one's responses to LBP, is the patient's and society's perceptions and responses to pain (Pincus et al., 2013). When the above perceptions and responses are exaggerated, negative behavioral responses may occur, such as avoidance of physical activities or movements thought to cause pain. Similar to the Brewer et al. (2002) model, the biopsychosocial model proposed by Waddell (1987) assumes a relationship between biological, psychological, and social factors that influence LBP patients' behavior and function. More recently, Waddell & Burton (2004) have also stressed that since LBP has biopsychosocial components, there is a need for chronic LBP rehabilitation to address all three factors in order to enhance patient outcomes.

Thus far, several studies have examined the influence of various biological, psychological, and social factors on the experience of chronic LBP (Adams, 2006; Campbell et al., 2013; Mitchell et al., 2009; George & Beneciuk; 2015). The following papers highlight some of the evidence supporting use of a biopsychosocial approach to underpin and explain responses to the rehabilitation process in chronic LBP.

Anchored in Waddell's (1987) biopsychosocial model of disability, Adams (2006) examined various biological and psychological factors proposed to be related to chronic LBP. When compared to matched controls (n=23), participants with LBP (n=23) had significantly increased EMG activity of the paraspinal muscles and asymmetry than the control group. Of the two neuropeptides collected (substance P and neurokinin A), only substance P was found to be significantly increased in the chronic LBP group compared to the control group. The chronic LBP groups also displayed a significantly higher frequency of psychological distress, such as depression, hypochondriasis, hysteria, and psychasthenia. A correlational analysis failed to find any correlations between biological and psychological factors, however the biological factors (EMG activity and neuropeptide levels) were correlated with one another and the psychological factors (depression, hypochondriasis, hysteria, and psychasthenia) were also correlated with one another. While these results did not support a relationship between biological and psychological factors, this may be due to the inclusion of only specific factors from the biopsychosocial model, and the exclusion of social factors.

In a cross-sectional study, Mitchell et al. (2009) evaluated the contribution of multiple biopsychosocial factors to the experience of chronic LBP in nursing students. Of the 170 female students who participated in this study, 31% were classified as experiencing significant LBP, 48% as mild LBP, and only 21% reported no previous history of LBP. The biological factors examined in this study included body mass index, spinal postures and kinematics during functional tasks, leg and back muscular endurance, spinal repositioning error (proprioception), and cardiorespiratory fitness. Psychological factors were measured and quantified using the Depression Anxiety Stress Scales (Lovibond & Lovibond, 1995) (to assess for depression, anxiety, and stress), the Back Beliefs Questionnaire (Symonds et al., 1996) (to assess beliefs surrounding the impact of low back pain), the General Short Form 19-item Coping Scale for Adults (Frydenberg & Lewis, 2004) (to assess coping strategies) and the Pain Catastrophizing Scale (Sullivan et al., 1995) (to assess catastrophizing). Sociodemographic factors (socio-economic status, marital status, alcohol consumption, and tobacco use) were gathered using a participant questionnaire (Brašnić, 2003) and physical activity level was assessed using the International Physical Activity Questionnaire (Booth, 2000). The students with more significant LBP maintained a more extended posture during performance of a functional bed transfer task than the other two groups. The significant LBP group also was more physically active, had higher stress scores, and were more likely to use passive coping strategies than those in the mild LBP and no LBP groups. Regression analysis revealed that spinal kinematics, stress, coping, physical activity level, and age all contributed to the presence of LBP, accounting for 23% of the variance. These findings further demonstrate the interrelationships between biological factors (i.e., spinal kinematics), psychological factors (i.e., stress), and sociodemographic factors (i.e. age, physical activity level) in the experience of chronic LBP, providing support for the biopsychosocial framework as appropriate for conceptualizing chronic LBP.

An observational cohort study of 1,591 chronic LBP patients in England (Campbell et al., 2013) measured self-reported disability, pain severity, and a range of psychological factors with an aim to better understand the complex interrelationships among the factors. Self-reported disability was assessed using the Roland-Morris Disability Questionnaire (RMDQ) (Roland & Morris, 1983), and pain intensity was measured using a numerical rating scale (Williamson & Hoggart, 2004). The psychological factors measured in this study included depressive and anxiety symptoms (Hospital Anxiety and Depression Scale, HAD; Zigmond & Snaith, 1983), kinesiophobia (TSK; Miller et al., 1991), coping styles (Coping Strategies Questionnaire, CSQ; Frydenberg & Lewis, 2004), pain self-efficacy (Pain Self Efficacy Questionnaire; Nicholas, 2007), and illness perceptions (Illness Perception Questionnaire-Revised; Moss-Morris et al., 2002). Exploratory factor analysis of the all of the psychological measures (including subscores) resulted in four factors, which were defined by the authors as “pain-related distress,” “cognitive coping,” “causal beliefs,” and “perceptions of the future” (Campbell et al., 2013). When examining the relationships of these derived factors to the outcome measures of pain severity and disability, the pain-related distress factor had the strongest association both measures, accounting for 34.6% and 51.1% of the variance in pain severity and disability, respectively. These findings support the relationship between self-reported disability and pain severity and psychological factors, such as pain-related distress.

Fear avoidance beliefs is a psychological factor that has been widely studied relative to chronic LBP in the literature. Saito & Nishida (2015) evaluated the effects of fear avoidance beliefs on chronic LBP in Japanese nurses (n=283). Fear avoidance was measured using the Fear Avoidance Beliefs Questionnaire (FABQ; Waddell, Newton, Henderson, Somerville, & Main, 1993). The participants self-reported the number of times they were required to help patients change their body position and transfer patients. Pain severity was assessed using a numerical rating scale (Williamson & Hoggart, 2004). Regression analysis revealed that fear avoidance beliefs were a significant predictor for perception of pain in this population. This finding provides support for a relationship between fear avoidance beliefs (a psychological factor) in individuals with chronic LBP.

Using an internet-based survey, Fujii et al. (2013) investigated the factors associated with fear avoidance beliefs among Japanese adults (n=52,650) with chronic LBP. The survey asked participants questions regarding selected injury characteristics such as duration of the worst LBP episode, cause of worst LBP experienced, history of radiating pain down the leg, and history of low back surgery. In addition, the participants were asked questions about selected sociodemographic factors, including their exercise routines, smoking habits, marital status, highest education attained, whether they had observed relatives experience chronic LBP, and current work status. The participants were also asked about the medical advice that had been provided to them to help them manage their pain. Finally, the participants completed the FABQ (Waddell et al., 1993) to measure fear avoidance beliefs. After controlling for age, gender, and LBP severity, history of chronic LBP, history of radiating pain down the leg, observation of relatives experiencing chronic LBP, receipt of workers' compensation, and medical advice to rest were all associated with more fear avoidance beliefs. Lower fear avoidance beliefs were associated with regular exercise and attributing chronic LBP to sports participation. These findings support the relationship among selected injury characteristics, sociodemographic factors, and fear avoidance beliefs (a psychological factor) in adults with chronic LBP.

Fear avoidance beliefs are also correlated with self-efficacy (another psychological factor) in individuals with chronic LBP. A cross sectional study (de Moraes Vieira et al., 2014) assessed the coexistence of self-efficacy and fear avoidance beliefs in adults with chronic LBP (n=215). Potential relationships between self-efficacy and selected sociodemographic factors, depression, fatigue, and disability were also explored. Self-efficacy was assessed using the

Chronic Pain Self-Efficacy Scale (Anderson et al., 1995), and fear avoidance was measured using the TSK (Miller et al., 1991). Depression was evaluated using the Beck Depression Inventory (Beck et al., 1961). The Piper Fatigue Scale (Piper et al., 1998) was used to quantify fatigue and the Oswestry Disability Index (Fairbank et al., 1980) was used to determine self-reported disability. High fear avoidance was associated with the male gender, lower income, depression, and level of self-reported disability. Furthermore, the results revealed that reduced self-efficacy and increased fear avoidance are related to an increase in self-reported disability in adults with chronic LBP. These findings support the relationship between select sociodemographic factors (in this case, gender and income) and psychological factors (depression, self-efficacy, and fear avoidance beliefs) on perceived disability in individuals with chronic LBP.

A more recent article (Panhale et al., 2016) assessed fear avoidance beliefs and perceived function in participants (n=30) with chronic LBP to determine if a relationship exists between these two factors. The FABQ (Waddell et al., 1993) was used to assess for fear avoidance beliefs and the participant's perception of function was measured using the Back Performance Scale (Strand et al., 2002). A strong relationship was found between elevated fear avoidance beliefs and perceived function in the participants for this study. The results of this study establish a relationship between fear avoidance beliefs (a psychological factor) and chronic LBP participants' perceptions of function.

George and Beneciuk (2015) conducted a prospective observational study in the US to investigate selected psychological factors predictive of recovery in a cohort of patients receiving physical therapy for LBP. The STarT Back Tool (SBT; Hill et al., 2008) was administered to categorize patients based on their risk for poor disability outcomes following treatment. Pain intensity was measured using numerical pain rating scales and disability was assessed using the RMDQ (Roland & Morris, 1983). The psychological factors studied included fear avoidance beliefs (FABQ; Waddell et al., 1993), pain catastrophizing (PCS; Sullivan et al., 1995), kinesiophobia (TSK; Miller et al., 1991), and depressive symptoms (Patient Health Questionnaire; Kroenke et al., 2001). The participants were assessed using these measures at intake, at 4-weeks after beginning treatment, and at 6 months post-intake. At the 6-month mark, recovery was determined using the NPRS and the RMDQ, with a successful recovery defined as a NPRS score of 0 and RMDQ score of $\leq 2$, indicating a full recovery. Only 12.6% of the 111 participants in this study achieved a full recovery following those guidelines. Not surprisingly, those who did not fully recover reported higher pain severity and disability at intake than those who did recover. When comparing the SBT scores at intake, those individuals who scored as high-risk on the SBT had the lowest recovery rates of the participants in this study. At 6 months post-treatment, those participants who did not fully recover reported higher fear-avoidance, kinesiophobia, and depressive symptoms than those who did recover. The results of this study provide support for the direct influence psychological factors have on the rehabilitation outcomes associated with LBP. In addition, the authors highlight the importance of adopting a biopsychosocial approach to treatment of LBP in order to increase the likelihood of achieving a successful outcome.

The evidence presented above demonstrates how the biopsychosocial framework has supported in the LBP rehabilitation literature. There is support in the literature to conclude that psychological factors, such as pain-related distress, kinesiophobia, and stress can all influence recovery and rehabilitation outcomes for participants with LBP. The paper by Mitchell et al. (2009) lends support for the inclusion of other factors, such as age and physical activity level (sociodemographic factors) in consideration for their influence on recovery and rehabilitation outcomes. These findings all suggest that LBP is most appropriately conceptualized as a biopsychosocial phenomenon, and that treatment interventions that are focused at more than just the pathomechanics of LBP are more effective and lead to improved outcomes for patients.

### ***Biopsychosocial Approach to Anterior Cruciate Ligament Injury***

Although not chronic injury, a knee injury that has received attention in the biopsychosocial literature is the anterior cruciate ligament (ACL) injury. In particular, existing ACL injury research has investigated interrelationships among psychological factors and intermediate biopsychosocial outcomes. Equally, there is evidence in support of using a range of interventions aimed at influencing psychological responses following ACL reconstruction.

One study investigating the range of biopsychosocial factors in ACL injury rehabilitation aimed to understand the relationship between adherence to physical therapy (behavior, a psychological factor) and post-operative physiological outcomes of laxity, functional ability, and self-reported symptoms and function (Brewer et al., 2004). A total of 108 males and females who had undergone ACL reconstruction completed demographic questionnaires prior to beginning their physical therapy. Adherence was measured for home exercises by self-report and by a hidden electronic counter placed in the video cassette of the home rehabilitation exercises that recorded each time the video was played. Clinic-based rehabilitation adherence was recorded as the ratio of sessions attended to sessions scheduled and by the Sport Injury Rehabilitation Adherence Scale (Brewer et al., 2000) completed by the supervising clinician. Regarding physiological outcomes, the Lachman test (Jonsson et al., 1982) was performed to assess laxity, and the one-leg hop test (Daniel et al., 1984) was used to assess functional ability. The Knee Outcomes Survey – Sports Activities Scale (KOS-SAS; Borsa et al., 1998) was used to quantify self-reported symptoms and function prior to surgery and 6 months post-surgery. The authors identified that greater adherence to clinic-based rehabilitation correlated to greater laxity of the knee. There were no significant relationships between adherence and functional ability. Greater adherence to clinic-based rehabilitation was also related to an improvement in symptom and function score on the KOS-SAS. The above results support the biopsychosocial model of sports injury rehabilitation (Brewer et al., 2002) in that adherence to physical therapy (behavior, a psychological factor) was related to intermediate ACL reconstruction biopsychosocial outcomes (laxity) and the sport injury rehabilitation outcomes (functional ability and subjective symptoms).

Another research study investigating the relationship between psychological factors and sport injury rehabilitation outcomes in ACL reconstruction examined fear of re-injury and athlete’s return to pre-injury level (Kvist et al., 2005). Using a retrospective design, Kvist et al. (2005) collected survey responses (n=87) from patients who had underwent ACL rehabilitation 3-4 years prior to the study. The TSK (Miller et al., 1991) was used to quantify fear of re-injury due to movement, and knee-related quality of life was assessed using the KOOS (Roos & Lohmander, 2003). A general questionnaire was used to gather information regarding pain severity using the VAS (Harrison et al., 1995) and return to pre-injury activity level. The statistical analyses revealed a negative correlation between fear of re-injury and knee-related quality of life. The results also revealed a weak negative correlation between fear of re-injury and pain. These findings are similar to those found with patients with chronic LBP, where elevated fear avoidance beliefs were associated with increased pain severity and decreased self-reported function (George & Beneciuk, 2015; Panhale et al., 2016). Alike to the Brewer et al.

(2004) study, these findings are supporting the relationship between psychological factors and sport injury rehabilitation outcomes.

Existing literature also supports the relationships between psychological factors, social and contextual factors, and intermediate rehabilitation outcomes following ACL reconstruction. Maddison et al. (2006) conducted a video modeling intervention with a goal to evaluate its effectiveness on reducing anxiety pre-ACL reconstruction surgery, patient reported expected pain levels post-surgery, crutch use following surgery, and a number of functional outcomes. This video intervention was aimed at modeling successful outcomes of patients who had undergone the same surgery and rehabilitation as the participants. This intervention was specifically targeting participant's cognitive appraisals occurring as part of the rehabilitation process. Seventy-two participants were allocated to either the modeling intervention group or the control group for this study. Anxiety was assessed using the State-Trait Anxiety Inventory (STAI; Spielberger et al., 1970) and all perceptions of pain were assessed by asking the participant to write down a number on a scale ranging from 0 to 100. Three types of self-efficacy (exercise, walking, and crutches) were quantified using a self-report scale from 0% (no confidence) to 100% (complete confidence) for increasing periods of time. The functional outcomes measured included crutch usage (the length of time each participant required the use of crutches for walking), knee assessment consisting of both subjective and objective measures, based on the International Knee Documentation Committee System (IKDC; Hefti et al., 1993) and range of motion for knee flexion and extension. The results revealed no differences in pre-surgery anxiety, experienced post-surgery pain, exercise self-efficacy, walking self-efficacy, or range of motion. However, the intervention group reported significantly lower perceptions of expected pain, higher crutch self-efficacy, and greater improvement in knee function than the control group. Overall, the results provide support for the biopsychosocial model (Brewer et al., 2002) in that the intervention provided (modeling video) had an effect on a range of cognitive appraisals associated with the ACL reconstruction surgery and behaviors post-surgery. The study did not however, support the influence of the intervention on intermediate functional outcomes (range of motion).

As highlighted by the studies described above, support exists within the ACL rehabilitation literature for the application of the biopsychosocial model (Brewer et al., 2002). Psychological factors, such as adherence (a behavior) and fear of re-injury (an affect) can have a direct influence on both intermediate biopsychosocial outcomes and sport injury rehabilitation outcomes (Brewer et al., 2004, Kvist et al., 2005). Furthermore, rehabilitation interventions aimed at influencing psychological factors led to enhanced intermediate biopsychosocial outcomes following ACL reconstruction (Maddison et al., 2006). These findings all support the dynamic relationship that psychological factors have with patient outcomes post-surgery for ACL injuries.

### ***Biopsychosocial Approach to Lateral Ankle Sprain***

To date, there is only one study that has explicitly applied the biopsychosocial model of sport injury rehabilitation to explain connections between biological and psychological factors. Arvinen-Barrow et al. (2019) performed a mixed-methods, single-subject case series design to explore the benefits of the addition to active video games to a rehabilitation program. Two female soccer athletes with lateral ankle sprains completed a 4-week balance training program. One of the participants utilized active video games as part of the balance training, while the other participant completed traditional balance exercises. Both balance training interventions were effective in restoring balance (an intermediate biopsychosocial outcome). The addition of the active video game to the balance training intervention had a positive impact on rehabilitation adherence (behavior, a psychological response), mood (affect, another psychological response). While the addition of the active video game to the balance training intervention was not a psychological intervention, it did have an influence on psychological factors associated with the rehabilitation process.

Additionally, the participant who completed the active video game balance training experienced a setback during her rehabilitation. This setback negatively influenced mood (affect) and perceived readiness to return to sport (cognitive appraisal). Despite this, the participant adhered to the rehabilitation protocol (behavior) suggesting that personal and situational factors may have contributed to this behavioral response. These findings validate the relationship between psychological factors and intermediate biopsychosocial outcomes included in the biopsychosocial model of sport injury rehabilitation (Arvinen-Barrow et al., 2019).

The biopsychosocial model of sport injury rehabilitation could be applied more broadly to other musculoskeletal injuries. In particular, the addition of the active video game to the balance training intervention could be viewed as a modification to the rehabilitation environment, which influenced the psychological factors relative to the rehabilitation process.

### ***Biopsychosocial Approach to Patellofemoral Pain***

In the absence of research explicitly using the biopsychosocial model of sport injury rehabilitation (Brewer et al., 2002) as a framework for PFP research, this section will synthesize the existing evidence on a range of factors associated with the model. In the interest of clarity, these are organized based on the biopsychosocial model components, with possible interrelationships between factors demonstrated as part of the review.

**Biological Factors.** Thus far, much of the PFP research has focused on the biological factors implicated within the etiology of PFP, as described earlier in the pathomechanical model of PFP (Powers et al., 2017). Several of the etiological factors within the pathomechanical model have been supported in the literature, such as decreased PFJ contact area (Besier et al., 2015; Brechter & Powers, 2002a; Brechter & Powers, 2002b; Salsich & Perman, 2013) and increased PFJ reaction forces (Chen & Powers, 2014; Brechter & Powers, 2002b). Other biological factors implicated in PFP and thought to influence PFJ contact area include patellar malalignment and maltracking (Biedert & Gruhl, 1997; Draper et al., 2009; Drew et al., 2016; Witoński & Góraj, 1999), altered tibiofemoral joint kinematics (Bryant et al., 2014; Huberti & Hayes, 1984; Liao et al., 2015), quadriceps weakness (Kaya et al., 2011; Lankhorst et al., 2012; Pappas & Wong-Tom, 2012), excessive internal rotation of the femur (Powers et al., 2003; Souza et al., 2010), and abnormal anatomy of the PFJ (Möller et al., 1986; Pal et al., 2013; Teng et al., 2014).

Several biological factors are presented as contributors to increased PFJ reaction forces, including altered tibiofemoral joint (Herrington, 2014; Nakagawa et al., 2012; Willson & Davis, 2008) and hip kinematics (Hollman et al., 2014; Meira & Brumitt, 2011; Neal et al., 2016), increased navicular drop (Barton et al., 2010; Boling, Padua, Marshall et al., 2009), decreased ankle dorsiflexion (Rabin et al., 2014; Wyndow et al., 2016), muscle tightness (Piva et al., 2005; Whyte et al., 2010), altered tibiofemoral joint kinetics (Aminaka et al., 2011; Paoloni et al., 2010), and altered trunk kinematics (Bazett-Jones et al., 2013; Boling & Padua, 2013). However, the exact mechanisms by which these factors collectively lead to elevated loading of the PFJ, and consequent pain and symptoms remains unclear (Powers et al., 2017).

Currently, treatment approaches for PFP target biological factors, such as improving hip and knee muscle strength and hip and knee biomechanics during dynamic movement. In accordance with the pathomechanical model of PFP (Powers et al., 2017), addressing strength and biomechanics would decrease the PFJ reaction forces and loading, thereby reducing pain and improving function. However, the outcomes resulting from these biologically targeted interventions are less than optimal. There are also several factors that are mentioned in the Biopsychosocial Model of Sport Injury Rehabilitation (Brewer et al., 2002) that have yet to be examined in the context of PFP rehabilitation. For example, it is unknown how factors such as quality and quantity of sleep, nutritional intake, and immune function may influence both psychological factors and intermediate rehabilitation outcomes in individuals with PFP.

### Psychological Factors.

***Perception of Pain.*** Defining the participant's perception of pain is a complex phenomenon that consists of both emotional and sensory components and can be described by location, quality, and intensity of the experience (Sternberg, 2007). Typically characterized by its unpleasantness, pain is an emotional dimension that consists of both pain *sensation* and pain *perception* (Sternberg, 2007). Pain *sensation* refers to the process by which energy contacts the sensory receptors resulting in a change in neural activity that is then transmitted to the central nervous system via afferent neural pathways (Sternberg, 2007). Pain *perception* on the other hand is defined as the 'conscious interpretation of the nociceptive stimulus as pain' (Sternberg, 2007). In other words, pain perception is an individual's interpretation of the sensation of pain and an attempt to attach meaning to the pain, which could influence their emotional and behavioral responses (Peacock & Watson, 2003). Based on previous definitions, for the purposes of this study the perception of pain was operationally defined as, “the individual’s interpretation of pain sensation and attempt to attach meaning to the pain”.

Currently within the PFP literature, pain is commonly studied as pain sensation or nociception resulting from elevated loading of the PFJ. Several studies have suggested that the pain experienced by individuals with PFP is the result of sensitization of peripheral nociceptors (Rathleff et al., 2013; Noehren et al., 2016). If this peripheral input continues for an extended period of time, localized and distal hyperalgesia may occur, leading to reduced pressure pain threshold (Arendt-Nielsen & Graven-Nielsen, 2011). However, it can be argued that nociception, along with other biopsychosocial factors, influences an individual’s perception of pain.

A cross-sectional study by Rathleff et al., 2013 compared pressure pain thresholds (PPTs) between adolescent females with PFP (n=57) and age-matched, healthy control females (n=22). A handheld pressure algometer was used to measure PPTs at three sites around the patella and one site on the patella, as well as the tibialis anterior. The participants were also asked to report duration of symptoms and complete the KOOS (Roos & Lohmander, 2003) to quantify pain intensity and knee-related quality of life. This information was gathered to determine if these variables were related to PPTs. The PFP group had significantly lower PPTs at each of the five sites tested. Multivariate modeling identified that a longer duration of symptoms was significantly associated with higher PPTs at all five sites. KOOS pain intensity and KOOS quality of life scores were not significantly associated with the PPTs, but when these variables were removed from the model, there was a 10% change in the correlation between symptom duration and PPTs. These findings demonstrate that while there is a biological component to pain experienced by individuals with PFP, this perception of pain (cognition, or psychological factor) is influenced by symptom duration (an injury characteristic).

A more recent study (Noehren et al., 2016) reported similar PPT findings in adult females (n=20) with PFP. When compared to age-matched healthy female control participants, the PFP group had significantly lower PPT values at the patella, lateral retinaculum, and elbow. This study also measured threshold to detect light touch using monofilaments on the patella and lateral retinaculum, as well as knee abduction during performance of a single-leg step down. Pain severity was assessed using the numeric pain rating scale. The PFP group had significantly higher thresholds to light touch over the patella, but not at the lateral retinaculum. The PFP group exhibited significantly more knee abduction during performance of the single-leg squat task. Greater knee abduction angle was also related to maximum pain levels reported on the numeric pain rating scale and lower PPT for the lateral retinaculum and patella in the PFP group. In this study, the participant's perception of pain (cognition, psychological factor) was related to knee abduction angle (biological factor), which suggests that a behavioral response occurred to the experience of pain.

The evidence discussed above supports the notion that within the context of PFP, self-reported pain is more appropriately considered a perception of pain. While there is a biological nociception component involved, the perception of pain is related to duration of symptoms (an injury characteristic) and hip and knee biomechanics (both a biological factor and an intermediate biopsychosocial outcome). This is important to acknowledge, especially since many researchers and clinicians alike utilize measures of self-reported pain to quantify nociception in participants with PFP. More appropriately, these measures, such as the VAS (Harrison et al., 1995), should be considered a measure of the participant's perception of pain.

***Perception of Function.*** Based on the literature, for this study we operationally defined perception of function as “a participant’s self-reported subjective symptoms and functional limitations” (Kujala, 1993). A participant’s perception of their function can be influenced by several factors, such as the perception of pain (Maly et al., 2006) and level of exertion during functional tasks (Stratford & Kennedy, 2006). Additionally, there is evidence to support that objective measures of function and participant’s perception of function differ at various points of the recovery process in individuals undergoing a total knee arthroplasty (Mizner et al., 2011). Further research is warranted to examine the factors that may influence the perception of function for individuals with PFP, to determine if injury characteristics and sociodemographic factors may also be related to the perception of function.

Thus far, research investigating PFP patients’ perceptions of pain and function have received attention solely as outcome measures in the literature. However, since these constructs may be influenced by injury characteristics, sociodemographic factors, biological factors, and social and contextual factors, perceived pain and function may be arguably regarded as cognitions (psychological factors). The following section will review other factors associated with PFP that are within the biopsychosocial model (Brewer et al., 2002) and how they are related to perceived pain and function.

***Other Psychological Factors***. Piva et al. (2009) examined the relationship between selected physical factors (muscle strength, soft tissue flexibility, and quality of movement) and psychological factors (perceptions of pain and function, anxiety, and fear-avoidance beliefs) associated with PFP in 74 participants. Isometric hip abduction and external rotation and quadriceps muscle strength and flexibility and length of the hamstrings, quadriceps, plantar flexors, ITB complex, and lateral retinacular structures were assessed using clinical examination techniques. Quality of movement was assessed by scoring the performance of a lateral step-down task, awarding points based on the number of errors observed during performance of the task (Piva et al., 2006). Perception of pain was measured using the numerical pain rating scale (NPRS; Katz & Melzack, 1999), and perception of function was assessed using the Activities of Daily Living Scale of the Knee Outcome Survey (ADLS; Irrgang et al., 1998). The Beck Anxiety Index (Beck et al., 1961) was used to determine the level of anxiety, and the FABQ (Waddell et al., 1993) was administered to measure fear avoidance beliefs. After controlling for age and gender, the results revealed no significant relationships between any of the physical factors (biological factors) and participant perceptions of pain and function (cognitions, or psychological factors). A significant relationship between perception of function (cognition) and psychological variables of anxiety and fear avoidance beliefs (affects, other psychological factors) were found. Fear avoidance beliefs about work and physical activity were associated with perception of pain. The findings of this study provide support for a relationship between cognitions related to pain and function and selected psychological factors, in that participants' perceptions of pain and function in PFP and fear-avoidance beliefs are related. This supports a link between cognitions and affects (both psychological factors) in individuals with PFP.

Domenech et al. (2013) performed a cross-sectional study to determine the relationship between kinesiophobia, catastrophizing, anxiety, depression and participant's perceptions of pain and disability in 97 participants with PFP. Kinesiophobia was measured using the TSK (Miller et al., 1991), and catastrophizing was assessed using the PCS (Sullivan et al., 1995). The HAD subscale (Zigmond & Snaith, 1983) was administered to determine the levels of anxiety and depression. The VAS (Harrison et al., 1995) and Lysholm Scale (Esculier et al., 2013) were used to quantify the participants' perceptions of pain and disability, respectively. The participants reported relatively high levels of kinesiophobia, catastrophizing, anxiety, and depression. Pain and disability were moderately correlated with one another, and catastrophizing also correlated with pain and disability. Levels of kinesiophobia, anxiety, and depression were related to both pain and disability. Regression analysis revealed that catastrophizing and depression accounted for 56% of the variance in disability, while catastrophizing alone explained 37% of the variance in pain. These findings demonstrate the relationships that exist among kinesiophobia, catastrophizing, anxiety, depression (affects, or psychological factors) and participants' perceptions of their pain and disability (cognitions).

In a follow-up to the study above, a longitudinal observational study (Domenech et al., 2014) examined the relationship between changes in psychological variables following treatment and participant perceptions of pain and disability in patients with PFP (n=47). The psychological variables measured in this study were the same as the previous study described above (kinesiophobia, catastrophizing, anxiety, depression) with the addition of pain coping strategies measured using the CSQ (Frydenberg & Lewis, 2004). The VAS (Harrison et al., 1995) was used to quantify the participant's perception of pain, and the Lysholm Scale (Esculier et al., 2013) was used to quantify participants' perceptions of disability. Kinesiophobia, anxiety, and depression, and the pain coping strategy of catastrophizing were all significantly reduced following treatment compared to baseline measures. Additionally, participants who reported decreased levels of kinesiophobia, catastrophizing, anxiety, and depression demonstrated a greater improvement in their perceptions of pain and function post-treatment. Regression analysis identified that changes in catastrophizing predicted improvement in the perception of pain, while changes in both catastrophizing and anxiety predicted changes in the perception of disability following treatment. The results of this study support the relationship between changes in catastrophizing and anxiety (affects, psychological factors) and participant's perception of their pain and function (cognitions) following treatment for PFP.

A cross-sectional study by Maclachlan et al. (2018) examined differences in selected psychological factors between individuals with PFP and healthy controls and the relationship between these factors and the perception of disability in the PFP group. The psychological factors examined in this study included kinesiophobia, catastrophizing, anxiety, and depression. Kinesiophobia was assessed using the TSK (Miller et al., 1991), catastrophizing was measured using the PCS (Sullivan et al., 1995), and anxiety and depression were determined using the HAD Scale (Zigmond & Snaith, 1983). The PFP group completed the KOOS (Roos & Lohmander, 2003) to determine the severity of their condition and perception of disability, allowing for subgrouping of the PFP group according to the severity of their symptoms. There were no significant differences between the control group and the PFP group as a whole in regards to the kinesiophobia, catastrophizing, anxiety, or depression, indicating that the affects were similar among the groups. However, when the PFP group was divided into the subgroups by severity, those participants with more severe symptoms reported significantly higher levels of catastrophizing and depression than the control group. Compared to the less severe symptom group, the more severe symptom group reported significantly higher levels of kinesiophobia, catastrophizing, and depression. Regression analysis revealed that kinesiophobia and depression were related with the perception of disability in the PFP group. These finding highlights the link between symptom severity (injury characteristic) and affects (psychological factors) in individuals with PFP. These results are in concord with the results from Domenech et al. (2013), identifying a relationship between kinesiophobia and the perception of disability in participants with PFP.

A case-control study (Priore et al., 2019) explored differences between women with PFP (n=55) and pain-free women (n=40) in levels of kinesiophobia, pain catastrophizing, and physical function during a forward step-down, single leg hop, and dynamic balance task. Similar to the studies presented above, the TSK (Miller et al., 1991) was used to measure kinesiophobia, and the PCS (Sullivan et al., 1995) was used to assess pain catastrophizing. The PFP group reported significantly higher levels of kinesiophobia and pain catastrophizing and lower objective function  than the control group. No relationship was found between the measures of kinesiophobia and pain catastrophizing and the physical function measures in the PFP group. Contrary to the findings of Piva et al. (2009) and Maclachlan et al. (2018), function in this study was quantified using objective, physical measures rather than self-report measures that measure the perception of function, which may explain the difference in findings between these studies.

**Social and Contextual Factors**. Social and contextual factors refer to the factors that constitute the situational circumstances and the environment in which rehabilitation takes place (Brewer et al., 2002). As demonstrated in the PFP treatment section, research suggests that modifying the rehabilitation environment has related to other components of the biopsychosocial model, namely psychological factors such as perceptions of pain and function, and intermediate rehabilitation outcomes such as hip and knee biomechanics and muscular strength. For example, the addition of an external support may influence psychological factors, such as perceptions of pain and function (Barton, Menz et al., 2011; Kurt et al., 2016; Petersen et al., 2016; Uboldi et al., 2018). Similarly, the addition of gait retraining has been related to both perception of pain (psychological factor) as well as hip and knee biomechanics and muscular strength (intermediate biopsychosocial outcomes) (Roper et al., 2016; Willy et al., 2012). It is currently unknown how other social and contextual factors such as existence of social network, life stresses, or other situational characteristics influence the rehabilitation process for those with PFP.

### **Injury Characteristics**.

***Duration of Symptoms.*** Given that PFP symptoms may persist for years (Collins et al., 2012) it is unsurprising that duration of symptoms in relation to rehabilitation outcomes have received much attention in the literature. A prospective cohort study by Gerbino et al. (2006), the relationship between duration of symptoms (injury characteristic) and the perception of pain (cognition, psychological factor) was explored. Patients from a sports medicine practice in the United States (n=100) with PFP reported their duration of symptoms and their perception of pain using a 0-9 point ordinal scale. Duration of symptoms was inversely correlated with perceived pain. Participants who reported experiencing symptoms for less than seven months reported a median of a 7 out of 10 for pain intensity, compared to those participants who experienced symptoms lasting for more than 24 months, who reported a median pain severity of 4 out of ten. These findings suggest that longer duration of symptoms is associated with lower perceived pain intensity – suggesting that pain is appraised differently over time.

Lankhorst et al. (2015) conducted a secondary exploratory analysis of a randomized controlled trial to identify patient characteristics (including duration of symptoms) that may interact with treatment effects of “usual care” as compared to exercise therapy in 131 patients with PFP. The primary outcomes of interest for this study were self-reported pain using the NRS (Katz & Melzack, 1999) and function using the AKPS (Kujala et al., 1993) at 3 months post-intervention. The patient characteristics examined in this study were limited to gender, age, body mass index, duration of symptoms, and sports participation. While none of these patient characteristics had a significant interaction with treatment for the outcomes of pain or function, there was a positive trend for patients with a longer duration of symptoms to report higher levels of function following exercise therapy than those with a shorter duration of symptoms when compared to usual care. The authors suggested that patients who have experienced symptoms for a longer duration of time may have decreased lower extremity muscular strength than those who have experienced symptoms for a shorter duration of time, which would explain why those individuals responded more favorably to exercise therapy. These findings demonstrate that duration of symptoms (injury characteristic) can influence muscle strength (intermediate biopsychosocial outcome).

Earl-Boehm et al. (2017) performed a secondary analysis of data from a single-blinded randomized clinical trial for 199 participants with PFP to explore potential relationships among perceptions of pain and function, duration of symptoms, selected patient demographics, and isometric hip muscle strength. The VAS (Harrison et al., 1995) and the AKPS (Kujala et al., 1993) were used to measure perceptions of pain and function, respectively. A weak, positive correlation was identified between duration of symptoms and patient weight and body mass index, indicating that patients with symptoms for a longer duration were heavier than those experiencing symptoms of PFP for a shorter period of time. There was also a weak, negative correlation between duration of symptoms and hip abduction, external rotation, and internal rotation strength. This finding is consistent with the results presented by Lankhorst et al. (2015) suggesting that a longer duration of symptoms is associated with muscular weakness in the lower extremity. However, the relationship between duration of symptoms and muscular strength was weak, which supports the idea that there may be other factors, such as psychological factors, that could influence intermediate rehabilitation outcomes such as strength.

Duration of symptoms is related to changes in perception of pain (Gerbino et al., 2006), as well as select sociodemographic factors such as body weight and body mass index (Earl-Boehm et al., 2017). There was also a weak relationship identified between duration of symptoms and hip muscle strength (Earl-Boehm et al., 2017), which may help to explain the finding that those who experience symptoms for a longer period of time are more likely to respond favorably to exercise-based rehabilitation (Lankhorst et al., 2015). However, there is a need to better determine how duration of symptoms influences other factors involved in the rehabilitation process from PFP. The Biopsychosocial Model (Brewer et al., 2002) provides a framework to help underpin how duration of symptoms (an injury characteristic) is related to psychological factors and intermediate biopsychosocial outcomes.

***Painful Locations.*** Painful location(s) is an emergent area of research in PFP. Thus far, only three studies have attempted to better understand the painful locations relative to PFP. Boudreau et al. (2017) conducted a cross-sectional study to explore detailed drawings of pain location patterns in adolescents and young adults (n=35) experiencing PFP for greater than 10 months. Fifty-seven percent of the participants reported pain along the lower peripatellar region of the patella, suggesting involvement of the infrapatellar fat pad and synovium. Duration of symptoms was related to self-reported perception of pain for participants who experienced pain for less than 5 years. In addition, those individuals who experienced pain for 5 years or more reported a greater area of knee pain than those with pain for less than 5 years, suggesting that the longer an individual has PFP, the more likely they are to report diffuse pain in the affected knee(s). Another finding for participants with longer symptom duration was the report of pain in an “O” shape that follows around the peripatellar region of the knee, which differed from the “U” shaped pattern found around the patella in individuals who experienced symptoms for a shorter duration. Seventy-seven percent of the participants in this study reported experiencing bilateral knee pain, and 82% of those with bilateral pain reported symmetrical pain patterns on the left and right knee. The authors attributed this observation to the bilateral exposure of overuse mechanisms, but stated that this may be able to provide further insight into the natural progression of PFP.

Similar findings were reported in Boudreau et al. (2018), where digital knee pain mapping was utilized to explore spatial variation of pain distribution for patients with PFP (n=299). Three pain distribution patterns were identified, resembling an anchor, hook, and an ovate shape around the patella, and the variations in these patterns were independent of sex and age (sociodemographic factors) and pain intensity. Bilateral knee pain as well as symmetrical knee pain was associated with a longer duration of pain, as well as the hook and ovate distribution patterns. This suggests that other adjacent structures to the patella (such as the fat pad and patellar tendon) might be implicated the experience of pain from PFP, as well as the possibility that pain could be driven in part by central neuronal mechanisms (Boudreau et al., 2018). Within the context of the biopsychosocial model of sport injury rehabilitation, this suggests that painful locations are closely related to duration of symptoms, another injury characteristic within the model.

A prospective diagnostic study by Décary et al. (2018) assessed the validity of clustering history elements, including painful locations, and physical examination tests to diagnose PFP. The selected history elements for this study included gender, age, level of education, employment status, comorbidities, affected side, duration of symptoms, location of knee pain, acute or insidious onset, and use of an ambulatory aid. The participants also completed the KOOS (Roos & Lohmander, 2003) to quantify pain, symptoms, function, and knee-related quality of life and the K6 screening scale (Kessler et al., 2010) to assess psychological distress. Using a two-step method, the selected history elements outlined above were combined with physical examination tests used to diagnose PFP to develop diagnostic clusters for both diagnosing PFP as well as ruling the condition out. Patient reports of isolated anterior knee pain in individuals under the age of 40 and isolated or anterior or diffuse pain in those individuals between 40 and 58 years of age was included in the diagnostic cluster to rule in PFP. Patient reports of isolated medial, lateral, or posterior knee pain in individuals under the age of 58 was included in the diagnostic cluster to rule out PFP. These findings support that painful locations are an important injury characteristic to consider when diagnosing an individual with PFP.

Studies by Boudreau et al. (2017), Boudreau et al. (2018) and Décary et al. (2018), have demonstrated that painful locations (an injury characteristic) does have an impact on the patients' perception of pain (cognition, a psychological factor). Equally, Décary et al. (2018) also found differences in how painful locations influence pain perceptions, depending on the patients age (a sociodemographic factor). While these studies inform how painful locations are implicated in the experience of PFP, understanding how painful locations affect the PFP rehabilitation warrants further exploration.

### Sociodemographic Factors.

***Gender***. Driven by the epidemiological information that PFP is more common in women than men, most studies to date have focused primarily on examining PFP in females more so than in males. Previous research has examined differences based on sex or anatomical differences between males and females. In the context of the biopsychosocial model of sport injury rehabilitation, gender as a sociodemographic factor is defined as the gender that each individual self-identifies with, regardless of their anatomical features. However, the previous PFP literature has addressed differences strictly between males and females based on anatomical sex.

Boling et al. (2010) examined the association between genders and prevalence and incidence of PFP in the military cadet population. The participants for this prospective study included 1,529 United States Naval Academy cadets. While gender was not identified as a significant predictor of prevalence, females were 25% more likely to have experienced PFP previously when compared to males. Gender was determined to be a significant predictor for the development of PFP, with females 2.23 times more likely to develop PFP than their male counterparts (Boling et al., 2010). The authors attributed the gender differences to biomechanical and anatomical factors such as altered mechanics during dynamic movements and diminished hip and knee strength. These findings indicate that perhaps there are anatomical and biomechanical differences (biological factors) that exist between males and females which warrant differences in rehabilitation interventions based on gender. The authors also noted that female military recruits may be more likely to report a musculoskeletal injury than males, perhaps due to gender socialization. This finding supports that gender has implications as both a sociodemographic factor that may influence the social and contextual environment surrounding rehabilitation in addition to the biological differences between males and females.

As referenced above, differences in biomechanics and anatomical factors have been identified between healthy males and females. These differences have been hypothesized to contribute to the increased incidence of PFP in females. Boling et al. (2019) conducted a prospective cohort study to examine any potential relationships existing between selected biomechanical factors and the risk of PFP in males and females. The participants (n=4,543) were monitored for the development of PFP during their time in the naval academy, and logistic regression analysis was utilized to determine which risk factors were relevant for each gender. The risk factors identified as significant for females included exhibiting less than 10 degrees of hip abduction at initial contact and greater than 10 degrees of knee internal rotation at 50% of the stance phase of a jump-landing task. This differed from the male participants, where greater than 20 degrees of knee flexion at initial contact and 0-5 degrees of hip external rotation at 50% of the stance phase of the jump-landing task decreased the risk of PFP. These findings do support that gender differences exist in regards to risk factors for developing PFP, and may be important to consider while designing treatment interventions.

In the study previously discussed by Lankhorst et al. (2015), no interaction was noted for gender (sociodemographic factor) and perception of pain (cognition, psychological factor). However, a positive trend was identified for improvements in perceptions of function in females with PFP following exercise therapy. This trend was not observed with the male participants of this study. Gender was not associated with poor prognosis following treatment. The authors cited that biomechanical differences between males and females, as identified in the study by Boling et al. (2019), could explain why females responded more favorably to exercise therapy. This conclusion however fails to acknowledge the role that other psychosocial variables could play in the gender differences seen in individuals with PFP. Further research examining gender as a component of a biopsychosocial framework is warranted to better understand how gender as a sociodemographic factor may influence psychological factors, which in turn can impact intermediate biopsychosocial outcomes.

***Age.*** After review of the literature, there are two studies that examine age as a potential factor to influence outcomes for individuals with PFP. Lack et al., (2014) conducted a systematic review and meta-analysis including 15 cohort studies to identify outcome predictors for commonly used conservative interventions for individuals with PFP, such as foot orthoses and exercise therapy. The authors identified limited evidence to suggest that higher self-reported function, greater forefoot valgus, and greater rearfoot eversion magnitude predict improved outcomes with an intervention utilizing foot orthoses. Exercise therapy intervention success was predicted by shorter symptom duration, lower frequency of pain, younger age, faster vastus medialis oblique reflex response time, negative patellar apprehension, absence of chondromalacia patella, greater total quadriceps cross-sectional area, and reduced eccentric quadriceps peak torque. A trend was identified for older age to predict a successful outcome for interventions that included the use of a foot orthosis (Lack et al., 2014). In the discussion, the authors speculated that that movement patterns may be more ingrained in older individuals, and that younger individuals may have a greater capacity for neuromuscular adaptation and strength gains resulting from exercise therapy (Lack et al., 2014). The results from this meta-analysis demonstrate that age is related to PFP rehabilitation outcomes.

In contrast to these findings, the paper by Lankhorst et al. (2015) discussed earlier reported that age was not a significant predictor for perception of pain or perception of function in their sample of individuals with PFP. While differences in intervention approach may help explain the difference in findings, further research is warranted to determine if age, a sociodemographic factor does play a meaningful role in the recovery for patients with PFP.

**Intermediate Biopsychosocial Outcomes.** Intermediate biopsychosocial outcomes are utilized in the rehabilitation process to assess progress, and may be measures of biological or psychological factors within the Biopsychosocial Model (Brewer et al., 2002).

***Hip Strength***. One of the intermediate biopsychosocial outcomes of primary interest is hip muscle strength, due to the role it has on proximal kinematics in the pathomechanical model of PFP (Powers et al., 2017). The measurement of hip strength (biological factor) can be viewed as an intermediate biopsychosocial outcome within the Biopsychosocial Model (Brewer et al., 2002) because the intended outcome of exercise focused rehabilitation is muscular strengthening. Hip strengthening exercises are commonly included within an exercise therapy intervention for patients with PFP and have been credited with improving function and reducing pain in several studies (Collins et al., 2018; Earl & Hoch, 2011; Ferber et al., 2015). As stated earlier, weakness of the hip musculature has been reported in the literature in individuals with PFP. Independent of assessing hip strength as an outcome following an exercise therapy-based intervention, very little is known about the interrelationships among hip strength and perceived pain and function. The following will summarize what is understood about the interrelationships among hip strength, perception of pain, and perception of function.

The contributions of muscle strength and perception of pain on perception of function in females with PFP (n=21) were explored in an observational study conducted by Long-Rossi & Salsich (2010). The perception of pain during performance of a single-leg squat was assessed using the VAS (Harrison et al., 1995). Isometric strength was measured for gluteus medius, gluteus maximus, and hip external rotators, and the perception of function was assessed using the AKPS (Kujala et al., 1993). The perception of pain and isometric hip external rotation strength were identified as significant predictors of the perception of function in females with PFP. None of the isometric hip strength measures were associated with the perception of pain, suggesting a relationship between hip muscle strength and the perception of function but not with the perception of pain in females with PFP.

Another study (Nakawaga et al., 2011) examined the relationship between eccentric hip and knee strength measures and perception of pain and function in females with PFP. The VAS (Harrison et al., 1995) was used to determine the perception of pain during the last week, and the AKPS (Kujala et al., 1993) was used to measure the perception of function. Strength of the hip abductors and external rotators and the knee extensors was measured eccentrically using an isokinetic dynamometer. Hip external rotation strength was related to the perception of pain, which differs from the findings of the study by Long-Rossi & Salsich (2010). The difference in findings between these two studies could be attributed to differences in the assessment of muscle function. Consistent with the findings of Long-Rossi & Salsich (2010), eccentric hip external rotation strength was associated with the perception of function. These findings support the relationship between hip external rotation strength (intermediate biopsychosocial outcome) and the perception of function (cognition, psychological factor) in females with PFP.

While these findings suggest a relationship between hip strength and perception of function, which is commonly used as an outcome measure for individuals with PFP, it is unknown how injury characteristics, such as duration of symptoms and painful locations, and sociodemographic factors, such as sex and age, may interact with psychological factors to influence intermediate biopsychosocial outcomes such as hip muscle strength.

***Hip and Knee Biomechanics***. In addition to muscular strength, biomechanics of the hip and knee are another commonly reported intermediate biopsychosocial outcome in intervention studies for PFP (Collins et al., 2018). The measurement of the biomechanics of the hip and knee biomechanics (biological factors) can be viewed as an intermediate biopsychosocial outcome with in the Biopsychosocial Model (Brewer et al. 2002) because they are also intended outcomes following rehabilitation. There is some evidence to support that particular hip and knee biomechanics, namely knee abduction, are related to the perception of pain in individuals with PFP (Noehren et al., 2016). The following section will summarize the body of PFP literature regarding hip and knee biomechanics and their relationship with perceptions of pain and function.

Nakagawa et al. (2013) examined the relationship between perception of pain, perception of function, and hip and knee kinematics during a step-down task in both males (n=20) and females (n=20) with PFP. The VAS (Harrison et al., 1995) was used to determine perception of pain, and the AKPS (Kujala et al., 1993) was used to evaluate the perception of function. Three-dimensional analysis of hip and knee kinematics and kinetics was performed during the performance of a step-down task. Greater perceived pain was related to greater peak hip adduction, internal rotation, and knee abduction. Regression analysis identified peak hip internal rotation and hip adduction were significant predictors of the perception of pain, and peak hip adduction was the only predictor of perception of function. These findings support a relationship between perceptions of pain and function (psychological factors) and specific hip and knee biomechanics (an intermediate biopsychosocial outcome).

After review of the existing literature in individuals with PFP, it is evident that the vast majority of studies have focused on the biomechanics of the hip and knee from a predominantly biomedical perspective. There is support that hip and knee biomechanics are related to the perceptions of pain (Noehren et al., 2016) and function (Nakagawa et al., 2013) in individuals with PFP, but future research is warranted to better establish the relationships between perceptions of pain and function (psychological factors) and hip and knee biomechanics (an intermediate biopsychosocial outcome) as illustrated in the Biopsychosocial Model (Brewer et al., 2002).

Within the PFP literature, there is evidence to suggest that perceptions of pain and function (cognitions - psychological factors) are related to injury characteristics (duration of symptoms and painful locations), sociodemographic factors (gender and age), and intermediate biopsychosocial outcomes (hip strength and hip and knee biomechanics). Each of these factors have been primarily studied in isolation of one another. Pain and function, both commonly utilized as outcome measures in the PFP literature, have been related to other psychological factors, or affects, such as kinesiophobia, depression, and fear-avoidance beliefs (Domenech et al., 2013; Maclachlan et al., 2018; Domenech et al., 2014). These findings suggest that measures of pain and function are more appropriately viewed as perceptions of pain and function, considered cognitions or psychological factors within the biopsychosocial model of sport injury rehabilitation. Duration of symptoms (Gerbino et al., 2006; Lankhorst et al.,2015; Earl-Boehm et al., 2017) is an injury characteristic that has been related to psychological factors (perceptions of pain and function) and intermediate biopsychosocial outcomes (hip muscle strength) in individuals with PFP. Another injury characteristic, painful locations, also has evidence to support a relationship with perceptions of pain (psychological factor).

Gender, a sociodemographic factor within the biopsychosocial model of sport injury rehabilitation, may be related cognitions or psychological factors, which in turn relates to intermediate biopsychosocial outcomes for PFP. There is evidence to support that females and males differ in regards to muscle strength and biomechanics (Boling et al., 2010), suggesting perhaps differences in response to treatment interventions according to gender. Another sociodemographic factor presented in the PFP rehabilitation literature is age, with evidence to support that there are differences in intermediate biopsychosocial outcomes following treatment interventions for patients depending on their age (Lack et al., 2014).

In regards to intermediate biopsychosocial outcomes, hip strength and hip and knee biomechanics are two outcome measures that are well-researched in the PFP rehabilitation literature. Hip strength has been related to perceptions of function (Long-Rossi & Salsich, 2010) and pain (Nakagawa et al., 2011), however this relationship differs depending on the method of measuring muscle strength. Hip and knee biomechanics, namely dynamic malalignment, has been associated with perceptions of pain and function (Nakagawa et al., 2013) in individuals with PFP.

The Biopsychosocial Model of Sport Injury Rehabilitation (Brewer et al., 2002) provides a conceptual framework that can illustrate the interrelationships among all of these factors in the context of PFP rehabilitation. This approach may help to better understand the multitude of biopsychosocial factors that interact to influence the outcomes and prognosis following PFP rehabilitation.

### Literature Review Conclusions

Thus far, a vast majority of the research regarding PFP etiology and rehabilitation has focused on participants who are recruited from health care facilities or from closed populations, such as the military or athletic populations. As such, future studies should examine PFP within a sample from the general population to better depict how individuals who may not elect to seek medical attention or are not physically active respond to treatment interventions. The use of survey screening instruments could be utilized to identify those within the general population who have PFP and allow for recruitment for future studies.

This analysis of the existing evidence regarding PFP suggests that the current understanding of the etiology of PFP, largely anchored in the pathomechanical model (Powers et al., 2017) that focuses on PFP as a biological condition is not consistently supported. While the pathomechanical model (Powers et al., 2017) provides a framework to explain the etiology of PFP from a biological perspective, treatment interventions designed to address these factors exclusively have not been consistently successful in producing positive patient outcomes. Research involving other conditions, such as chronic LBP, ACL injury, and lateral ankle sprains has adopted a biopsychosocial framework to underpin the rehabilitation process and has resulted in enhanced patient outcomes and psychological responses. This same approach can be taken when considering the rehabilitation and recovery for PFP, in an attempt understand how not only the biological factors, but also how psychological factors, social and contextual factors, injury characteristics, and sociodemographic factors may collectively influence intermediate biopsychosocial outcomes. The evidence presented in this literature review demonstrates that many of these factors of the model have been examined individually or relative to one other factor, but there has yet to be a study to examine the interrelationships among these factors in PFP anchored in a biopsychosocial model. There is support within the PFP literature to warrant conceptualizing PFP rehabilitation as biopsychosocial in nature, rather than a simply a chronic musculoskeletal condition resulting from increased patellofemoral joint stresses.

To date, self-reported measures for pain and function within the PFP literature are viewed as outcome measures that merely reflect the pain sensation severity experienced by the patient due to biological factors. However, these measures may more accurately be viewed as outcomes that reflect the constructs of perceptions of pain and function, which are cognitions or psychological factors within the Biopsychosocial Model (Brewer et al., 2002). A biopsychosocial framework may also be used to conceptualize treatment interventions. Within a treatment intervention, there are several elements of the intervention that may be modified, resulting in an alteration to the rehabilitation environment. Within the Biopsychosocial Model (Brewer et al., 2002), the rehabilitation environment itself is a type of social and contextual factor. Any alterations to the rehabilitation environment can directly influence psychological factors, such as perceptions of pain and function. Changes in perceptions can in turn influence intermediate biopsychosocial outcomes such as muscle strength and biomechanics and vice versa. Specific to PFP, treatment interventions that incorporate exercise therapy have yielded the most favorable outcomes. The addition of movement retraining, which is an emerging treatment intervention, has produced optimal improvements in both participant perceptions of pain and function and biomechanics. Further evidence is warranted to determine the effectiveness of a movement retraining intervention focused on improving participants' perceptions of pain and function and intermediate biopsychosocial outcomes during an everyday task.

# Chapter Three: Injury Characteristics & Sociodemographic Factors Associated with Perceptions of Pain and Function in Individuals with Patellofemoral Pain

## Introduction

Patellofemoral pain is a chronic musculoskeletal condition resulting in peri- and retro-patellar pain with load-bearing activities, such as navigating stairs, squatting, jumping, and kneeling (Crossley et al., 2016). It is estimated that as high as 40% of visits to healthcare providers for knee pain have been diagnosed as PFP (Witrvouw et al., 2014), however preliminary evidence suggests that up to 37% of individuals with PFP elect not to seek medical attention for their knee pain, indicating that the prevalence of this condition may be much higher (Thorpe et al., 2019).

Traditionally, PFP has been grounded in a pathomechanical model that suggests a combination of faulty lower extremity mechanics during weight bearing and impaired neuromuscular function of the surrounding musculature may alter the position of the patella, leading to nociception (Powers et al., 2017). While there is evidence to support that these factors may contribute to the development of PFP, therapeutic interventions designed to correct mechanics and neuromuscular function are not as effective in the long term in eliminating perceptions of pain and improving function (van Linschoten et al., 2009). Therefore, it is likely that factors other than those in the pathomechanical model may play a role in the etiology and rehabilitation of PFP.

A broader biopsychosocial framework has been adopted to understand other musculoskeletal injuries, such as chronic low back pain (Waddell, 1987) and anterior cruciate ligament (ACL) injuries (Brewer et al., 2002; Brewer et al., 2004). In chronic low back pain, several affects, or psychological factors all relate to rehabilitation outcomes (Saito & Nishida, 2015; Fujii et al., 2013; Panhale et al., 2016, George & Beneciuk, 2015). Within the ACL injury rehabilitation literature, the use of interventions focused on addressing psychological factors (Maddison et al., 2006) have reported favorable outcomes, providing support that rehabilitation should be viewed as biopsychosocial in nature. The Biopsychosocial Model of Sport Injury Rehabilitation (Brewer et al., 2002), consists of a core of biological, psychological, and social and contextual factors (Figure 2). This dynamic core is conceptualized to be influenced by injury characteristics and sociodemographic factors (Brewer et al., 2002). The psychological factors within this model are proposed to have a bidirectional relationship with intermediate biopsychosocial outcomes and sport injury rehabilitation outcomes (Brewer et al., 2002). Intermediate biopsychosocial outcomes are also said to affect the overall sport injury rehabilitation outcomes as well (Brewer et al., 2002).

Researchers and clinicians often assess the self-reported outcomes of pain and function in patients with PFP. The measures for self-reported pain are interpreted as assessments of pain sensation or nociception, the process by which energy contacts the sensory receptors resulting in a change in neural activity that is then transmitted to the central nervous system via afferent neural pathways (Sternberg, 2007). However, the measures commonly used to quantify pain sensation include descriptors including numbers or statements for the participant to attach meaning to the pain sensation they are experiencing at that time. Therefore, it may be more appropriate to view these measures as assessments of the construct "perception of pain", or the individual's interpretation of the pain sensation and an attempt to attach meaning to the pain (Peacock & Watson, 2003). Similarly, self-reported functional assessments, such as the Knee Injury and Osteoarthritis Outcome Score (KOOS; Roos et al., 1998) and Kujala Anterior Knee

Pain Scale (AKPS; Kujala et al., 1993), are assessments of the individual's perception of functional ability. "Perception of function" is an individual's interpretation of the subjective symptoms and functional limitations resulting from their condition (Kujala et al., 1993), influenced by both the perception of pain and the level of exertion during functional tasks (Stratford & Kennedy, 2006). Both the perception of pain and the perception of function may be viewed as cognitions, or psychological factors within the Biopsychological Model (Brewer et al., 2002).

There are several factors described in the Biopsychosocial Model (Brewer et al., 2002) that are found in the body of literature about PFP. Duration of symptoms is one injury characteristic of PFP that is associated with poorer long-term prognosis, as individuals who experienced symptoms for a longer period of time had a poorer outcome (Lankhorst et al., 2015). This is concerning since it appears that as many as 37% of individuals with knee pain lasting over 1 month have not sought medical attention for their knee pain (Thorpe et al., 2019).

Painful locations, or the painful areas around the knee identified by a with PFP patient on a knee pain map, is an emerging topic in PFP research. This approach is used to quantify localized versus widespread pain in this population. Longer duration of symptoms (five years or longer) is associated with more widespread pain than those who have experienced their symptoms for a shorter period of time (Boudreau et al., 2017). Painful locations of the knee and duration of symptoms are injury characteristics that have not yet been studied relative to perceptions of pain and function in this population.

The sociodemographic factors of gender and age are also described in the Biopsychosocial Model (Brewer et al., 2002). Gender is a sociodemographic factor that may have an impact on how an individual perceives their pain and function. For instance, gender could influence the rehabilitation process by the interaction of hormonal influences (biological factor), emotional reactions (psychological factor), and societal expectations based on gender (social and contextual factor) (Brewer et al., 2002) Age is another sociodemographic factor that may impact patient perceptions of pain and function. While there is some evidence to suggest that age could influence which treatment options are more beneficial in reducing pain and increasing function (Lack et al., 2014), there is also evidence to suggest that age is not a significant predictor of perceptions of pain or function in individuals with PFP (Lankhorst et al., 2015).

Currently, the long-term prognosis for PFP is less than optimal, with many individuals experiencing pain and symptoms months or even years after diagnosis (Collins et al., 2018; van Linschoten et al., 2009; Price et al., 2000; Stathopulu & Baildum, 2003). Many of the current treatment interventions focus primarily on changing biological factors (e.g. strength or biomechanics) to improve perception of pain and function. This approach fails to acknowledge the relationship of other biopsychosocial factors, such as injury characteristics and sociodemographic factors, that may be related to perceptions of pain and function in this population.

While researchers have acknowledged that the experience of PFP may be biopsychosocial in nature (Smith et al., 2018), there is yet to be a study to examine PFP using a biopsychosocial model as a framework to explain relationships among factors. The Biopsychosocial Model of Sport Injury Rehabilitation (Brewer et al., 2002) may better explain the interrelationships among perceptions of pain and function (cognitions, or psychological factors), injury characteristics, sociodemographic factors, and intermediate biopsychosocial outcomes that are implicated in PFP rehabilitation.

Therefore, the purpose of this study was to identify relationships between selected injury characteristics (duration of symptoms and painful locations), sociodemographic factors (gender and age), and psychological factors (participant's perceptions of pain and function) in individuals with PFP. We hypothesized that there would be relationships between duration of symptoms, painful locations, gender, age, and participant's perceptions of pain in individuals with PFP.

## Methods

### *Study Design & Protocol*

This study was a cross-sectional design utilizing an online survey developed using Qualtrics software (Qualtrics, Provo, UT, USA).

### *Recruitment & Participants*

While previous studies have utilized recruitment from health care providers or the recommended clinical criteria to identify individuals with PFP to participate in their studies, we wanted to recruit from the general population. Not everyone who experiences knee pain or PFP will seek medical attention, so therefore we opted to utilize a survey specifically designed to identify individuals with PFP from the general community. The Survey instrument for Natural history, Aetiology and Prevalence of Patellofemoral pain Studies (SNAPPS) has been used in previous studies examining the prevalence of PFP within the general population, and can be used to differentiate PFP from other conditions of the knee (Dey et al., 2016).

Participants were recruited using social media invitations, in person at community events, and via email invitation. Consent was assumed if the individual clicked next on the consent page at the start of the survey, in accordance with the University of Wisconsin-Milwaukee's Institutional Review Board's approved protocol for this study. The next several questions determined eligibility for the study, and included age (18-45 years), state or United States territory, and if they experienced knee pain in the last year.

***Measures***

An online version of SNAPPS was utilized, adapted from the original version using Qualtrics software. This questionnaire asked the participant a series of questions regarding their knee pain, which are broken down into four sections. The first section consisted of screening and demographic questions including age. This section included the question, "Have you had pain or problems in the last year around the knee?" to screen for inclusion for the remaining survey questions.

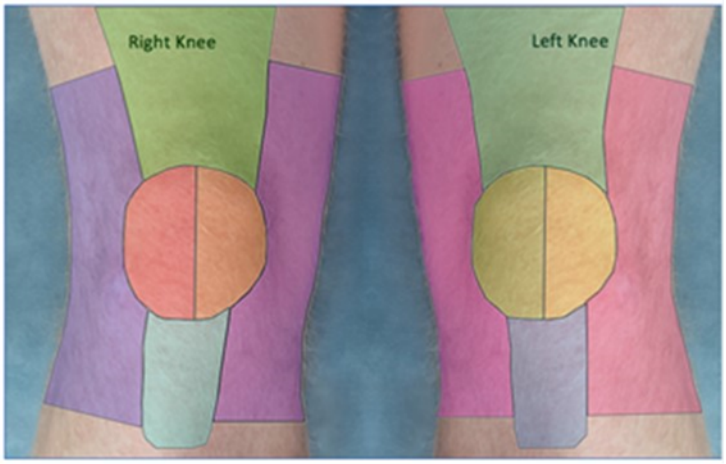
Section two of SNAPPS included questions relative to the clinical features of the participant's knee pain. The questions in this section are aimed at identifying the presence of bilateral pain, previous survey, history of dislocation, swelling of the knee, presence of pain for more than one month, the main complaint for the involved knee(s), and perceived onset of symptoms. This was followed up by a question asking the participant to report (in months) how long their experienced their symptoms. This response was used to quantify the duration of symptoms for each participant.

The third section of SNAPPS asked the participant if they had experienced pain with 14 different activities, including sitting for long periods of time, running, and squatting. This section provides demographic information about the presence of pain with various activities of daily life.

Section four of SNAPPS included a digital picture of a right and left knee and asked the participant to identify the location of their pain by clicking on the image in the corresponding region. Participants could click as many times in as many locations as they desired. This question was developed in Qualtrics using the heat map question option. The knee images were divided into six anatomical regions, which were only visible on the administrator view of the survey. These anatomical regions included the quadriceps tendon, medial knee, lateral knee, medial patella, lateral patella, and patellar tendon for both the right and left knees (Figure 3).

**Figure 3**

*Painful Locations Regions on Knee Pain Map in SNAPPS*



The Multidimensional Sex/Gender Measure (MSGM; Bauer et al., 2017) was used to determine gender identity, which asked the participant to share their assigned sex at birth and to what gender they most closely associate.

The Numerical Pain Rating Scale (NPRS; Katz & Melzack, 1999), was selected as the measure of perception of pain due to its easy adaptability for online use. The NPRS has been reported to have excellent test-retest reliability (Alghadir et al., 2018) and has been validated for online use in participants with chronic pain (Junker et al., 2008). Participants were prompted to rate their perception of their “usual” pain over the past week using the 10-point slider tab provided in Qualtrics. They rated their perception of pain for the involved knee or in the case of bilateral pain, the most painful knee. Previous studies have reported that the measure of “usual” pain over the past 7 days are more stable and reliable than asking for worst pain experienced over the course of one week (Haefeli & Elfering, 2006).

The Anterior Knee Pain Scale (AKPS; Kujala et al., 1993) was utilized to assess the participant’s perception of function. The AKPS asks a series of questions regarding subjective symptoms and functional limitations associated with PFP (Kujala et al., 1993).
Participants were asked to respond to 13 questions regarding the presence of specific symptoms and the impact of those symptoms on activities of daily living. This measure has good test-retest reliability and previous studies have identified that the AKPS is a reliable, valid, and responsive instrument for assessing the perception of function in individuals with PFP (Crossley et al., 2004). The AKPS is typically administered by a clinician or researcher present, who provides verbal instruction to aid the participant in answering the items on the scale. In order to adapt the AKPS for online use, the verbal instruction was included alongside each item on the scale. While the AKPS has not been used previously in an electronic format, there is ample evidence to suggest that the responses from paper patient reported outcome measures are equivalent to those from electronic versions, and provide many advantages over the traditional paper format (Coons et al., 2009).

### ***Procedures***

Once a participant accessed the online survey, they were presented with a consent to participate in online survey research, as approved by the university’s Institutional Review Board. The participant then selected their current state or United States territory of residence from a drop-down menu to ensure that they met the inclusionary criteria regarding geographical location. The participant completed the screening questions included in section one of SNAPPS, as described above. If a participant indicated that they were under the age of 18 or over the age of 45, no additional information was collected. If the participant was between 18-45 years of age they were asked to report their age in years. Similarly, if the participant responded that they have not experienced knee pain or problems in the past year, no additional information was collected. If the participant indicated that they had experienced knee pain or problems in the past year, they completed the rest of SNAPPS.

Upon competition of SNAPPS, which included duration of symptoms (reported in months) and age (reported in years), the participant completed the remaining measures in the following order: MSGM, NPRS, and AKPS. Once the participant completed the survey, their participation in the study was complete.

### ***Data Processing***

The data were reviewed and screened (Microsoft Excel software (Microsoft Corporation, Redmond, WA, USA) to ensure that only the responses from those who met the inclusionary criteria and had completed the entire survey were included in the final analysis.

Responses from Section 2 of SNAPPS consistent with a diagnosis of PFP were scored as a “1” and those that were consistent with another knee pathology were scored as a “0”. Section 4 consisted of a digital image of two knees and the respondent identified the location(s) of their knee pain by clicking on the image. Identification of pain on the medial or lateral patella or the patellar tendon were scored as a “1”. Scores for Section 2 and 4 were totaled together, and a score of “6” or higher classified them as having PFP. A score of 6 or greater is the threshold previous used for differentiating PFP from other knee conditions, with sensitivity and specificity of over 90% (Dey et al., 2016). Only those participants identified as having PFP using the SNAPPS were included in the final statistical analysis for this study.

On the knee pain map in SNAPPS (Figure 3), we counted how many regions in which the patient reported pain, with scores then ranging from 1-6. Heat map visualizations were also generated to provide descriptive information about the frequency of responses on the images sorted by variables of interest. The heat map visualization displays the digital knee image with plots on the image to indicate the number of times participants clicked on that region. The warmer colors (red and orange) represent a higher frequency of responses for that particular area of the image.

Responses to questions from the MSGM were reviewed and coded to classify the gender identity for each participant included in the final analysis (Bauer et al., 2017). Since there were minimal responses for gender identities other than cisgender male and cisgender female, the participants were coded by the gender to which they most closely identified. Scoring for the AKPS was performed using the standard scoring criteria (Kujala et al., 1993). The maximum score possible was 100, with a lower score indicating a lower level of function. Once all of the data were carefully reviewed, the CSV file was imported in SPSS Software (IBM Corporation, Armonk, NY).

### ***Statistical Analysis***

The *a priori* planned statistical analysis had been to perform two separate, stepwise regressions to identify the independent variables (duration of symptoms, painful location(s), gender, age, and perception of pain/perception of function) that best predicted the dependent variables perception of pain and perception of function. The level of significance was set at $p \leq .05$. Multicollinearity of the independent variables included in the final predictive models was to be assessed using variance inflation factors. However, upon checking whether or not the data set met the assumptions for these tests, the assumption of normality was violated for several of the variables and the statistical plan was modified.

The data for each of the dependent and independent variables was tested for normality visually using histogram and Q-Q plots and Shapiro-Wilks tests in SPSS software. The dependent variable of perception of function was left skewed ($W(137) = .917$, $p < .001$), so a reflection and square root transformation was used to transform this data into a normal distribution. Due to the reflection, the interpretation of the values for perception of function changed so that a lower value actually indicates higher function and a higher score indicates lower function. This transformed variable will be referred to as perception of function transformed.

The dependent variable of perception of pain ($W(137) = .971$, $p = .005$), as well as the independent variables duration of symptoms ($W(137) = .606$, $p < .001$) and painful location(s) ($W(137) = .862$, $p < .001$) were right skewed, and were not able to be transformed into a normal distribution. Therefore, these variables were categorized. For the perception of pain values, we calculated the quartiles for the observed values in our sample to create four perception of pain categories, with the descriptive names adapted from a previous study (Boonstra et al., 2016): mild pain, mild/moderate pain, moderate pain, and moderate/severe pain. Duration of symptoms was categorized following those established by Lankhorst et al. (2016), with the addition of a category for the longer durations we had in our sample: 0-2 months, 3-6 months, 6-12 months, 12-36 months, and 36 months and up. Since the intent of examining painful location(s) was to compare differences between those with localized pain and those with more widespread pain, we categorized painful locations into 1 region, 2 regions, and 3-6 regions. The variable gender was dummy coded for entry into the statistical analyses.

A multinomial logistical regression was used to identify the independent variables (duration of symptoms categories, painful location categories, gender code, age, and perception of function transformed) that best predicted the dependent variable of perception of pain categories. All variables were entered in the model and removed stepwise until the model of best fit was identified.

A stepwise regression was used to identify the independent variables (duration of symptoms categories, painful location categories, gender code, age, and perception of pain categories) that best predicted the dependent variable of perception of function transformed. The level of significance for both tests was set at $p \geq .05$.

As a result of the categorization of variables, additional post-hoc analyses were planned to examine differences between categories. Separate one-way ANOVAs identified if significant differences existed between categories of duration of symptoms and painful locations for the dependent variables of perception of pain category and perception of function transformed. Tukey HSD tests were also performed to determine the nature of any significant differences between categories.

## Results

### *Demographic Data*

Out of 400 responses, 243 males and females between the ages of 18-45 who either currently experienced knee pain or had experienced knee pain in the past month completed the entire online survey (61% completion rate). A total of 137 participants scored as likely to have PFP on the SNAPPS and were included in the analysis for this study. Demographic information and means for all variables for the PFP group can be found in Table 1.

**Table 1**

*Demographics of PFP Group Identified Using SNAPPS*

| Variable | **n=137** | **SD** | **%** |
|---|---|---|---|
| Gender | | | |
| Female | n=105 | | 76.6 |
| Male | n=32 | | 23.4 |
| Age (years) | 30.8 | ± 8.7 | |
| Duration of symptoms (months)[b] | 15 | ± 57.0 | |
| 0-2 months | n=26 | | 19.0 |
| 2-6 months | n=28 | | 20.4 |
| 6-12 months | n=11 | | 8.0 |
| 12-36 months | n=26 | | 19.0 |
| 36 months + | n=43 | | 31.4 |
| Painful location(s) (regions)[b] | 2.0 | ± 2.0 | |
| 1 region | n=45 | | 32.8 |
| 2 regions | n=45 | | 32.8 |
| 3-6 regions | n=47 | | 34.3 |
| Perception of pain (0-10)[b] | 3.1 | ± 3.5 | |
| Mild pain (0-1.63) | n=34 | | 24.8 |
| Mild/moderate pain (1.64-3.13) | n=35 | | 25.5 |
| Moderate pain (3.14-5.05) | n=34 | | 24.8 |
| Moderate/severe pain (5.06+) | n=34 | | 24.8 |
| Perception of function (0-100)[b] | 83.5 | ± 14.0 | |
| Perception of function transformed[a] | 4.3 | ± 1.3 | |

*Note:* [a] Transformed score was reflected, so a lower value reflects a higher perception of function. [b] These values were non-normally distributed, therefore central tendency values reported are the median and measure of variability is the interquartile range.

***Perception of Pain***

Table 2 includes the step summary for the variables that were excluded from the multinomial logistic regression model created to predict membership into the four perception of pain categories.

**Table 2**

*Step Summary for Multinomial Logistic Regression*

| | | | | | | **Effect Selection Tests** | | |
|---|---|---|---|---|---|---|---|---|
| **Model** | **Action** | **Effect(s)** | **AIC** | **BIC** | **-2 Log Likelihood** | **Chi-Square** | **df** | **Sig.** |
| Step 0 | Entered | ALL | 361.247 | 413.408 | 325.247 | | | |
| Step 1 | Removed | Age | 355.484 | 398.951 | 325.484 | .237 | 3 | .971 |
| Step 2 | Removed | Duration of symptoms categories | 351.867 | 386.641 | 327.867 | 2.383 | 3 | .497 |
| Step 3 | Removed | Painful location(s) categories | 348.442 | 374.523 | 330.442 | 2.575 | 3 | .462 |
| Step 4 | Removed | Gender | 346.338 | 363.725 | 334.338 | 3.896 | 3 | .273 |

*Note:* Stepwise Method: Backward Stepwise
The chi-square for entry and removal is based on the likelihood ratio test.

The only predictor to significantly predict perception of pain category was perception of function transformed, -2 Log Likelihood = 334.338, $\chi^2$(3 N = 134) = 36.917, p < .001. The Nagelkerke psuedo $R^2$ indicated that the model accounted for approximately 25.7% of the total variance from the predicted mean. Table 3 includes the results of the multinomial logistic regression. Prediction success for the cases used in development of the model was less than optimal, with an overall prediction success rate of 41.8%, and correct prediction rates of 61.8%, 37.1%, 0.0%, and 64.7% for mild pain, mild/moderate pain, moderate pain, and moderate/severe pain groups, respectively.

**Table 3**

*Multinomial Logistic Regression Results*

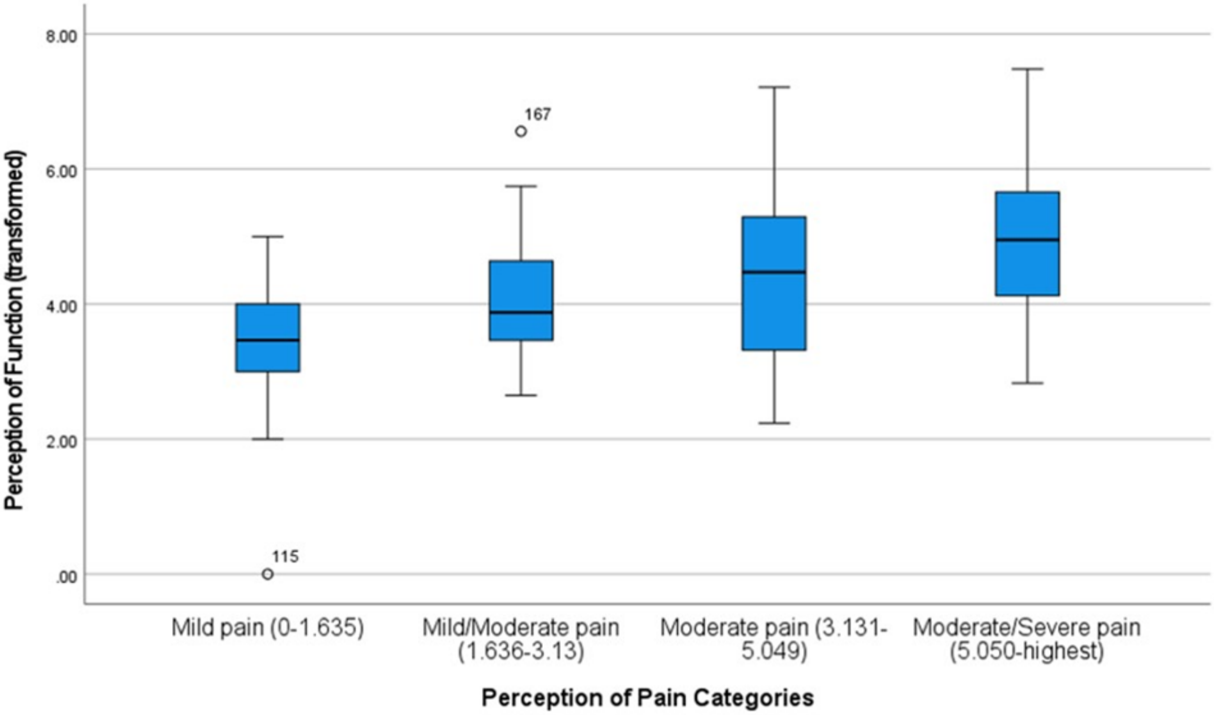
| Variable | *B* | *SE* | *Wald* | *df* | *P* | *Exp(B)* | *95% CI* |
|---|---|---|---|---|---|---|---|
| **Mild/Moderate pain** | | | | | | | |
| Intercept* | -2.663 | 1.051 | 6.426 | 1 | .011 | | |
| Perception of function[a]** | .715 | .272 | 6.905 | 1 | .009 | 2.045 | [1.199-3.487] |
| **Moderate pain** | | | | | | | |
| Intercept** | -4.045 | 1.148 | 12.422 | 1 | <.001 | | |
| Perception of function[a]** | 1.010 | .287 | 12.413 | 1 | <.001 | 2.746 | [1.566-4.818] |
| **Moderate/Severe pain** | | | | | | | |
| Intercept** | -6.208 | 1.268 | 23.982 | 1 | <.001 | | |
| Perception of function[a]** | 1.485 | .301 | 24.314 | 1 | <.001 | 4.416 | [2.447-7.970] |

*Note*: The dependent variable was perception of pain category with Mild pain (0-1.65) as the reference category.
[a] Transformed score was reflected, so a lower transformed value reflects a higher perception of function.
*p < .05, **p < .01.

A one-way ANOVA was performed to explore difference in perception of function transformed values across the four perception of pain categories. A significant difference was identified among the perception of pain categories (F(3,133) = 13.361, p < 0.05). Tukey's HSD was used and identified that the moderate/severe pain group had lower perception of function transformed values (5.0738 ± 1.20270) than the mild pain group (3.4177 ± .96698) and the mild/moderate pain group (4.1139 ± .91818). The moderate pain group did not differ significantly from the moderate/severe pain group (4.4749 ± 1.29273). (Note: the mean perception of function transformed values reported above were reflected, meaning that a lower score actually is representative of higher function). Figure 4 presents a boxplot to illustrate the differences in perception of function transformed across the four perception of pain categories.

**Figure 4**

*Boxplot Comparing Perception of Function (Transformed) by Perception of Pain Categories*



*Note:* This variable was reflected, so a lower value reflects a higher perception of function.

### *Perception of Function*

The independent variables (age, gender, duration of symptoms categories, painful location categories, and perception of pain categories) were used in a stepwise multiple regression analysis to predict perception of function transformed. The correlations of the variables are shown in Table 4.

**Table 4**

*Correlations for Study Variables*

| Variable | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| 1. Perception of function[a] | — | .482** | .313** | .318** | .089 | .160* |
| 2. Perception of pain categories | .482** | — | .160* | .230* | .098 | .073 |
| 3. Duration of symptoms categories | .313** | .160* | — | .174* | .151* | .147* |
| 4. Painful location categories | .318** | .230* | .174* | — | .049 | .040 |
| 5. Gender | .089 | .098 | .151* | .049 | — | -.028 |
| 6. Age | .160* | .073 | .147* | .040 | -.028 | — |

*Note:* [a]Transformed score was reflected, so a lower transformed value reflects a higher perception of function. *p < .05, **p < .01.

The prediction model contained three of the five predictors and was reached in four steps with the variables of age and gender removed. The model was statistically significant, F(3, 134) = 20.533, p < .001 and accounted for approximately 32% of the variance in perception of function transformed values ($R^2 = .322$, Adjusted $R^2 = .306$). Perception of function transformed values were primarily predicted by perception of pain category, shorter duration of symptoms, and fewer painful locations. Table 5 includes the results of the multiple regression.

**Table 5**

*Stepwise Multiple Regression Results for Perception of Function (Transformed)*

| | | | | | | | Change Statistics | | |
|---|---|---|---|---|---|---|---|---|---|
| *Model* | *R* | *$R^2$* | *Adjusted $R^2$* | *SE* | *$\Delta R^2$* | *$\Delta F$* | *df1* | *df2* | *ΔSig. F* |
| 1[a] | .575 | .330 | .304 | 1.03695 | .330 | 12.619 | 5 | 128 | <.001 |
| 2[b] | .574 | .330 | .309 | 1.03305 | .000 | .031 | 1 | 128 | .861 |
| 3[c] | .567 | .322 | .306 | 1.03559 | -.009 | 1.640 | 1 | 129 | .203 |

*Note:* [a]Predictors: (Constant), age, gender, duration of symptoms categories, painful location categories, perception of pain categories.

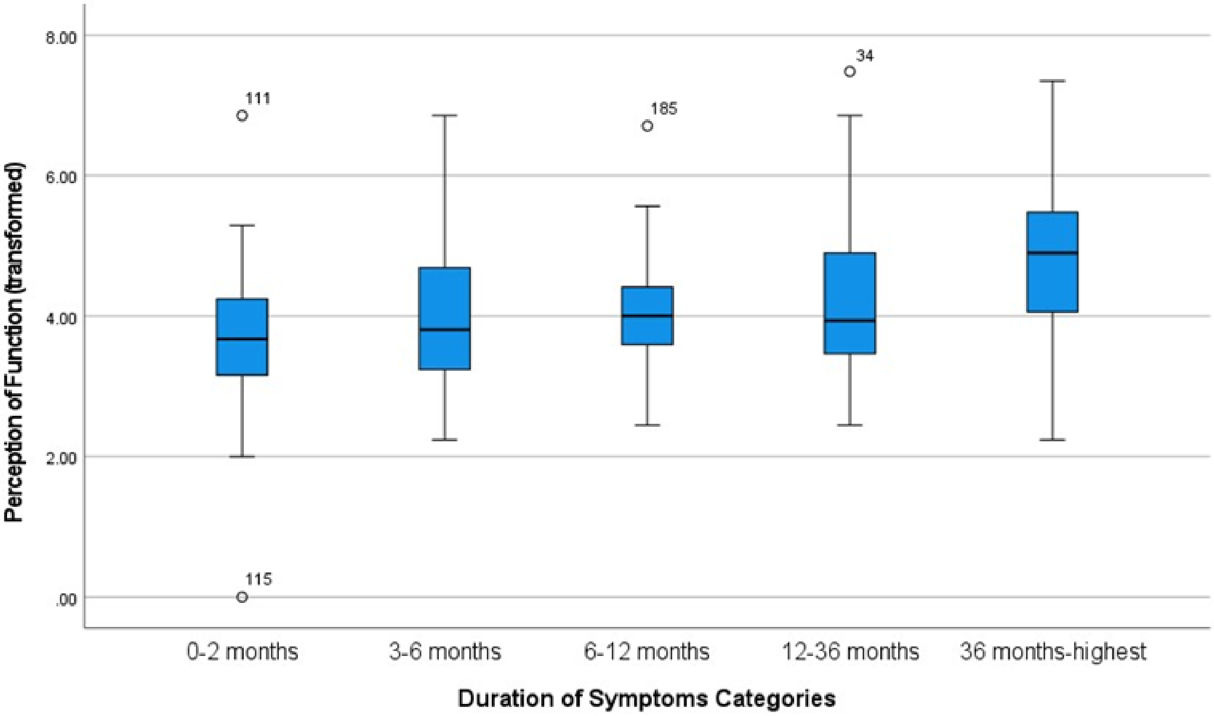
[b]Predictors: (Constant), age, duration of symptoms categories, painful location categories, perception of pain categories.

[c]Predictors: (Constant), duration of symptoms categories, painful location categories, perception of pain categories.

Separate one-way ANOVAs were performed to compare perception of function transformed values across the duration of symptoms categories and the painful location categories. A significant difference was identified among the duration of symptom categories ($F(4,133) = 3.993$, $p < 0.05$) as well as the painful location categories ($F(2,136) = 8.143$, $p < 0.05$). Tukey's HSD was used to determine the nature of the differences in perception of function values across the both the duration of symptoms categories and the painful location categories. Participants who had symptoms for 0-2 months (3.7398 ± 1.25467) and 3-6 months (3.9980 ± 1.11298) had significantly higher perception of function transformed values than participants who had pain for 36 months or longer (4.8165 ± 1.9967). Participants with pain for 6-12 months (4.1150 ± 1.21391) and 12-36 months (4.1885 ± 1.18084) did not have significantly different perception of function transformed values than the other groups. Participants who reported having pain in 1 region (3.8048 ± .84684) and in 2 regions (4.1859 ± 1.29266) of their knee had significantly higher perception of function transformed values than participants who reported having pain in 3-6 regions of their knee (4.7928 ± 1.34623). Figure 5 presents a boxplot to illustrate the differences in perception of function transformed values across the duration of symptoms categories, and Figure 6 illustrates the differences in perception of function transformed values across the painful location categories.

**Figure 5**

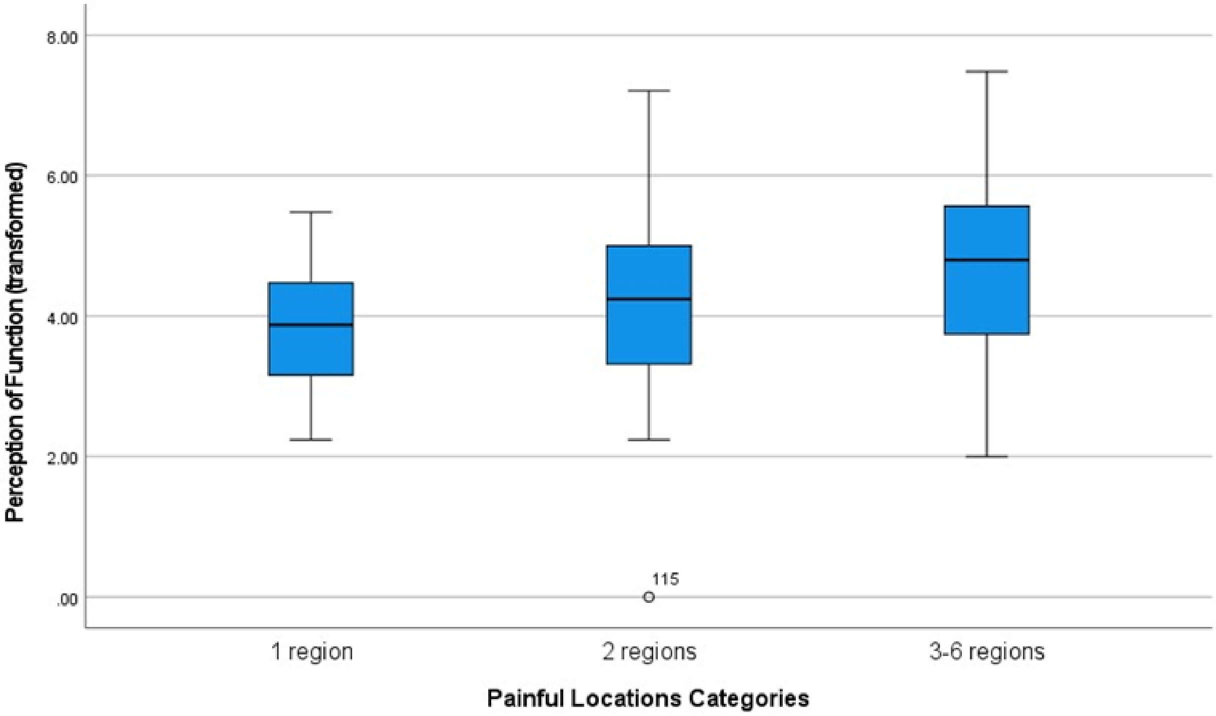
*Boxplot Comparing Perception of Function (Transformed) by Duration of Symptoms Categories*



*Note:* Transformed score was reflected, so a lower value reflects a higher perception of function.

**Figure 6**

*Boxplot Comparing Perception of Function (Transformed) by Painful Location Categories*



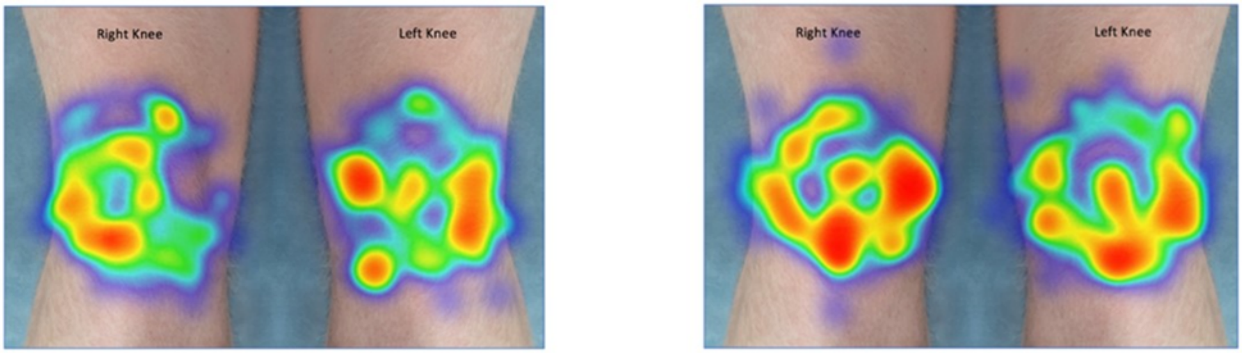
*Note:* Transformed score was reflected, so a lower value reflects a higher perception of function.

### *Painful Locations*

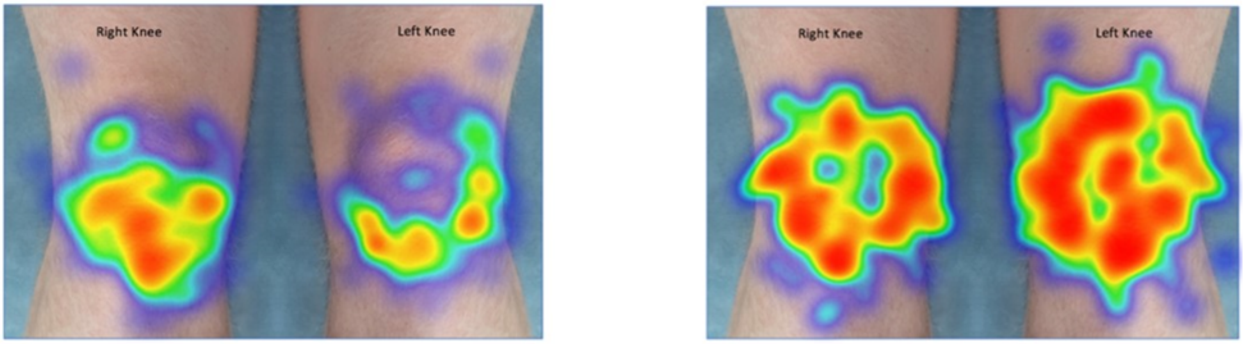
Figure 7 provides a heat map plot demonstrating the frequency of responses for each perception of pain category. The warmer hues (with red being the warmest) indicate more selections of that region on the knee pain map, while the colder hues (blue being the coldest) represent fewer selections.

**Figure 7**

*Heat Map Plots from SNAPPS for Perception of Pain Categories*



A. Mild pain category B. Mild/moderate pain category



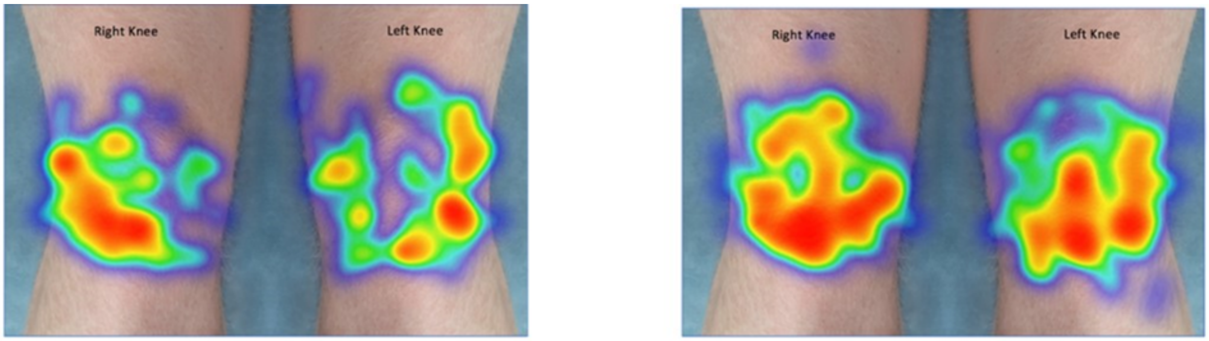
C. Moderate pain category D. Moderate/severe pain category

*Note:* The warmer hues (with red being the warmest) indicate more selections by participants of that region on the knee pain map within SNAPPS, while the colder hues (blue being the coldest) represent fewer selections.

Figure 8 includes the heat map plots from Qualtrics illustrating the frequency of responses on the knee pain map in SNAPPS for perception of function scores in intervals.

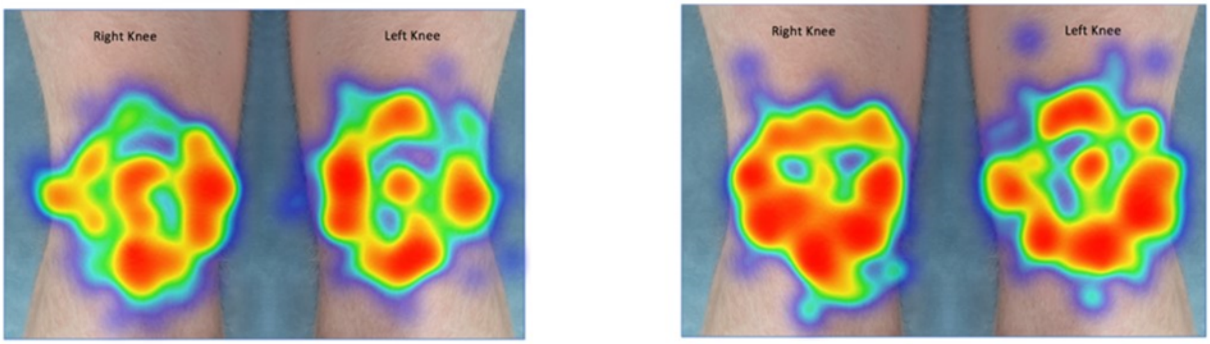
**Figure 8**

*Heat Map Plots from SNAPPS for Perception of Function*



A. Perception of highest function (> 90)

B. Perception of moderate function (80 > 90)



C. Perception of poorer function (70 > 80)

D. Perception of least function (< 70)

*Note:* The warmer hues (with red being the warmest) indicate more selections by participants of that region on the knee pain map within SNAPPS, while the colder hues (blue being the coldest) represent fewer selections. Perception of function was assessed using the AKPS, with scores of > 90 indicating highest function, 80 > 90 moderate function, 70 > 80 poorer function, and < 70 least.

## Discussion

The purpose of this study was to identify relationships between selected injury characteristics (duration of symptoms and painful location(s)), sociodemographic factors (gender and age), and psychological factors (participant's perceptions of pain and function) in individuals with PFP. We hypothesized that there would be relationships between the duration of symptoms and painful location(s) and participant's perceptions of pain and function, as well as between gender and age and participant's perceptions of pain and function.

The findings of this study provide partial support for the interrelationships proposed in the Biopsychosocial Model (Brewer et al., 2002) for PFP. Duration of symptoms and painful location(s) (both considered injury characteristics in the model) predicted perception of function, but not with perception of pain. Gender and age (both considered sociodemographic factors in the model) were not related to perception of pain or perception of function in our sample of individuals with PFP. Perception of pain and perception of function correlated with one another.

### *Perception of Pain*

Perception of pain was not related to the selected injury characteristics or sociodemographic factors in this study. This suggests that these selected factors are not significantly related to the conscious interpretation of the sensation of pain, particularly in regards to the intensity of that pain. It could be that other factors from the model, such as biological factors, are more likely related to this perception of pain in this population.

Perception of function however was associated with perception of pain. Individuals who consciously interpreted that their function was more negatively impacted by their PFP also reported higher perceptions of pain. Within the Biopsychosocial Model (Brewer et al., 2002), these two constructs can be viewed as cognitions, and these two cognitions are closely related to one another in individuals with PFP. Previous researchers have identified a relationship between the perception of pain and perception of disability using different measures in individuals with PFP (Domenech et al., 2013). This finding does suggest that perhaps one mechanism for changing perception of pain could be by changing the perception of function, or vice versa. This concept has been supported in the chronic low back pain literature (Waddell, 1987; Waddell &

Burton, 2004), where interventions aimed at changing the perception of function led to a change in perception of pain as well.

In contrast to our findings, Hott et al. (2020) identified that duration of symptoms was a significant predictor of perception of pain (for worst pain) in their sample (n=112) recruited from physician clinics. Also differing from the findings of this study, Gerbino et al. (2006) identified a trend towards lower perception of pain as duration of symptoms increased. The median duration of symptoms for their population was 20 months (range of 3-20 months) compared to the median of 15 ± 74.0 months in our sample. However, their sample consisted of 100 adolescent patients with PFP from a sports medicine practice, while our sample consisted of adult individuals in the community, where 26.3% of our sample had not seen a doctor for their knee pain. Van Cant et al. (2021) reported that participants with a shorter duration of symptoms (32.4 ± 32.2 months) had more frequent and severe pain (4.2 ± 1.2 NPRS score) than those with a longer duration of symptoms (49.9 ± 39.9 months; 2.2 ± 1.3 NPRS score). The mean duration of symptoms in their sample was 41.2 ± 29.1 months, which was longer than our sample. It is apparent however that individuals with PFP appraise their pain differently as time progresses.

### ***Perception of Function***

In addition to perception of pain, both duration of symptoms and the spatial extent of painful location(s) were also related to the perception of function in this study. More specifically, longer duration of symptoms and a greater number of painful location(s) had a negative impact on how the participants consciously interpreted their function. Previous research has supported that a loss of physical and functional ability is a significant complaint for individuals with PFP (Smith et al., 2018; Maclachlan et al., 2018). This loss of physical and functional ability has in part been attributed to a lack of understanding of the cause of knee pain and the decision to avoid painful movements out of fear of making the condition worse (Smith et al., 2018). This supports the idea that early interventions, focused on patient education and encouraging physical activity may be key to maintaining positive perceptions of function in this population. As supported in our results, maintaining a positive perception of function can also relate to the perception of pain in this population.

### ***Duration of Symptoms***

Lankhorst et al. (2016) reported a positive trend for those with a longer duration of symptoms to report increased levels of function following exercise therapy compared to those who had symptoms for a shorter duration of time. The sample from this study reported higher perception of function values (83.5 ± 14.0) compared to Lankhorst et al. (2016), who reported baseline perception of function values ranging from 64.9 ±15.1 to 75.2 ± 8.67. Longer duration of symptoms has been associated with higher body mass and decreased hip muscle strength in this population (Earl-Boehm et al., 2017). This is concerning as it suggests a link between longer duration of symptoms and decreased physical activity, which may contribute to other health issues. These findings collectively underscore the importance of duration of symptoms as it relates to perception of function in this population.

### ***Painful Locations***

On the knee pain maps from SNAPPS, the regions identified in our sample as being painful were consistent with those of Gerbino et al. (2006). They identified the patella (with anterior/posterior compression; 100% of sample reported pain), distal pole of the patella (64%), medial plica (63%), medial condyle (50%), and medial patella (24%) as the most common sites of pain during the palpation portion of a physical exam in their sample. The median pain intensity for their sample was 6 out of 9 (Gerbino et al., 2006), so in comparison to the moderate/severe perception of pain category, it appears that our sample self-reported pain in similar regions of the knee.

Individuals who reported more widespread pain also reported worse perceptions of function. The heat map plot images in Figure 8 for those with lower perceptions of function illustrate an “O” pattern of pain around the patella. This is similar to the pattern reported by participants who had pain for 5 years of more (Boudreau et al., (2017). This is consistent with our findings, where symptom duration, perception of pain, and location of pain were significant predictors of perceived function. Consistent with our findings, Boudreau et al. (2017) reported that 57% of their sample had pain along the lower peripatellar region of the patella, which from the heat map plot images also appears to be a region frequently selected by our sample. This may indicate involvement of adjacent structures to the patella, such as the fat pad and patellar tendon (Boudreau et al., 2018). Bilateral pain may be considered a progression of PFP, as it has been associated with longer symptom duration in individuals with PFP (Boudreau et al., 2018). Bilateral pain was similar in our sample (73%) and the sample of Boudreau et al., 2017 (77%). These results combined with the previous findings of Boudreau et al. (2018), strengthen the evidence that the number of painful locations, which may be reflective of the progression of PFP, is related to perception of pain and perception of function. Furthermore, early recognition and treatment for those with PFP may be paramount to improving health outcomes for this population.

### ***Age and Gender***

The two sociodemographic factors from the biopsychosocial model of sport injury rehabilitation that we included in our study – age and gender – were not associated with perception of pain or perception of function. A previous study identified that younger PFP patients responded more favorably to exercise-based treatment approaches, while older PFP patients responded more favorably to orthotic devices as a means of reducing pain and improving function (Lack et al., 2014). Our findings are consistent with those of Lankhorst et al., (2016), who also reported that age was not a significant predictor of perception of pain and perception of function in their sample.

Self-identified gender was included as a sociodemographic factor to determine if there was a relationship with perceptions of pain and function. PFP is more prevalent in females (Boling et al., 2009), but does also occur in males. Previous studies have reported differences in risk factors for PFP based on anatomical sex, as well as differences in responses to exercise therapy (Boling et al., 2019; Lankhorst et al., 2016). Lankhorst et al. (2016) also found no relationship between anatomical sex and perception of pain, but did identify a positive trend for females to improvements in perception of function following exercise therapy. It appears that while gender is related to exercise therapy outcomes, it may be via other intermediate factors related to gender and outcome, and not gender itself.  Likewise, gender did not relate to perception of pain in this PFP sample.  It should be noted that previous studies defined gender based on anatomical sex, and our study used self-reported gender identity.

### ***Clinical Impact***

The results of this study suggest that duration of symptoms as well as painful location(s) are related to perception of function in individuals with PFP. More specifically, those individuals with a longer duration of symptoms and more painful locations have lower perceptions of their function, which is one treatment outcome that clinicians rely on to determine recovery. Previous research identified individuals with PFP report feeling a loss of physical & functional ability (Smith et al., 2018), which was attributed to their perception of pain. This emphasizes the need for earlier recognition and interventions for PFP, when symptoms have only been present for a short time and before the perception of function is more adversely impacted.

### *Limitations*

While partial support for the relationships among selected injury characteristics and perception of pain and perception of function were identified in this study, there are several limitations to this study. The responses were all gathered via online survey, and while every attempt was made to make the questions and options very concise and clear, participants were not able to ask for clarification if needed, like they could if they were completing these surveys in person.

In addition, we relied solely on the SNAPPS to identify our PFP sample for this study. While this instrument has excellent sensitivity and reliability in differentiating PFP from other soft tissue knee pathologies (Dey et al., 2006), this approach relies on self-reported responses to questions. The objective was to recruit from the general population and not rely on recruitment from medical settings, as not everyone with PFP may seek medical attention for their condition.

### *Future research*

Our results provide partial support for the interrelationships between selected injury characteristics (duration of symptoms and painful locations) and psychological factors (perception of pain and perception of function, both cognitions), however further research is warranted to explore what, if any, other factors from the Biopsychosocial Model (Brewer et al., 2002) are interrelated. Previous researchers have identified that several affects in individuals with PFP, such as fear avoidance beliefs, catastrophizing, and anxiety, are also associated with perception of pain as well as function (Maclachlan et al., 2018). It remains unclear what if any relationships exist between these affects and injury characteristics and sociodemographic factors as illustrated in the model in this population.

The decision on which factors to include in this study was based on the existing PFP literature. To date, only one qualitative study summarizes the lived experiences of individuals with PFP (Smith et al., 2018). Additional qualitative studies with this population may help identify factors within the Biopsychosocial Model (Brewer et al., 2002) that warrant further exploration as they relate to one another and impact the rehabilitation process.

## Conclusion

The results of this study support that injury characteristics such as symptom duration and painful locations are related to perception of function in individuals with PFP. The selected sociodemographic factors (gender and age) were not related to the perception of pain or the perception of function in this sample. The perception of pain and perception of function (both cognitions, or psychological factors) were related to one another. Therefore, this study's findings provide partial support for the Biopsychosocial Model (Brewer et al., 2002) as a conceptual framework to conceptualize PFP evaluation and treatment. Further work is needed to determine how other factors within the model may be related to perception of pain and perception of function in this population.

# Chapter Four: Exploring the Relationships Between Lower Extremity Strength, Biomechanics, and Perceptions of Pain and Function in Individuals with Patellofemoral Pain

## Introduction

Patellofemoral pain (PFP) is a chronic musculoskeletal condition characterized by retro- and peri-articular pain with several activities of daily living, such as navigating stairs, squatting, and sitting with the knees flexed for an extended period of time (Crossley et al., 2016). The etiology of PFP is complex and multifaceted, and previous researchers have widely adopted a biomechanical approach to explain the mechanisms theorized to contribute to PFP. The pathomechanical model (Powers et al., 2017) postulates that PFP is the result of elevated stress within the patellofemoral joint, which is caused by a decrease in patellofemoral joint contact area and/or increased patellofemoral joint reaction forces.

Within the pathomechanical model, the lower portion of the model suggests that the interaction of several impairments in muscle function and biomechanics leads to the elevation of patellofemoral joint reaction forces (Powers et al., 2017). The musculature at the hip, particularly the hip abductors and external rotators, are speculated to have an influence on patellar position (Powers et al., 2017). These muscles are theorized to contribute to control of the femur in the transverse and frontal plane during weight-bearing tasks (Boling et al., 2009). Weakness of these muscle groups is believed to lead to an altered movement pattern, known as dynamic malalignment (Powers et al., 2017). Dynamic malalignment is characterized by increased knee abduction, hip adduction, hip internal rotation, and trunk flexion and rotation (Powers et al., 2017). This movement pattern is commonly identified during single-leg loading tasks, such as stepping and single-leg squats (Willson & Davis, 2008; Nakagawa et al., 2012, Herrington, 2014, Bazett-Jones et al., 2013). Dynamic malalignment is believed to cause patellar malalignment and maltracking as well as elevated loading of the patellofemoral joint (Powers et al., 2010).

Several studies have reported weakness of the hip and knee musculature in individuals with PFP as compared to their healthy counterparts (Boling, Padua, & Creighton, 2009; Finnoff et al., 2011; Magalhães et al., 2010; Prins & van der Wurff, 2009; Kaya et al., 2011; Lankhorst et al., 2012; Pappas & Wong-Tom, 2012). However, there are also studies that refuted the presence of hip muscle weakness in individuals with PFP (Thijs et al., 2011; Finnoff et al., 2011; Boling, Padua, Marshall, et al., 2009; Herbst et al., 2015). Additionally, while deficits in knee extension strength are consistently reported in the PFP literature, it is unclear if this is a contributing factor or consequence of PFP (Pappas & Wong-Tom, 2012). There also is conflicting evidence surrounding the proposed link between hip and knee muscle weakness and altered movement patterns in this population (Powers et al., 2017).

Currently, treatment interventions for PFP widely target muscle weakness and altered movement patterns as a means of reducing pain and restoring function (Collins et al., 2018). Exercise-based therapy is a common approach that targets strengthening of the hip and knee musculature as a means of improving movement patterns (Collins et al., 2018). However, there is evidence to suggest that following these interventions, improvements in pain and self-reported function occur independent of changes in strength or biomechanics (Şahin et al., 2016; Pairot de Fontenay et al., 2018). Furthermore, these improvements in pain and function are reported in the short-term, but not as commonly in the long-term following exercise-based therapy (van Linschoten et al., 2009).

Due to the inconsistencies in the pathomechanical model (Powers et al., 2017) and corresponding treatment interventions highlighted above, there is a need to examine this condition from a different perspective. Other musculoskeletal conditions, such as chronic low back pain and anterior cruciate ligament (ACL) injuries, have adopted biopsychosocial frameworks to inform research regarding effective rehabilitation strategies (Waddell, 1987; Brewer et al., 2014). There are several studies that suggest PFP is biopsychosocial in nature (Smith et al., 2018; Maclachlan et al., 2018; Piva et al., 2009; Domenech et al., 2013; Maclachlan et al., 2017), however there has not been a study that has used a biopsychosocial framework to explain the interrelationships of factors that influence rehabilitation and recovery.

The Biopsychosocial Model of Sport Injury Rehabilitation (Brewer et al., 2002) is a theoretical framework that illustrates the interrelationships between a multitude of factors surrounding the experience and recovery from injury. The core of the model consists of biological, psychological, and social/contextual factors that are interrelated with one another (Brewer et al., 2002). This core is influenced by both injury characteristics and sociodemographic factors (Brewer et al., 2002). Psychological factors are proposed to have a bidirectional relationship with intermediate biopsychosocial outcomes and sport injury rehabilitation outcomes (Brewer et al., 2002). Both biological factors and social/contextual factors influence the intermediate biopsychosocial outcomes (Brewer et al., 2002). Intermediate biopsychosocial outcomes also can affect the overall sport injury rehabilitation outcomes (Brewer et al., 2002).

Currently in PFP research and in clinical practice, measurements of pain and self-reported function are commonly viewed as clinical outcomes that reflect biological processes contributing to PFP. Self-reported pain is interpreted as the measure of intensity of pain sensation, or the process by which energy contacts the sensory receptors resulting in a change in neural activity that is then transmitted to the central nervous system via afferent neural pathways (Sternberg, 2007). The measures commonly used to quantify self-reported pain include descriptors that ask the individual to attach meaning to the pain sensation they are experiencing. Therefore, these measures may be more accurately viewed as a way to quantify the perception of pain, or the individual's interpretation of the pain sensation and attempt to attach meaning to the pain (Peacock & Watson, 2003). Self-reported functional assessments that ask individuals about their subjective function and limitations may be better viewed as a measurement of the individual's perception of function. The perception of function can be defined as an individual's interpretation of the subjective symptoms and functional limitations resulting from their PFP (Kujala et al., 1993), and is influenced both by perception of pain and the level of exertion during functional tasks (Stratford & Kennedy, 2006). Both the perception of pain and the perception of function are cognitions, or psychological factors within the Biopsychosocial Model (Brewer et al., 2002).

Several of the factors listed earlier from the pathomechanical model (Powers et al., 2017), such as hip and knee strength and trunk, hip, and knee biomechanics, are biological factors and intermediate biopsychosocial outcomes within the Biopsychosocial Model (Brewer et al., 2002). As the model suggests, biological factors and intermediate biopsychosocial outcomes are related to psychological factors. Therefore, the purpose of this study was to identify relationships between selected biological factors (hip/knee strength and hip/trunk biomechanics) and psychological factors (participant's perceptions of pain and function) in individuals with PFP, using the Biopsychosocial Model (Brewer et al., 2002) as a conceptual framework. We hypothesized that the selected biological factors will be related to participant's perception of pain and perception of function, as suggested by the model.

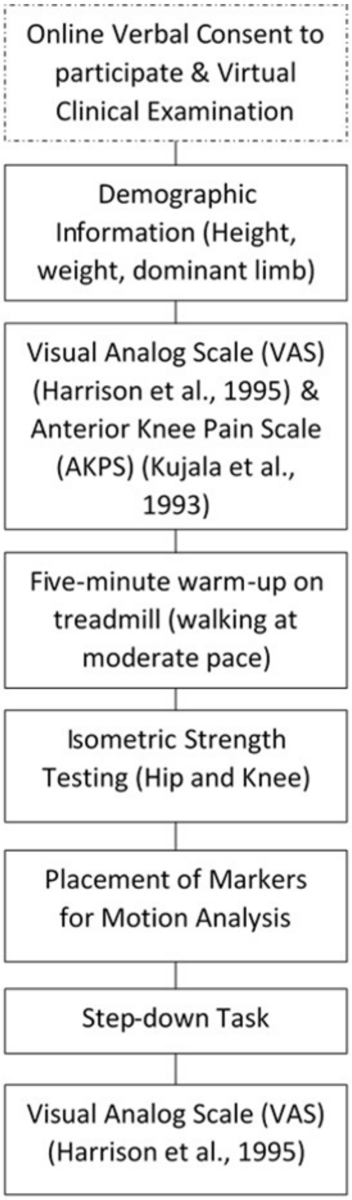
## Methods

### *Study Design & Protocol*

This was a cross-sectional study design conducted both online and in the laboratory. Figure 9 shows the study protocol.

**Figure 9**

*Flow Chart of Study Protocol*



### *Recruitment & Participants*

Participants were recruited both from a previous online survey study examining PFP as well as via word of mouth through social media posts and flyers hung at various locations within the community. In order to be eligible for this study, individuals had to be between the ages of 18 and 45, identified as having PFP using an online screening survey, had access to the internet and an electronic device with a camera, and were willing to travel to the laboratory for the data collection session. The exclusionary criteria are listed below in Table 6, and were screened for during the online screening survey. In addition, all potential participants will be asked to refrain from the use of any nonsteroidal anti-inflammatory drug or corticosteroid within 24 hours of the testing session in the laboratory.

**Table 6**

*Exclusionary Criteria*

| |
|---|
| The presence of meniscal or other intra-articular injury |
| Current injury or laxity of the cruciate or collateral ligaments of the knee |
| Isolated tenderness of the iliotibial band or pes anserine |
| A positive finding on the patellar apprehension test |
| Current diagnosis of Osgood-Schlatter, Sinding-Larsen-Johansson syndrome, or osteoarthritis of the knee |
| Any current effusion of the knee joint |
| Referred pain from the hip or lumbar region |
| History of patellar subluxation or dislocation |
| Surgery within the past 24 months to the lower extremity |
| History of any neurological or vestibular disorder that may affect balance within the past 6 months |
| Current pregnancy |

### *Measures*

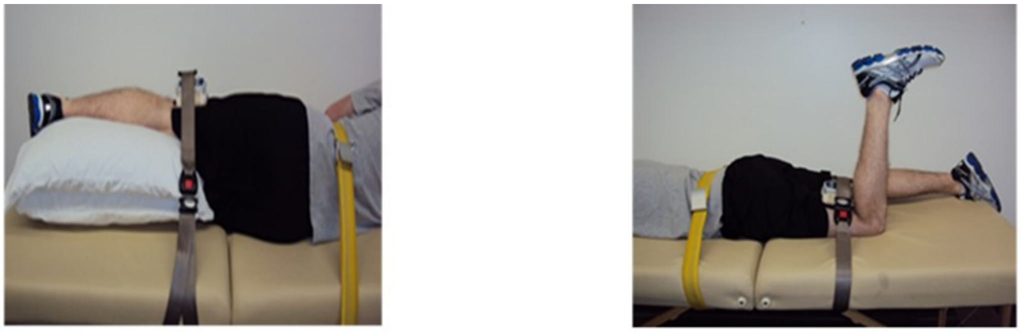
All of the measures outlined below were performed during a single visit to the laboratory. Hip and knee strength were assessed using a Lafayette Manual Muscle Testing System hand-held dynamometer (HHD). Isometric peak force was recorded for hip abduction, hip extension, hip external rotation, and knee extension for the involved limb, or in the case of bilateral pain, the more painful limb. For each motion, the participant was instructed in the performance of the task, and was be secured to a treatment table using stabilizing straps. For each trial, the participant was provided with specific directions regarding the direction of their force. Prior to completing the test trials, the participant was instructed to perform three practice trials at 50%, 75%, and 100%

of their perceived maximal effort to gain familiarity with the task. For each practice and test trial, the participant was instructed to maintain their effort for 5 seconds, which was timed using the HHD and confirmed by the researcher. Following each trial, the participant was provided a period of 60 seconds of rest. Three test trials were performed for each motion, with a fourth repetition performed only if one of the previous repetitions was more than 10% greater than or less than the other repetitions. This procedure has been performed in several previous studies and is a highly reliable means of quantifying hip and knee isometric muscle strength (Jaramillo et al., 1994; Ireland et al., 2003, Boling, Padua, Marshall, et al., 2009). Verbal encouragement was provided to all participants during the test trials to encourage a maximal effort.

Hip abduction (ABD) strength was measured with the participant positioned in side-lying on the treatment table with the limb being tested on top (Figure 10). The torso was secured to the table with a strap placed over the waist and around the treatment table, and the HHD was secured to the limb being tested approximately 5 cm above the lateral joint line (Ireland et al., 2003). The participant was instructed to "lift the top limb straight up towards the ceiling".

**Figure 10**

*Isometric Strength Testing Positions*



A. Hip abduction

B. Hip extension

C. Hip external rotation

D. Knee extension

Hip extension (EXT) force was tested with the participant lying prone on the treatment table. A stabilizing strap was positioned across the hips to secure the torso to the table during testing (Figure 10). The HHD was positioned approximately 3 cm proximal to the popliteal fossa of the limb being tested and secured to the table using a second stabilizing strap (Ireland et al., 2003). For this motion, the participant was instructed to flex the knee to 90 degrees and to "push the heel up towards the ceiling."

Hip external rotation (ER) strength was tested also with the participant in a prone position on the treatment table (Figure 10). A stabilizing strap was positioned across the hips to secure the torso, as described for hip extension strength testing. The limb being tested was flexed at the knee to 90 degrees (Ireland et al., 2003). Foam rolls were placed on both sides of the legs to aid in stabilizing the limb for testing. The HHD was placed 1 cm above the medial malleolus and was maintained in position by the researcher, who was positioned on the medial side of the leg being tested. The participant was instructed to "rotate their lower leg inwards" while the researcher maintained the position of the HHD. This testing position has been used in previous research (Boling, Padua, Marshall, et al., 2009).

Knee extension (EXT) force was tested with the participant also in the prone position on the table (Figure 10). A stabilizing strap was positioned over the distal trunk and to the table to help stabilize the torso. The limb being tested was flexed at the knee to 90 degrees. The HHD was placed 1 cm above the anterior ankle mortise of the limb being tested and secured by the researcher. The participant was instructed to "straighten their leg down to the table" while the researcher maintained the position of the HHD. This position has also been utilized in previous research (Boling, Padua, Marshall, et al., 2009) and is a reliable method of quantifying knee extension strength.

Three-dimensional (3-D) biomechanics of the trunk and hip were recorded using a 10-camera Motion Analysis Eagle System (Motion Analysis Corp., Santa Rosa, CA) at 200 Hz. Reflective markers were placed on the participant to allow for identification of structures and joint centers (Figure 11). The single reflective markers were placed on the spinous process of C7, sternal notch, and right scapula, bilaterally on the acromioclavicular joints, anterior superior iliac spines, posterior superior iliac spines, iliac crests, greater trochanters, lateral and medial femoral epicondyles, medial and lateral malleoli, and the 1st and 5th metatarsal heads. In addition to these single reflective markers, marker clusters consisting of four reflective markers affixed to a rigid plastic shell were positioned bilaterally to the lateral thigh, lateral shank, and a marker cluster of three reflective markers was positioned on the posterior heel counter to allow for tracking of each of these segments. Each of the marker clusters were secured to the participant using elastic straps and athletic tape. Once the reflective markers were placed on the participant, a standing calibration trial was completed for 3-D kinematic analysis. After the calibration trial was complete, the reflective markers on the right scapula, acromioclavicular joints, greater trochanters, medial and lateral epicondyles, medial and lateral malleoli, and 1st and 5th metatarsal heads were removed.

**Figure 11**

*Placement of 3-D Reflective Markers*

The variables of interest were the angles for trunk flexion (FLEX), hip adduction (ADD), and hip internal rotation (IR) at peak knee flexion. These three joint angles were selected due to their relationship with dynamic malalignment, as identified in previous studies (Willson & Davis, 2008).

Two-dimensional (2-D) biomechanics of the trunk and knee were measured simultaneously with the 3-D measures. Fluorescent markers were placed bilaterally on the participant’s greater trochanters, lateral femoral epicondyles, center of the patella, lateral malleoli, and anterior ankle mortise. Two Yi 4k+ action cameras (Yi Technology, Shanghai, China) were used to record the participant’s movement in both the frontal and sagittal planes. Both cameras were positioned at a height of 104 cm, 162.5 cm from the front of the step, and 167.5 cm from the side of the step on the stance limb side.

The variables of interest for 2-D analysis were trunk lateral motion angle (LTM) and knee frontal plane projection angle (FPPA) at the point of peak knee flexion. These measures were selected due to their relationship with dynamic malalignment (Willson & Davis, 2008).

A visual analog scale (VAS, Harrison et al., 1995) was used to assess the participant’s perception of pain. The VAS consists of a bidirectional 10-cm line, with labels on each end designating “no pain” and “severe pain”. The participants were instructed to draw a vertical mark on the line to correspond with their ‘usual’ pain on average over the past week, as well as current pain before the testing and current pain after the testing. The distance from the left side of the scale (or ‘0’) to the participant’s vertical mark was then measured and recorded in cm. The VAS is a reliable, valid, responsive, and commonly used measure to assess the perception of pain, particularly in individuals with PFP (Crossley et al., 2004).

The Anterior Knee Pain Scale (AKPS, Kujala et al., 1993) was utilized to assess the participant’s perception of function. The participants completed a paper version of the AKPS for this study.

### *Procedures*

Verbal informed consent for this study was obtained in an online, virtual meeting in accordance with the university's Institutional Review Board's approved protocol for this study. In the same meeting, once consent was obtained, the researcher conducted a telehealth-style clinical examination due to the data collection period being within the COVID-19 pandemic. During this clinical examination, the researcher asked questions about the duration of symptoms, pain management strategies utilized since the onset of their knee pain, physical activity level, and whether they experienced pain with any of the following: during or after activity, navigating stairs, kneeling, or squatting. The researcher then guided the participant through self-palpation of the knee to identify any areas of point tenderness. The participant was instructed to position their camera on their knees so that the researcher could see where they were palpating to ensure they were on the correct anatomical structure, and to press on the identified structure with "enough pressure to indent the skin." The participants were shown a visual slide with a photograph of two knees, and as the researcher advanced through the palpation, the structure to be palpated was highlighted on the slide.

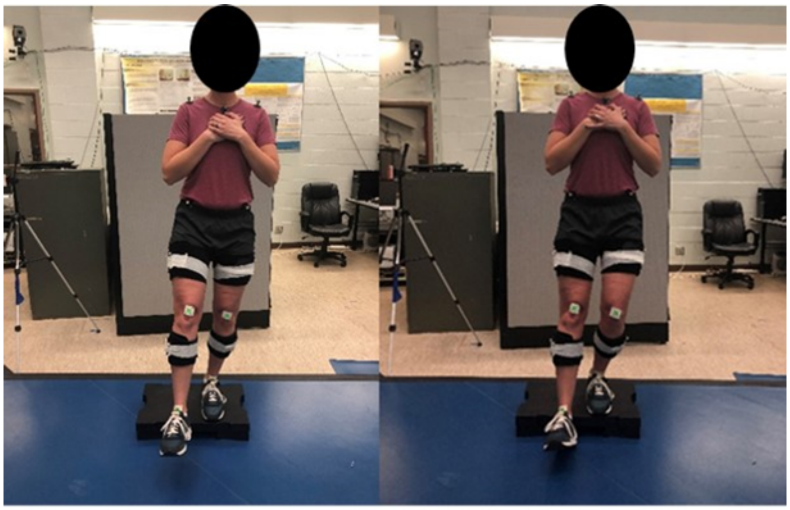
The participant then attended an in-person data collection session in the lab, which consisted of gathering demographic information such as height, weight, and dominant limb defined by asking the participant their preferred limb for kicking a ball. They then completed the VAS (Harrison et al., 1995) for 1.) usual pain over the past 7 days and 2.) current pain to assess their perception of pain, and the AKPS (Kujala et al., 1993) to assess their perception of their function.

Once this was completed, the participant was provided with standardized shoes (Saucony Jazz, Lexington, MA) to ensure consistency in footwear between all participants. Next the participant was asked to warm-up for five minutes by walking at a self-selected, moderate pace on a treadmill. Upon completion of the warm-up, isometric hip and knee strength was assessed as described earlier.

The 3-D and 2-D measures were completed while the participant performed a forward step-down task from a height of 4 inches (Thorpe et al., 2021). The primary investigator first demonstrated the performance of the task for the participant. The step-down task was initiated from a standing position on top of the step, with the stance leg positioned with the foot facing forward on the edge of the step (Figure 12). The rate of movement for this task was standardized to 60 bpm set by a metronome. The participant was instructed to touch the non-stance foot to the floor on a beep, and return to the starting position on the subsequent beep. The only cues that were provided to the participant were to keep their arms folded across their chest and to maintain their weight on the stance foot during performance of the step-down. The participant was allowed complete as many practice trials as necessary to familiarize themselves with the task. The stance limb was the involved limb, or the more painful limb in the case of bilateral pain. After the practice trials, the participant was instructed in the test trials. The participant was asked to complete three sets of five successive step-downs. In the event that a participant lost their balance or placed their foot completely down on the floor, the trial was stopped and repeated after a period of rest.

**Figure 12**

*Start and End Position for the Step-down Task*



A. Start position B. End position

Once the participants completed the step-down task, they were asked to complete the VAS once again, this time indicating their current perception of pain. This will help identify if the testing resulted in an increase in the perception of pain.

### ***Data Processing***

The isometric hip and knee strength measures for each of the four motions were averaged across the three test trials. The averages were then normalized to body mass and recorded as a percentage of body mass in kg.

For 3-D kinematic analysis, joint angle data was collected from the step-down task trials and was filtered using a 4th order Butterworth filter with a cutoff frequency of 12 Hz. The segment coordinate systems for the lab set-up in this study followed the right-hand convention. The X-axis aligned with the medial-lateral direction, the Y-axis aligned in the anterior-posterior direction, and the Z-axis aligned in the vertical direction. The angles of trunk FLEX, hip ADD, and hip IR at the point of peak knee flexion were calculated using a joint coordinate system approach (Grood & Suntay, 1983) for the middle three repetitions of the five step-down trials for each set. The kinematic data were processed using Visual 3D software (C-Motion, Inc., Rockville, MD). The angles of interest were averaged and reported in degrees.

For the 2-D biomechanical analysis, the videos recorded on the Yi 4k+ action cameras were uploaded into Dartfish 8 software (Dartfish USA, Inc., Alpharetta, GA) and synced. In Dartfish, the angles for LTM and kFPPA were calculated at the point of maximum knee flexion for the middle three repetitions of each set of step-downs. This approach has been used in previous research (Dingenen et al., 2013). The LTM angle was calculated as the angle between a vertical line starting from the anterior superior iliac spine and the horizontal line connecting the anterior aspect of the acromioclavicular joint and the sternal notch (Figure 13). Negative or smaller values indicate more lateral trunk lean over the stance limb, while larger values indicate lateral trunk lean away from the stance limb (Dingenen et al., 2013). The kFPPA was calculated as the angle between the line connecting the anterior superior iliac spine and the center of the patella and the line connecting the center of the patella and the anterior ankle mortise (Figure 14). A value of 180 degrees would indicate a neutral position of the knee relative to the hip. Values less than 180 would indicate dynamic malalignment, or positioning of the knee medial to the stance foot, and values over 180 would indicate positioning of the knee lateral to the stance foot (Dingenen et al., 2013). These values were reported in degrees.

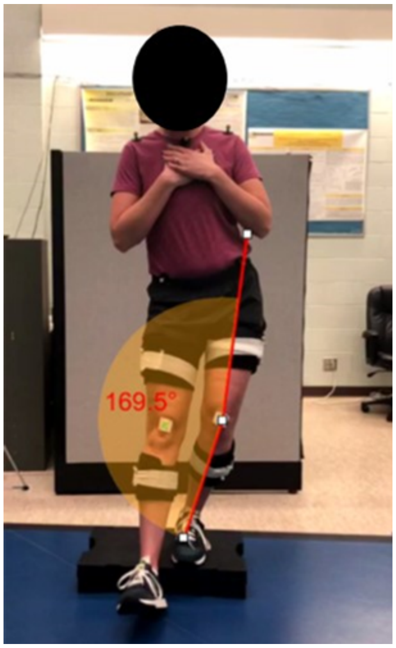
The VAS (Harrison et al., 1995) was measured in cm from the left end of the scale to the mark that the participant marked on the scale. The AKPS was scored using the standard scoring criteria (Kujala et al., 1993). The maximum score possible was 100, with a lower score indicating a lower level of function.

**Figure 13**

*Calculation of Lateral Trunk Motion (LTM) in Dartfish*

**Figure 14**

*Calculation of Knee Frontal Plane Projection Angle (kFPPA) in Dartfish*



### *Statistical Analysis*

The *a priori* planned analysis consisted of a correlation matrix to assess relationships between each of the strength measures, 3-D joint angles, 2-D joint angles, and the participant's perception of pain and perception of function. In addition, a model selection regression using a stepwise approach was planned to determine which independent variables (strength and biomechanical measures) had the most significant influence on the dependent variables of perception of pain and perception of function. The level of significance for all analyses set at $p \leq .05$. However, upon checking whether or not the data set met the assumptions for these tests, several assumptions of normality were violated and the statistical plan was modified.

The data collected for each measure was tested for normality using Shapiro-Wilk tests. We identified that five of the outcome variables (hip ABD strength, $W(38) = .923$, $p = .012$, hip EXT strength, $W(38) = .923$, $p = .012$, hip ER strength, $W(38) = .873$, $p < .001$, kFPPA, $W(38) = .905$, $p = .003$, and hip ADD angle, $W(38) = .926$, $p = .015$) violated the assumptions of normality. A square root transformation was applied to hip ABD strength and hip EXT strength and successfully transformed the data into a normal distribution while maintaining the same interpretation of these values (i.e. a higher value indicates more strength). A natural log transformation was used for normalized hip ER strength, which also maintained the scaling and interpretation of these values. Hip ADD angle was not able to be transformed into a normally distributed variable, so this data was categorized into two categories – one including all participants who exhibited hip adduction (values greater than 0) and those who exhibited hip abduction (values less than 0). The kFPPA values were left-skewed, so a reflection and square root transformation was used to transform the data into a normal distribution. Therefore, larger values indicated more 2-D adduction of the knee.

The transformations of hip ABD strength, hip EXT strength, hip ER strength and kFPPA and the categorization of the hip adduction angle allowed for us to continue with the more robust parametric statistical analysis as originally planned.

## Results

### *Demographic Data*

Thirty-eight adults (8 males, 30 females, 33.92 ± 7.49 years old) identified by the SNAPPS survey as having PFP were included in this study. Demographic information for the 38 participants and means for all outcome measures can be found in Table 7. Table 8 presents descriptive data from the clinical examination.

**Table 7**

*Demographic Information & Outcome Measures*

| Variable | **n=38** | **SD** | **%** |
|---|---|---|---|
| Gender | | | |
| Female | n=30 | | 78.9 |
| Male | n=8 | | 21.1 |
| Age (years) | 33.92 | ± 7.49 | |
| *Range (years)* | *(20-45)* | | |
| Height (cm) | 169.88 | ± 9.71 | |
| Weight (kg) | 81.03 | ± 19.36 | |
| Duration of symptoms (months)$^f$ | 36.0 | ± 90.00 | |
| *Range (months)* | (1-420) | | |
| 0-2 months | n=2 | | 5.2 |

| Variable | **n=38** | **SD** | **%** |
|---|---|---|---|
| 2-6 months | n=3 | | 7.9 |
| 6-12 months | n=7 | | 18.4 |
| 12-36 months | n=8 | | 21.1 |
| 36 months + | n=18 | | 47.4 |
| Involved limb | | | |
| Right knee | n=11 | | 28.2 |
| Left knee | n=8 | | 20.5 |
| Both knees | n=19 | | 51.3 |
| Usual Perception of pain | 3.55 | ± 3.20 | |
| Perception of pain pre-task | 2.08 | ± 2.02 | |
| Perception of pain post-task | 3.24 | ± 2.18 | |
| Perception of function | 80.49 | ± 7.87 | |
| Strength | | | |
| Normalized Hip ABD Strength (%BW) [f] | 0.31 | ± 0.15 | |
| *Transformed Hip ABD Strength* [a] | *0.56* | *± 0.10* | |
| Normalized Hip EXT Strength (%BW) [f] | 0.23 | ± 0.18 | |
| *Transformed Hip EXT Strength* [b] | *0.50* | *± 0.12* | |
| Normalized Hip ER Strength (%BW) [f] | 0.12 | ± 0.05 | |
| *Transformed Hip ER Strength* [c] | *0.37* | *± 0.06* | |
| Normalized Knee EXT Strength (%BW) | 0.23 | ± 0.09 | |
| 3-D joint angles at peak knee flexion | | | |

| Variable | n=38 | SD | % |
|---|---|---|---|
| Hip ADD angle [d,f] | 5.46 | ± 17.21 | |
| *Hip ABD group (n=16)* | -10.00 | ± 4.72 | |
| *Hip ADD group (n=22)* | 9.21 | ± 3.92 | |
| Hip IR angle | -1.63 | ± 5.15 | |
| Trunk FLEX angle | -1.31 | ± 3.93 | |
| 2-D joint angles at peak knee flexion | | | |
| LTM | 15.83 | ± 2.97 | |
| kFPPA [f] | 188.38 | ± 7.72 | |
| *Transformed kFPPA* [e] | 3.52 | ± 0.95 | |

*Note:* [a,b,c] These measures were transformed, but their interpretation remains the same.
[d] Hip ADD angle was categorized into hip ABD group (<0 degrees) and hip ADD group (>0 degrees).
[e] kFPPA was reflected then transformed, so larger angles represent more 2-D adduction of the knee.
[f] These values were non-normally distributed, therefore central tendency values reported are the median and measure of variability is the interquartile range.

**Table 8**

*Clinical Examination Findings*

| Clinical feature | Yes<br>n (%) | No<br>n (%) |
|---|---|---|
| Presence of peri- or retro-patellar pain with self-palpation: | 31 (81.6) | 7 (18.4) |
| Presence of peri- or retro-patellar pain on knee pain map: | 31 (81.6) | 7 (18.4) |
| Presence of peri- or retro-patellar pain with the following: | | |
| During/After Activity | 31 (81.6) | 7 (18.4) |
| Prolonged Sitting | 27 (71.1) | 11 (28.9) |
| Navigating Stairs | 26 (68.4) | 12 (31.6) |
| Kneeling | 30 (78.9) | 8 (21.1) |
| Squatting | 22 (57.9) | 16 (42.1) |

| | | |
|---|---|---|
| Palpation of patellar facets | 14 (36.8) | 24 (63.2) |
| Step-down | 14 (36.8) | 24 (63.2) |
| Met clinical criteria for PFP? | 36 (94.7) | 2 (5.3) |

### ***Correlation Analysis***

Pearson correlations were performed for all the variables of interest (transformed hip ABD strength, transformed hip EXT strength, transformed hip ER strength, knee EXT strength, hip ADD angle category, hip IR angle, trunk flexion angle, LTM, transformed kFPPA, and perception of pain, and perception of function). The significance level was set at $p \leq .05$. The correlations of the variables are shown in Table 9. Perception of pain was significantly correlated with perception of function and hip IR angle, while perception of function was significantly correlated with perception of pain, transformed hip ABD strength, transformed hip ER strength, knee EXT strength, and LTM.

**Table 9**

*Pearson Correlations for All Variables of Interest*

| Variable | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. Perception of pain | — | -.470** | -.074 | -.045 | -.147 | -.196 | .012 | -.332* | .056 | .172 | -.124 |
| 2. Perception of function | -.470** | — | .331* | .314 | .345* | .376* | .002 | .066 | .053 | -.336* | -.057 |
| 3. Hip ABD strength$^{a}$ | -.074 | .331* | — | .806** | .795* | .785** | -.048 | -.116 | -.085 | -.440 | .043 |
| 4. Hip EXT strength$^{b}$ | -.045 | .314 | .806** | — | .785** | .752** | .018 | .033 | -.063 | -.515** | .201 |
| 5. Hip ER strength$^{c}$ | -.147 | .345* | .795** | .785** | — | .825** | .052 | -.053 | -.311 | -.755** | .194 |
| 6. Knee EXT strength | -.196 | .376* | .785** | .752** | .825** | — | -.047 | -.097 | -.195 | -.580** | .047 |
| 7. Hip ADD angle category$^{d}$ | .012 | .002 | -.048 | .018 | .052 | -.047 | — | -.372* | -.408* | .008 | .410* |
| 8. Hip IR angle | -.332* | .066 | -.116 | .033 | -.053 | -.097 | -.372* | — | .110 | -.155 | .245 |
| 9. Trunk FLEX angle | .056 | .053 | -.085 | -.063 | -.311 | -.195 | -.408* | .110 | — | .190 | -.340* |
| 10. LTM | .172 | -.336* | -.440** | -.515** | -.755** | -.580** | .008 | -.155 | .190 | — | -.155 |
| 11. kFPPA$^{e}$ | -.151 | -.045 | .115 | .241 | .265 | .109 | .410** | .241 | -.342** | -.282 | — |

*Note:* $^{a,b,c}$ These measures were transformed, but their interpretation remains the same.
$^{d}$ Hip ADD angle was categorized into hip ABD group (<0 degrees) and hip ADD group (>0 degrees).
$^{e}$ kFPPA was reflected then transformed, so larger angles represent more 2-D adduction of the knee.
*p < .05, **p < .01.

### ***Perception of Pain***

The independent variables that were significantly correlated (hip IR angle and perception of function) were used in a stepwise multiple regression analysis to predict perception of pain. The prediction model contained both of the predictors and was reached in two steps. The model was statistically significant, F(2, 37) = 6.799, p = .003 and accounted for approximately 28% in the variance in perception of pain ($R^2$ = .280, Adjusted $R^2$ = .239). Perception of was primarily predicted by less hip IR and lower perception of function values. Table 10 includes the results of the multiple regression.

**Table 10**

*Stepwise Multiple Regression Results for Perception of Pain*

| | | | | | | | Change Statistics | | |
|---|---|---|---|---|---|---|---|---|---|
| *Model* | *R* | $R^2$ | *Adjusted* $R^2$ | *SE* | $\Delta R^2$ | $\Delta F$ | *df1* | *df2* | *ΔSig. F* |
| 1[a] | .433 | .187 | .165 | 1.5313 | .187 | 8.302 | 1 | 36 | .007 |
| 2[b] | .529 | .280 | .239 | 1.14620 | .092 | 4.491 | 1 | 35 | .041 |

*Note:* [a] Predictors: (Constant), Perception of function
[b] Predictors: (Constant), Perception of function, Hip IR angle

Figures 15 & 16 present scatterplots of the relationships between perception of pain and perception of function and hip IR angle, respectively. Lower perception of function was associated with higher perception of pain, and less hip IR was associated with higher perception of pain.

**Figure 15**

*Scatterplot of Perception of Pain versus Perception of Function*

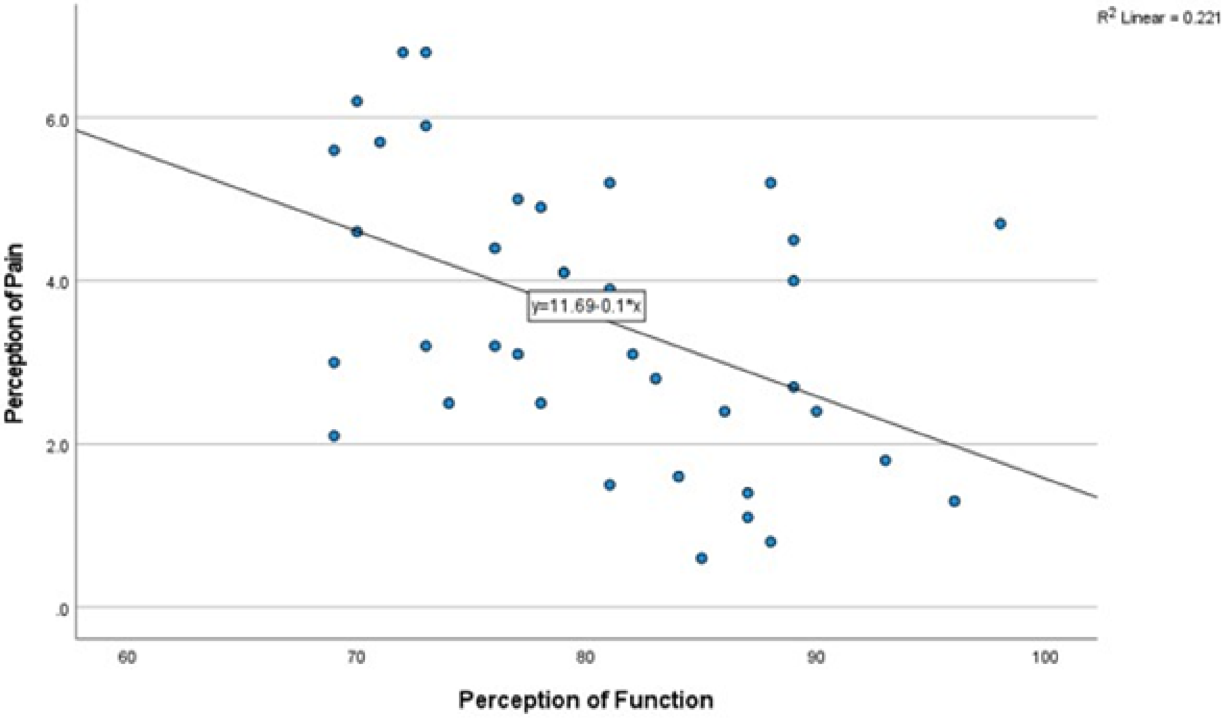
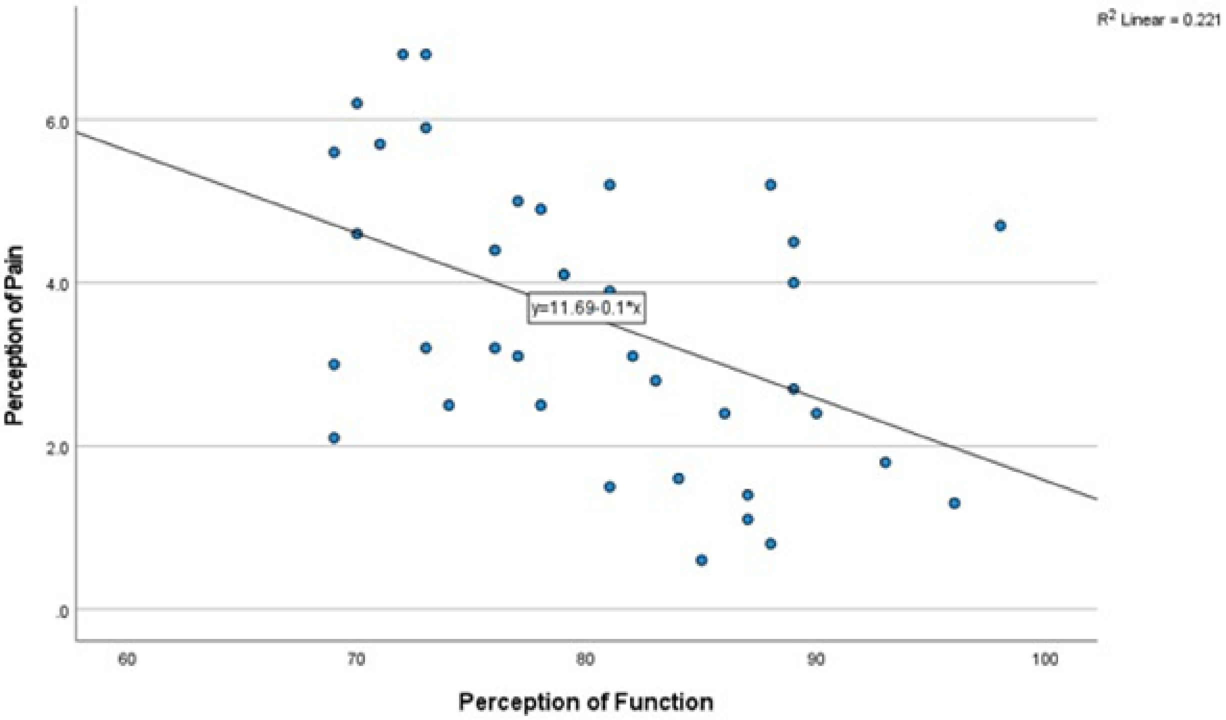


**Figure 16**

*Scatterplot of Perception of Pain versus Hip IR Angle*



*Note:* For Hip IR, 0.0 represents neutral. Negative values for Hip IR angle indicate more hip ER.

### *Perception of Function*

A separate stepwise multiple regression was performed to predict perception of function using the independent variables that were significantly correlated (transformed hip ABD strength, transformed hip ER strength, knee extension strength, LTM, and perception of pain). The prediction model included one of the five predictors and was reached in one step with all but the perception of pain removed. The model was statistically significant, F(1,37) = 8.302, p=.007 and accounted for approximately 43% of the variance in perception of function ($R^2$ = .433, adjusted $R^2$ = .165). Table 11 includes the results of the multiple regression to predict perception of function.  As mentioned earlier and depicted in Figure 15, higher perception of pain was associated with lower perception of function.

**Table 11**

*Stepwise Multiple Regression Results for Perception of Function*

| | | | | | | | Change Statistics | | |
|---|---|---|---|---|---|---|---|---|---|
| *Model* | *R* | *$R^2$* | *Adjusted $R^2$* | *SE* | $\Delta R^2$ | $\Delta F$ | *df1* | *df2* | $\Delta$*Sig. F* |
| 1[a] | .433 | .187 | .165 | 6.896 | .187 | 8.302 | 1 | 36 | .007 |

*Note:* [a]Predictors: (Constant), Perception of pain

## Discussion

The purpose of this study was to identify relationships between selected biological factors (hip and knee strength and trunk, hip, and knee biomechanics) and psychological factors (participant's perception of pain and perception of function) in individuals with PFP. We hypothesized that the selected biological factors would be related to the participant's perception of pain and perception of function in our sample of individuals with PFP.

### *Perception of Pain*

In our sample, only perception of function and hip IR angle significantly predicted perception of pain, with none of the strength variables being significantly related. Similar to the findings reported in Chapter 3, the perception of function and perception of pain are closely related. Out of all of the biological factors examined in this study, only hip IR angle was included as a significant predictor for the perception of pain. However, due to the relatively small value of this joint angle and large standard deviation of this measure, we question the clinical significance of this finding.

The lack of significant relationships between the selected biological factors and perception of pain does provide support that the perception of pain is a cognition rather than solely an outcome measure to assess pain sensation. Psychological factors (including cognitions such as the perception of pain) are situated at the core of the Biopsychosocial Model (Brewer et al., 2002), and are influenced by injury characteristics, sociodemographic factors, biological factors, social/contextual factors, intermediate biopsychosocial outcomes, and sport injury rehabilitation outcomes. It is possible that factors from these other dimensions of the model have a stronger relationship with the perception of pain in individuals with PFP. For example, there may be other underlying biological factors, such as central sensitization (Sigmund et al., 2021), that are present and thereby influencing the perception of pain.

### ***Perception of Function***

We also identified that lower perception of function was correlated with higher perception of pain, lower hip ABD strength, lower hip ER strength, and lower knee EXT strength, and greater LTM away from the stance leg. However, when entered into the regression model only perception of pain was a significant predictor of perception of function.

Muscle strength of the muscles contributing to hip ABD, hip ER, and knee EXT all had a weak correlation with perception of function. This finding helps to support the evidence supporting the use of exercise-based therapy targeting strengthening of the hip and knee musculature for individuals with PFP. These interventions have been effective in changing perceptions of pain and function in the short-term independent of changes in strength (Şahin et al., 2016; Pairot de Fontenay et al., 2018). A potential explanation for this change in perception of function could be that participants viewed the exercises included in the intervention (a component of the rehabilitation environment) that were aimed at correcting muscle strength (a biological factor). The participants may have felt the exercises contributed to a change in their perception of function (cognition, psychological factor), supporting the relationships within the Biopsychosocial Model (Brewer et al., 2002).

### ***Hip & Knee Strength***

Within the context of the Biopsychosocial Model (Brewer et al., 2002), it appears that biological factors such as hip and knee strength do not predict the perception of pain in individuals with PFP. Despite weak correlations between several of the strength variables, none of the hip or knee strength variables predicted perception of function either.

The hip strength values collected from our sample were consistent with those reported in previous studies using a sample of individuals with PFP. Our sample exhibited slightly greater hip ABD strength (33 ± 12% of body weight, or BW) than reported in a systematic review (Prins & van der Wurff, 2009) reviewing hip strength in individuals with PFP (ranging 16 ± 9 to 29 ± 8% BW) and as reported by Long-Rossi & Salsich (2010) (10.3 ± 3.9% BW). Our values were consistent with those reported by Boling, Padua, Marshall et al. (2009) from a military population (35.9 ± 9% BW).  Our sample's hip EXT strength (23 ± 9% BW) was consistent with Prins & van der Wurff (range of 16 ± 8 to 29 ± 8% BW) and Boling, Padua, Marshall et al. (30 ± 7% BW), but slightly higher than reported by Long-Rossi & Salsich (21.3 ± 6.0% BW). Hip ER strength for our sample (14 ± 5% BW) was consistent with Prins & van der Wurff (range of 11 ± 3 to 21 ± 4% BW) and Long-Rossi & Salsich (14 + 3.4% BW), but lower than Boling, Padua, Marshall et al. (21 ±4% BW).

We adopted the same knee EXT strength testing method as Boling, Padua, Marshall et al. (2009). Our sample had much lower knee EXT strength values (23 ± 9% BW) than their sample (46 ± 9% BW); however, their sample consisted of military cadets, while our sample consisted of individuals who were older, from the general community, with current PFP. Furthermore, our data collection took place during the COVID-19 pandemic, when many individuals were working remotely. It is plausible that this could also explain the difference in knee EXT strength as well, especially if our participants were less active in general.

Similar to Long-Rossi & Salsich (2010) and Nakagawa et al. (2011), we also found a significant, albeit weak, correlation between hip ER strength and perception of function in our sample. We did not find any significant relationships between any of the hip strength measures and perception of pain, which is also consistent with the results from Long-Rossi & Salsich. In contrast, Nakagawa et al. reported that hip ER strength was associated with perception of pain, however they utilized a different method for assessing hip ER strength than both our study and Long-Rossi & Salsich. Additionally, Nakagawa et al. reported higher perception of pain in their sample (4.56 ± 2.6) than in our sample (3.55 ±3.2) and in Long-Rossi & Salsich (3.12 ± 1.7). This could also potentially explain the difference in findings between studies as well. Our sample on average had higher perception of function (80.49 ± 7.87) than Long-Rossi & Salsich (76.3 ± 11.8) and Nakagawa et al. (73.88 ± 9.57).

Knee extension strength was also weakly correlated with lower perception of function in our sample. Given that the AKPS asks about several activities that involve flexing the knee, this finding is not surprising. Hip and knee strengthening exercises are commonly included in exercise therapy interventions for patients with PFP and has been credited with improving the perception of function in several studies (Collins et al., 2018; Earl & Hoch, 2011; Ferber et al., 2011; Ferber et al., 2015).

### ***Trunk, Hip, and Knee Biomechanics***

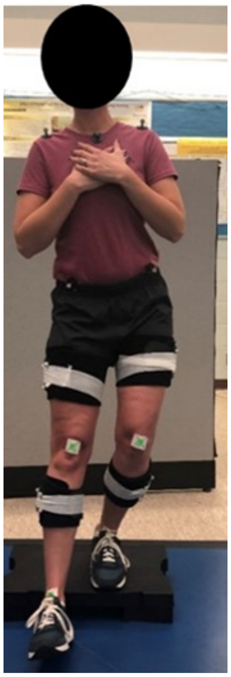
Based on previous research (Powers et al., 2003; Powers et al., 2017; Nakagawa et al., 2012), we anticipated that our sample would display dynamic malalignment at the point of peak knee flexion during performance of the step-down task. Dynamic malalignment is characterized by excessive medial displacement of the knee in the frontal plane, and has been associated with 3-D hip adduction and hip internal rotation angles. Within the pathomechanical model of PFP (Powers et al., 2017), dynamic malalignment during weight-bearing activities is theorized to increase the laterally directed component of the patellofemoral joint reaction force vector. Due to this proposed relationship, we expected that this movement pattern would influence the participant's perception of pain in our sample.

Interestingly, we identified 3-D hip IR angle as a significant predictor for perception of pain, and 2-D LTM was correlated with perception of function. However, in contrast to the movement pattern we expected to see based on the pathomechanical model, we identified that increased hip *external rotation* was associated with worse perception of pain in our sample. Two previous studies also reported decreased hip IR (or more external rotation) during walking in individuals with PFP as compared to healthy controls (Barton et al., 2011; Powers et al., 2002). This was hypothesized to be a compensatory movement to reduce patellofemoral joint stress while walking, but those two studies did not assess the perception of pain. Our finding conflicts with another study, Nakagawa et al. (2013), who reported that greater perception of pain was related to greater peak internal rotation, as well as greater peak hip adduction and knee abduction during a step-down task. Nakagawa et al. (2013) also identified greater hip adduction as a significant predictor for perception of function, while none of our 3-D measures were associated with perception of function. However, it should be noted that we measured our joint angles at the point of maximum knee flexion as compared to peak angle during the duration of the movement, which could explain the differences in findings in our study.

An interesting observation in our sample was that while we expected to see participants exhibit dynamic malalignment during the step-down task, we actually saw a larger proportion of our sample exhibit a different movement pattern at the point of maximum knee flexion (Figure 17). This movement pattern included a drop of the contralateral pelvis during single-leg support, leading to a shift of the center of mass away from the stance limb. This shift increases the distance from both the resultant ground reaction force vector and knee joint center, leading to an increase in varus moment at the knee (Powers, 2010). This type of movement pattern was observed in eleven of the 38 participants in this study.

**Figure 17**

*Movement Pattern Observed at Peak Knee Flexion of Step-down Task*



Also, interestingly, LTM was correlated with perceived function in our sample. Individuals who reported worse perception of function also tended to exhibit more lateral trunk lean away from the stance leg at the point of peak knee flexion. This suggests that our sample may have adopted a “trunk dominance” movement pattern of leaning their trunk away from the stance leg to avoid dynamic malalignment, which would be consistent with the movement pattern described earlier. Our sample demonstrated greater LTM during the step-down (15.83 ± 2.97 degrees) than reported by Dingenen et al. (2014) during performance of a single leg squat in healthy individuals (10.8 ± 6.5 degrees), which supports this possibility. Also supporting this finding, our sample also reported higher mean kFPPA angles (186.69 ± 7.11 degrees) than Dingenen et al. did with the single leg squat (178 ± 6.9 degrees), indicating that our sample moved their knee into a more varus position at the point of maximum knee flexion. However, we did not find a relationship between kFPPA values and participant perception of their pain or perception of function.

These findings suggest that the movement pattern we did observe in a third of our sample may be a compensatory movement specific to the step-down task to reach the foot to the ground. The step-down task from the height of 4-inches may not have been demanding enough to challenge the participants biomechanically. We may have witnessed more participants exhibit dynamic malalignment had we increased the step-height to 6-inches (Thorpe et al., 2021). Another potential explanation for this movement pattern is that the participants may have adopted this movement pattern in an attempt to avoid pain during the movement. The duration of symptoms for this sample was relatively long (36 ± 90 months), confirming the chronicity of their condition. It is plausible that there was an adaptation to their movement pattern over time to avoid pain, however we did not assess perception of pain during the step-down task so this explanation is purely speculative.

### *Clinical Impact*

While the results of this study identified correlations between hip IR rotation and perception of pain, and between hip ABD, hip ER, knee EXT strength, LTM, and perception of function, only hip IR was predictive of perception of pain. As mentioned earlier, given the value for the hip IR angle and standard deviation, we question the clinical significance of this finding. The perception of pain and perception of function were correlated and predictive of one another. Collectively, the results underscore the importance of considering the patient's perception of pain and perception of function in the design of treatment interventions for PFP. In particular, focusing treatment interventions on changing the perception of function for a patient with PFP could in turn change their perception of pain as well. These cognitions of perception of pain and perception of function appear to occur independent of muscle strength and biomechanics in this population, so therefore clinicians should consider more than just these factors when developing a plan of care.

Additionally, there was variability in the movement patterns observed in our sample. This may in part explain the inconsistencies in the pathomechanical model (Powers et al., 2017) and suggests that there isn't one specific altered movement pattern exhibited by individuals with PFP. This further emphasizes the need to target interventions on a patient's perceptions of pain and function.

### *Limitations*

One limitation of this study was the selection of factors from within the Biopsychosocial Model (Brewer et al., 2002). There are many other factors within the model that we did not account for or examine as part of this study. The decision to include the factors selected was based on existing PFP literature, suggesting a relationship with the perception of pain and perception of function (Nakagawa et al., 2011; Nakagawa et al., 2012; Powers et al., 2017). Due to the COVID-19 pandemic, we had to perform the clinical examination virtually, relying on patient responses to questions and researcher guided self-palpation to determine areas of point tenderness, which may differ from an in-person clinical examination where the clinician is palpating for tenderness. In our study we assessed isometric strength, which may differ from how muscles are activated during a dynamic task such as a step-down movement. We also had a relatively small sample for a multivariate regression model, which may not have adequate statistical power to adequately identify relationships, possibly resulting in a type II error. We based our sample size estimates on those in previous published studies with a similar design (Nakagawa et al., 2011; Nakagawa et al., 2012).

### ***Future Research***

More research is warranted to examine how other factors within the Biopsychosocial Model (Brewer et al., 2002), such as injury characteristics and sociodemographic factors alongside intermediate biopsychosocial outcomes and biological factors, may relate to the perception of pain and perception of function in patients with PFP.

There are also other psychological factors, such as fear avoidance, catastrophizing, and kinesiophobia that have been related to perceptions of pain and function in individuals with PFP (Maclachlan et al., 2018; Domenech et al., 2013). There is also support that fear-avoidance beliefs are associated with hip and knee strength and trunk biomechanics in individuals with PFP (Glaviano et al., 2019). There may be relationships between several of these affects and biological factors in this population that need to be better understood.

More research is warranted to examine perhaps other kinematic variables implicated in the pathomechanical model (Powers et al., 2017), such as pelvic position, and potential relationships with the perception of pain and perception of function in this sample. Given the movement pattern observed in a third of our sample and the correlation between LTM and perception of function, it is possible that motion at the pelvis might be related to the perception of function in this population.

## Conclusion

Higher usual pain was predicted by increased hip ER angle and worse perception of function. Worse perception of function was predicted by worse perception of pain, and correlated with decreased hip ABD strength, hip ER strength, and knee EXT strength, and increased LTM. Factors from the Biopsychosocial Model (Brewer et al., 2002) that predict perception of pain appear to be different than those that predict perception of function. This suggests that researchers and clinicians may wish to assess perception of function in individuals with PFP to determine a baseline, but also perhaps to gauge recovery from PFP following an intervention. In addition, since perception of function and perception of pain were highly related to one another, it would be advantageous to design exercise-based interventions that target these psychological factors within in the Biopsychosocial Model (Brewer et al., 2002) as a means of influencing both intermediate biopsychosocial outcomes and sport injury rehabilitation outcomes.

# Chapter Five: The Use of a Tele-health Squat Retraining Intervention for Individuals with Patellofemoral Pain (PFP)

## Introduction

Patellofemoral pain (PFP) is a chronic musculoskeletal condition characterized by retro- and peri-articular pain during activities such as squatting, navigating stairs, running, and sitting with the knees bent for a prolonged period of time (Crossley et al., 2016). Approximately 25% of the population has experienced PFP (Smith et al., 2018) and accounts for up to 40% of musculoskeletal conditions assessed in health care clinics (Witvrouw et al. 2014). The onset of pain and symptoms associated with PFP is insidious and is not the result of a specific acute trauma or direct tissue damage (Collins et al., 2018), and can interfere with the ability to engage in activities of daily living, physical activity, and occupational tasks (Smith et al., 2018). If left untreated, long-term PFP may ultimately contribute to the development of patellofemoral osteoarthritis (Crossley, 2014).

PFP is commonly treated conservatively, with interventions aimed primarily at addressing a pathomechanical mechanism theorized to cause an elevation in patellofemoral joint stress (Powers et al., 2017). External supports, such as taping (Kurt et al., 2016), bracing (Petersen et al., 2016; Uboldi et al., 2018), and orthotics (Barton et al., 2011) have been identified in previous studies to be effective in reducing participant's pain and function in the short term, but not as well in the long term. Exercise-based therapy is considered the gold standard treatment intervention for PFP (Collins et al., 2018) and often focuses on improving strength of the hip and knee musculature as a means of improving faulty movement patterns and biomechanics of the lower extremity. This approach is effective in improving hip and knee muscle strength (Ferber et al., 2015) and in some cases hip kinematics (Earl & Hoch, 2011) however these improvements are not always associated with improvements in participants' perception of pain /or perception of function (Pairot de Fontenay et al., 2018). Much like the evidence on external supports, exercise-based therapy that focuses on hip and knee strengthening does not improve the long-term prognosis for individuals with PFP (van Linschoten et al., 2009).

More recently, movement retraining has been explored as an adjunctive therapy focused on neuromuscular re-education of a movement that causes pain in individuals with PFP (Salsich et al., 2018; Roper et al., 2016; Willy et al., 2012; Noehren et al., 2011). In particular, running gait retraining has been a focus in this population as a means of not only significantly improving hip and knee biomechanics, but also improving participant's perceptions of pain and function (Roper et al., 2016; Willy et al., 2012; Noehren et al., 2011). Emerging evidence suggests the same approach may be utilized with a different task, such as step-down, that mimics a movement encountered in everyday life by the general population (Salsich et al., 2018). This is of significance since not all patients with PFP may be runners, or may be hesitant to try running due to their knee pain. The previous studies on these movement retraining interventions have also largely examined changes in 3-D joint kinematics using highly expensive and technical systems (Roper et al., 2016; Willy et al., 2012; Noehren et al., 2011; Salsich et al., 2018). There are more clinician-friendly measures, such as two-dimensional measurements like knee frontal plane projection angle (kFPPA) and lateral trunk motion (LTM) that may more practical and efficient to assess movement quality (Dingenen et al., 2013; Willson & Davis, 2008).

Collectively, the current treatment interventions primarily target muscular weakness or altered movement patterns that are theorized to cause PFP (Powers et al., 2017; Collins et al., 2018). Given the poor long-term prognosis following these interventions (van Linschoten et al., 2009), perhaps rehabilitation for PFP should be considered within a biopsychosocial framework.

The Biopsychosocial Model of Sport Injury Rehabilitation (Brewer et al., 2002) is a conceptual framework that considers the influence of a multitude of factors on the rehabilitation process. This model has been applied to the rehabilitation process for several acute injuries, including anterior cruciate ligament injuries (Brewer et al., 2004) and lateral ankle sprains (Arvinen-Barrow et al., 2019). The core of the Biopsychosocial Model consists of biological, psychological, and social and contextual factors, which are all interrelated (Brewer et al., 2002). The core is influenced by injury characteristics and sociodemographic factors, and influences intermediate biopsychosocial outcomes (Brewer et al., 2002). Psychological factors has a bidirectional relationship with intermediate biopsychosocial outcomes and sport injury rehabilitation outcomes, which are also interrelated (Brewer et al., 2002).

One of the social and contextual factors in the Biopsychosocial Model (Brewer et al., 2002) is the rehabilitation environment. The rehabilitation environment includes the treatment intervention selected for the patient along with the delivery of the intervention by a trained health care professional. This includes the decisions made by the health care professional regarding the delivery of the intervention. Modifications to the rehabilitation environment can have an impact on both psychosocial factors as well as intermediate biopsychosocial outcomes (Brewer et al., 2002; Arvinen-Barrow et al., 2019).

Within the context of movement retraining, there are several aspects of the delivery of the intervention that could be modified to enhance the rehabilitation environment. Consideration of factors that may enhance motor learning of the task, such as the progression, duration, and focus of attention on external cueing and tactile feedback schedule (Lorenz et al., 2010; Benjaminse et al., 2018; Aoyagi et al., 2019) are just some examples. In addition, adjusting the delivery of the treatment intervention to be more convenient for the patient, such as using tele-medicine, is another modification of the rehabilitation environment that may improve outcomes in this population (Tenforde et al., 2020).

Therefore, the purpose of this study was to determine if a synchronous, tele-health squat retraining intervention can change hip and knee strength, trunk, hip, and knee biomechanics (assessed in both 3D motion capture and 2D video), and participant's perception of pain and perception of function in individuals with PFP, and to determine the success rate of this approach. We hypothesized that the intervention would be effective in improving strength, biomechanics, and perception of pain and perception of function in individuals with PFP.

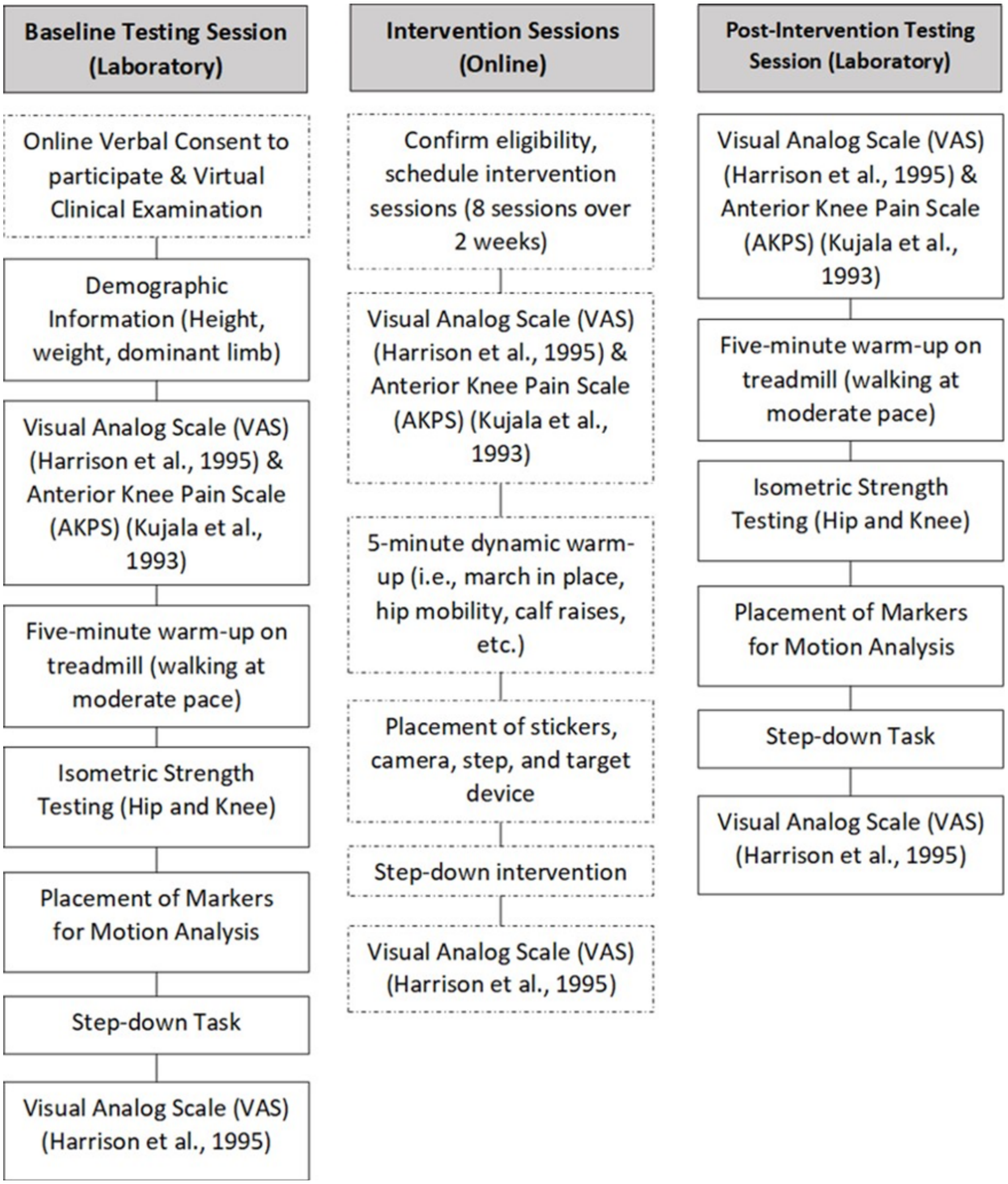
## Methods

### ***Study Design & Protocol***

The design for this study was a single-arm, repeated-measures feasibility study, conducted both in the laboratory and online. The study protocol is shown in Figure 18.

**Figure 18**

*Intervention Study Protocol Flow Chart*



### *Recruitment & Participants*

Participants were recruited from another study that identified individuals with PFP using a screening survey that included the Survey instrument for Natural history, Aetiology, and Prevalence of Patellofemoral pain Studies, or SNAPPS (Dey et al, 2016). This recruitment approach, rather than a clinical based approach, was used to sample from a broader general population instead of only those who are seeking medical care for their knee pain. Inclusion criteria from the other study that participants were recruited from included: 1.) between the ages of 18-45 years old; 2.) access to the internet and an electronic device with a camera; 3.) willing to travel to the laboratory data collection session(s). In addition, participants needed to report a score of a '3' or higher on the usual visual analog scale (VAS; Harrison et al., 1995). Following participation in the other study, the 2-D videos were reviewed and scored using a movement assessment rubric for a single-leg squat (Crossley et al., 2011) that was adapted for the step-down task used in this study. If a participant scored as "poor" or "fair", they were then invited to participate in this study. The exclusionary criteria also remained the same as the previous study (Table 6). If more than 2 weeks passed since the time the participant completed the baseline measurement, they were asked to complete an online VAS to confirm that their usual score on the VAS was still a '3' or higher prior to scheduling the sessions for the intervention.

### *Measures*

The following section includes all the measures included in this study and the time points when they were gathered.

Hip and knee strength were assessed isometrically using a Lafayette Manual Muscle Testing System hand-held dynamometer (HHD). Peak force was recorded for the motions of hip abduction (ABD), hip extension (EXT), hip external rotation (ER), and knee extension (EXT) for the involved or most painful limb (in the case of bilateral pain). The participant was instructed in the performance of each motion and secured to a treatment table using stabilizing straps. Prior to completing the test trials, the participant was instructed in the direction of the force and asked to perform three practice trials of increasing effort to gain familiarity with the task. The participant was instructed to maintain their maximum effort for each practice and test trial for a total of 5 seconds, which was timed using the HHD and confirmed by the researcher. Sixty seconds of rest was provided following each test trial. Three test trials were performed for each of the motions, with a fourth repetition performed if one of the previous repetitions was more than 10% greater or less than the other repetitions. The procedure, placement, and instructions for each of the four motions was replicated from previous studies and these methods are a reliable means of quantifying hip and knee isometric muscle strength (Figure 10; Jaramillo et al., 1994; Ireland et al., 2003, Boling, Padua, Marshall, et al., 2009). Verbal encouragement was provided to all participants during the test trials to encourage a maximal effort. These measures were performed at baseline and post-intervention in the laboratory.

Three-dimensional (3-D) biomechanics of the trunk & hip during a step-down task were recorded using a 10-camera Motion Analysis Eagle System (Motion Analysis Corp., Santa Rosa, CA) at 200 Hz. Reflective markers were placed on the participant prior to the movement trials to allow for identification of structures and joint centers (Figure 13). Single reflective markers were placed on the spinous process of C7, sternal notch, and right scapula; and bilaterally on the acromioclavicular joints, anterior superior iliac spines, posterior superior iliac spines, iliac crests, greater trochanters, lateral and medial femoral epicondyles, medial and lateral malleoli, and the 1st and 5th metatarsal heads. In addition, marker clusters consisting of four reflective markers affixed to a rigid plastic shell were positioned bilaterally to the lateral thigh, lateral shank, and a marker cluster of three reflective markers was positioned on the posterior heel counter. Once the reflective markers were in place, a standing calibration trial was completed and the markers on the right scapula, acromioclavicular joints, greater trochanters, medial and lateral epicondyles, medial and lateral malleoli, and 1st and 5th metatarsal heads were removed.

The variables of interest were the angles for trunk flexion (FLEX), hip adduction (ADD), and hip internal rotation (IR) at peak knee flexion. These three joint angles were selected due to their relationship with dynamic malalignment, as identified in previous studies (Willson & Davis, 2008). Kinematic analysis of these joint angles took place at the baseline and the post-intervention data collection sessions in the laboratory.

Two-dimensional (2-D) biomechanics of the trunk and knee were measured during performance of the step-down task both in the laboratory as well as during the online intervention sessions. During the laboratory sessions, fluorescent markers were placed bilaterally on the participant's greater trochanters, lateral femoral epicondyles, center of the patella, lateral malleoli, and anterior ankle mortise. Two Yi 4k+ action cameras (Yi Technology, Shanghai, China) were used to record the participant's movement during the step-down in both the frontal and sagittal planes. Both cameras were positioned at a height of 104 cm, 162.5 cm from the front of the step, and 167.5 cm from the side of the step on the stance limb side.

For the online intervention sessions, participants were instructed in the placement of the markers on the sternal notch, bilaterally on the anterior superior iliac spines, and on the center of patella and anterior ankle mortise of the stance limb. The participant's electronic device was positioned to allow a straight-on view of the participant on the step. The intervention sessions were recorded on the researcher's computer for later analysis.

The variables of interest for 2-D analysis were trunk lateral motion angle (LTM) and knee frontal plane projection angle (FPPA) at the point of peak knee flexion. These clinician-friendly measures were selected due to their relationship with dynamic malalignment (Willson & Davis, 2008).

For the purposes of this study, a visual analog scale (VAS; Harrison et al., 1995) was used to assess the participant's perception of pain for the past week, as well as the current perception of pain. Each participant was asked to rate their 'usual' perception of pain over the past 7 days at the beginning of the baseline and post-intervention sessions as well as at the beginning of each intervention session. This score was used to quantify the perception of pain for this study. Each of the participants was also asked to complete the VAS to assess current perception of pain before and after completing the step-downs and the intervention at the baseline testing session, intervention sessions, and post-intervention session.

The Anterior Knee Pain Scale (AKPS; Kujala et al., 1993) was utilized to assess the participant's perception of function. The AKPS was completed at the beginning of the baseline testing session, each intervention session, and at the post-intervention testing session.

At the end of the 8th and final intervention session, participants were asked to complete a brief, 5 question survey to gather information on the participant's opinions about the intervention delivery and set-up.

### *Procedures*

Eligible participants were included in this study from a previous study if they met the eligibility criteria listed earlier. Verbal consent for both this study and the previous study was obtained during a virtual online meeting in accordance with the university's Institutional Review

Board (IRB). In the same meeting, once consent was obtained, the researcher conducted a telehealth-style clinical examination due to the data collection period being within the COVID-19 pandemic. During this clinical examination, the researcher asked questions about the duration of symptoms, pain management strategies utilized since the onset of their knee pain, physical activity level, and whether they experienced pain with any of the following: during or after activity, navigating stairs, kneeling, or squatting. The researcher then guided the participant through self-palpation of the knee to identify any areas of point tenderness. The participant was instructed to position their camera on their knees so that the researcher could see where they were palpating to ensure they were on the correct anatomical structure, and to press on the identified structure with "enough pressure to indent the skin." The participants were shown a visual slide with a photograph of two knees, and as the researcher advanced through the palpation, the structure to be palpated was highlighted on the slide.

The participants then reported to the laboratory for their baseline testing session. During this session, anthropometric data such as height, weight, and dominant limb (defined as preferred limb for kicking a ball) was recorded. Participants also completed the VAS (Harrison et al., 1995) for both 'usual' perception pain over the past 7 days and current perception of pain followed by the AKPS (Kujala et al., 1993) to assess perception of function. Following a five-minute walking warm-up on the treadmill, isometric strength for hip ABD, hip EXT, hip ER, and knee EXT was measured as described in measures. Participants then completed the step-down task as described in measures, followed by another VAS (Harrison et al., 1995) to assess current perception of pain following the step-downs.

After this baseline testing session, the primary researcher reviewed the participant's VAS for 'usual' perception of pain to determine if they met the inclusion criteria of a score of a '3' or higher. If this was met, the participant's movement during the step-down task was reviewed and scored using a movement assessment rubric for a single-leg squat (Crossley et al., 2011) that was adapted for the step-down task used in this study. If a participant scored as "poor" or "fair", they were then invited to participate in this intervention phase of the study. If more than 2 weeks passed since the time the participant completed the baseline measurement, they were asked to complete an online VAS (Harrison et al., 1995) to confirm that their current pain level was still a '3' or higher prior to scheduling the sessions for the intervention.

All participants were informed that this was a novel intervention and the outcomes of this intervention are unknown. The primary researcher scheduled eight sessions with the participants over the course of two weeks for this intervention. All intervention sessions took place synchronously online, using Zoom (Zoom Video Communications, Inc., San Jose, CA). Upon completion of the intervention sessions, the participants were scheduled for a post-intervention testing session in the laboratory. During this post-intervention testing session, the participant returned the exercise kit and the measures from the baseline testing session were repeated.

Prior to the first intervention session, the primary researcher delivered an exercise kit that included all of the materials necessary to complete the intervention remotely (Figure 19). This exercise kit included an exercise step with adjustable risers to change the step height from 4 inches to 6 or 8 inches, fluorescent stickers, and an adjustable tripod for smaller electronic devices such as a cell phone or tablet. The kit also included a device consisting of a base and upright pole constructed of PVC pipes that served as the target for the movement during the intervention, as well as instructions for the intervention set-up.

**Figure 19**

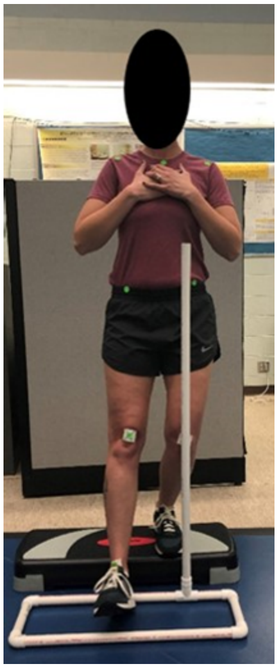
*Exercise Kit Provided to Participants*

During the first session, the participants were instructed in the set-up of the exercise step, positioning of the camera, safety measures, and placement of the fluorescent stickers. At the beginning of each session, the researcher would use the chat feature in Zoom to share the links for online versions of the VAS and AKPS in Qualtrics, which the participant would complete first. Next, the researcher would assist the participant as they adjusted their camera and position of the exercise step so that the researcher could see the participant and the exercise step in the screen. The researcher would then instruct the participant in proper placement of the fluorescent stickers on anatomical landmarks (sternal notch, bilaterally on the anterior superior iliac spines, and on the center of the patella and anterior ankle mortise on the involved limb). Next, the researcher led the participant through a 5-minute warm-up, consisting of marching in place, hip mobility exercises, quadriceps stretch, hamstring stretch, and calf raises.

Once the warm-up was complete, the researcher guided the participant in positioning of a target PVC pole in front of the involved limb. This PVC pole was positioned on a rectangular base and was attached to the base with an adjustable c-clamp. This allowed the participant to adjust the position of the target pole and to fold it down when it was not needed. This device provided an externally focused cue to direct the participants' knee position during the step-down exercise. For purposes of this exercise, the involved limb was the stance limb during performance of the step-down task. The target PVC pipe was positioned just lateral to the stance limb ASIS, and adjusted so that when the participant performed the step-down, they were able to touch the fluorescent sticker on the front of their knee to the pole in front of them while keeping their knee in proper alignment (Figure 20).

**Figure 20**

*Placement of the Target PVC Pole for the Intervention Sessions*



For the first session, all participants started with three sets of five repetitions of the step-down task on the involved limb. The participants were verbally instructed to "tap the pole in front of them" as they performed each repetition of the step-down. Participants were provided with verbal feedback as they requested during and after these repetitions. This feedback included directing the participant to slow down their motion to control movement as they lowered into the step-down motion, reminding the participant to lightly touch the reach limb to the floor instead of transferring their weight when performing the task, and counting the repetitions for the participant as they performed the task. Due to the use of teleconferencing for this intervention, the participants were able to view themselves while performing the task on their screen, as well as the researcher providing the cues, providing them with visual feedback of their performance. This portion of the session (the step-downs) were recorded using Zoom to allow for the researcher to watch later to calculate knee frontal plane projection angle as well as to ensure proper performance of the task and help in determining progression for the subsequent sessions.

Once the participant had completed the step-downs, they researcher shared a link to another online VAS to assess current pain following performance of the step-downs. The researcher then would confirm the next session with the participant.

The progression for this intervention was determined by the ability of the participant to execute a minimum of 80% of the repetitions during each session without errors. Errors were consistent with those used in another study using a similar task (Crossley et al., 2011) and include repositioning of the arms to aid in balance, complete transfer of weight to the non-stance limb, having to place the non-stance limb down to regain balance, and failure to touch the center of the patella to the pole. If the participant was able to perform at least 80% of these sets and repetitions without errors, they progressed as outlined in Table 12. This progression increased in the number of repetitions first, then step height (Lorenz et al., 2010).

**Table 12**

*Progression for Intervention Sessions*

| *Step 1* | *Step 2* | *Step 3* | *Step 4* | *Step 5* | *Step 6* | *Step 7* | *Step 8* |
|---|---|---|---|---|---|---|---|
| 3x5 on 4in step | 3x8 on 4in step | 3x10 on 4in step | 3x5 on 6in step | 3x8 on 6in step | 3x10 on 6in step | 3x5 on 8in step | 3x8 on 8in step |

The use of verbal and tactile cueing was also gradually reduced beginning with the second session, as outlined in Table 13 (Aoyagi et al., 2019). For each session that verbal and tactile cueing were provided, the participant was given the same verbal cueing to direct their alignment with the pole at the beginning of the intervention, but the pole was removed upon completion of the prescribed percentage of repetitions. Also, at this point, the researcher did not provide any verbal cues to the participant regarding the performance of their movement.

**Table 13**

*Verbal & Tactile Cueing Schedule*

| *Session 1* | *Session 2* | *Session 3* | *Session 4* | *Session 5* | *Session 6* | *Session 7* | *Session 8* |
|---|---|---|---|---|---|---|---|
| 100% of repetitions | 80% of repetitions | 60% of repetitions | 40% of repetitions | 20% of repetitions | None | None | None |

Upon completion of the step-downs on the final intervention session, the participants were asked to complete a brief participant input survey to provide information on the participant's opinions about the intervention and style of delivery. The participant was then scheduled for a post-intervention session in the lab to re-measure the pain and function measures, strength, and 3-D and 2-D biomechanical measures assessed in the baseline session.

***Data Processing***

The isometric hip and knee strength measures gathered at baseline and post-intervention testing sessions for each of the four motions were averaged across the three test trials. The averages were then normalized to body mass and recorded as a percentage of body mass in kg.

For 3-D kinematic analysis, joint angle data was collected from the step-down task trials performed in the laboratory and was filtered using a 4th order Butterworth filter with a cutoff frequency of 12 Hz. The segment coordinate systems for the lab set-up in this study followed the right-hand convention. The X-axis aligned with the medial-lateral direction, the Y-axis aligned in the anterior-posterior direction, and the Z-axis aligned in the vertical direction. The angles of trunk FLEX, hip ADD, and hip IR at the point of peak knee flexion were calculated using a joint coordinate system approach (Grood & Suntay, 1983) for the middle three repetitions of the five step-down trials for each set. The kinematic data were processed using Visual 3D software (C-Motion, Inc., Rockville, MD). The angles of interest were averaged and reported in degrees.

For the 2-D biomechanical analysis of the trials recorded in the laboratory, the videos recorded on the Yi 4k+ action cameras were uploaded into Dartfish 8 software (Dartfish USA, Inc., Alpharetta, GA) and synced. In Dartfish, the angles for LTM and kFPPA were calculated at the point of maximum knee flexion for the middle three repetitions of each set of step-downs. This approach has been used in previous research (Dingenen et al., 2013). The LTM angle was calculated as the angle between a vertical line starting from the anterior superior iliac spine and the horizontal line connecting the anterior aspect of the acromioclavicular joint and the sternal notch (Figure 14). Negative or smaller values indicate more lateral trunk lean over the stance limb, while larger values indicate lateral trunk lean away from the stance limb (Dingenen et al., 2013). The kFPPA was calculated as the angle between the line connecting the anterior superior iliac spine and the center of the patella and the line connecting the center of the patella and the anterior ankle mortise (Figure 15). A value of 180 degrees would indicate a neutral position of the knee relative to the hip. Values less than 180 would indicate dynamic malalignment, or positioning of the knee medial to the stance foot, and values over 180 would indicate positioning of the knee lateral to the stance foot (Dingenen et al., 2013). These values were reported in degrees. The videos from the intervention sessions were also uploaded into Dartfish and both LTM and kFPPA were calculated for these sessions to view the change in these measures across the intervention sessions.

For the baseline and post-intervention testing sessions in the laboratory, paper versions of the VAS and AKPS were utilized. The VAS (Harrison et al., 1995) was measured in cm from the left end of the scale to the mark that the participant marked on the scale. For analysis in this study, the ‘usual’ VAS score was used to quantify the perception of pain. The AKPS was scored using the standard scoring criteria (Kujala et al., 1993). The maximum score possible was 100, with a lower score indicating a lower level of function. During the intervention sessions, the VAS and AKPS were performed electronically using Qualtrics software. The participant input survey was also delivered electronically using Qualtrics. The values for all three of these measures were downloaded from Qualtrics in a CSV file for review and statistical analysis.

### *Statistical Analysis*

The *a priori* statistical analysis was to perform separate, one-sided, paired-sample t-tests to determine if there was a significant change in perception of pain, perception of function, hip or knee strength, 3-D joint angles, kFPPA, or LTM following completion of the intervention. The level of significance for this testing was set at $p \leq 0.05$. In addition, post-intervention perception of pain and perception of function were compared to baseline measures of these constructs to determine whether or not the intervention was successful or not for each participant based on the minimal clinically important difference (MCID) values for each measure. In order to be considered a successful outcome, the participant's perception of pain must have improved by at least 2cm on the VAS and/or the perception of function must have improved by at least 10 points on the AKPS (Crossley et al., 2004). The percentage of successful versus unsuccessful outcomes was calculated for this sample. Descriptive statistics were used to demonstrate changes in perception of pain, perception of function, kFPPA, and LTM across the intervention sessions.

The data were examined for each measure and tested for normality using Shapiro-Wilk tests. Baseline hip ABD strength, $W(10) = .722$, $p = .002$, baseline kFPPA, $W(10) = .746$, $p = .003$, and post-intervention hip ABD strength, $W(10) = .841$, $p = .045$ were not normally distributed. Therefore, related samples Wilcoxon Signed Rank tests were performed to determine if there were any significant differences in hip ABD strength and kFPPA from baseline to post-intervention, with the level of significance set at $p \leq 0.05$. The other outcome measures from this study were normally distributed, and the analysis for these variables was conducted as originally planned. Given the small sample size for this study, effect sizes were also calculated for each of the outcome measures in this study.

## Results

### *Demographic Data*

A total of ten participants were included in this study and completed the 8 sessions of the intervention and two testing sessions. Table 14 provides demographic information for each of the participants, as well as means for the outcome measures of interest. All ten of the participants attended all of the testing and intervention sessions and completed all of the sets and repetitions of the step-down task as prescribed in the intervention.

**Table 14**

*Intervention Participant Demographics*

| Variable | **n=10** | **SD** | **%** |
|---|---|---|---|
| Gender | | | |
| Female | n=9 | | 90 |
| Male | n=1 | | 10 |
| Age (years) | 36.30 | ± 6.48 | |
| Height (cm) | 172.15 | ± 11.06 | |
| Weight (kg) | 85.39 | ± 18.41 | |
| Duration of symptoms (months) [a] | 45.00 | ± 127.40 | |

Note: [a] These values were non-normally distributed, therefore central tendency values reported are the median and measure of variability is the interquartile range.

### *Comparison of Baseline and Post-Intervention Measures*

The perception of pain improved significantly from baseline to post-intervention (t(9) = 1.894, p = .045). Lateral trunk motion also significantly improved from baseline to post-intervention (t(9) = -2.206, p = .027). No significant differences were found for perception of function (t(9) = -1.291, p = .114) or any other biomechanical variables (hip ABD strength (Z = -.866, p = .386), hip EXT strength (t(9) = -.463, p = .327), hip ER strength (t(9) = -1.103, p = .149), knee EXT strength (t(9) = -.910, p = .193), hip ADD angle (t(9) = .526, p = .306), hip IR angle (t(9) = -.641, p = .269), trunk FLEX angle (t(9) = -1.007, p = .170), and kFPPA (Z = -.153, p = .878). The paired t-tests results for the baseline measures and post-intervention measures (except for Hip ABD strength and kFPPA), as well as means and effect sizes for all measures, are presented in Table 15. Small effect sizes were identified for the strength measures, 3-D joint angles, and AKPS scores, and kFPPA. Moderate effect sizes were identified for usual VAS scores and LTM.

**Table 15**

*Paired Samples Test Results & Effect Sizes*

|  |  |  |  |  |  | Significance | Cohen's d | 95% CI |  |
|---|---|---|---|---|---|---|---|---|---|
|  |  | Mean | SD | t | df | One-sided p | Point Estimate | Lower | Upper |
| Pair 1 | Baseline Perception of pain | 5.18 | 1.24 | 1.894 | 9 | .045* | .599 | -.092 | 1.26 |
|  | Post-Perception of pain | 3.57 | 2.47 |  |  |  |  |  |  |
| Pair 2 | Baseline Perception of function | 77.30 | 6.13 | -1.29 | 9 | .144 | -.408 | -1.045 | .249 |
|  | Post- Perception of function | 80.60 | 7.25 |  |  |  |  |  |  |
| Pair 3 | Baseline Hip EXT strength | .243 | .093 | -.463 | 9 | .327 | -.147 | -.766 | .481 |
|  | Post-Hip EXT strength | .260 | .091 |  |  |  |  |  |  |
| Pair 4 | Baseline Hip ER strength | .124 | .027 | -1.103 | 9 | .149 | -.349 | -.980 | .300 |
|  | Post-Hip ER strength | .135 | .033 |  |  |  |  |  |  |
| Pair 5 | Baseline Knee EXT strength | .198 | .058 | -.910 | 9 | .193 | -.288 | -.914 | .353 |
|  | Post-Knee EXT strength | .228 | .101 |  |  |  |  |  |  |
| Pair 6 | Baseline Hip ADD angle | .979 | 10.54 | .526 | 9 | .306 | .116 | -.463 | .786 |
|  | Post-Hip ADD angle | -.049 | 10.08 |  |  |  |  |  |  |
| Pair 7 | Baseline Hip IR angle | -.188 | 6.10 | -.641 | 9 | .269 | -.203 | -.824 | .429 |
|  | Post-Hip IR angle | .772 | 6.14 |  |  |  |  |  |  |
| Pair 8 | Baseline Trunk FLEX angle | -1.13 | 4.21 | -1.01 | 9 | .170 | -.318 | -.947 | .326 |
|  | Post-Trunk FLEX angle | -0.87 | 3.63 |  |  |  |  |  |  |
| Pair 9 | Baseline LTM | 15.93 | 2.27 | -2.206 | 9 | .027* | -.697 | -1.38 | .014 |
|  | Post-LTM | 17.46 | 2.70 |  |  |  |  |  |  |

* $p \leq 0.05$
**$p \leq 0.01$

### *Individual Participant Progress*

Table 16 presents the actual progression followed for each of the 10 participants in this study. Figures 21 and 22 present line graphs depicting the change in perception of pain and perception of function across the intervention sessions, respectively. Figure 23 illustrates the average kFPPA at peak knee flexion during the step-downs performed across the intervention sessions, and Figure 24 illustrates the average LTM at peak knee flexion across the intervention.

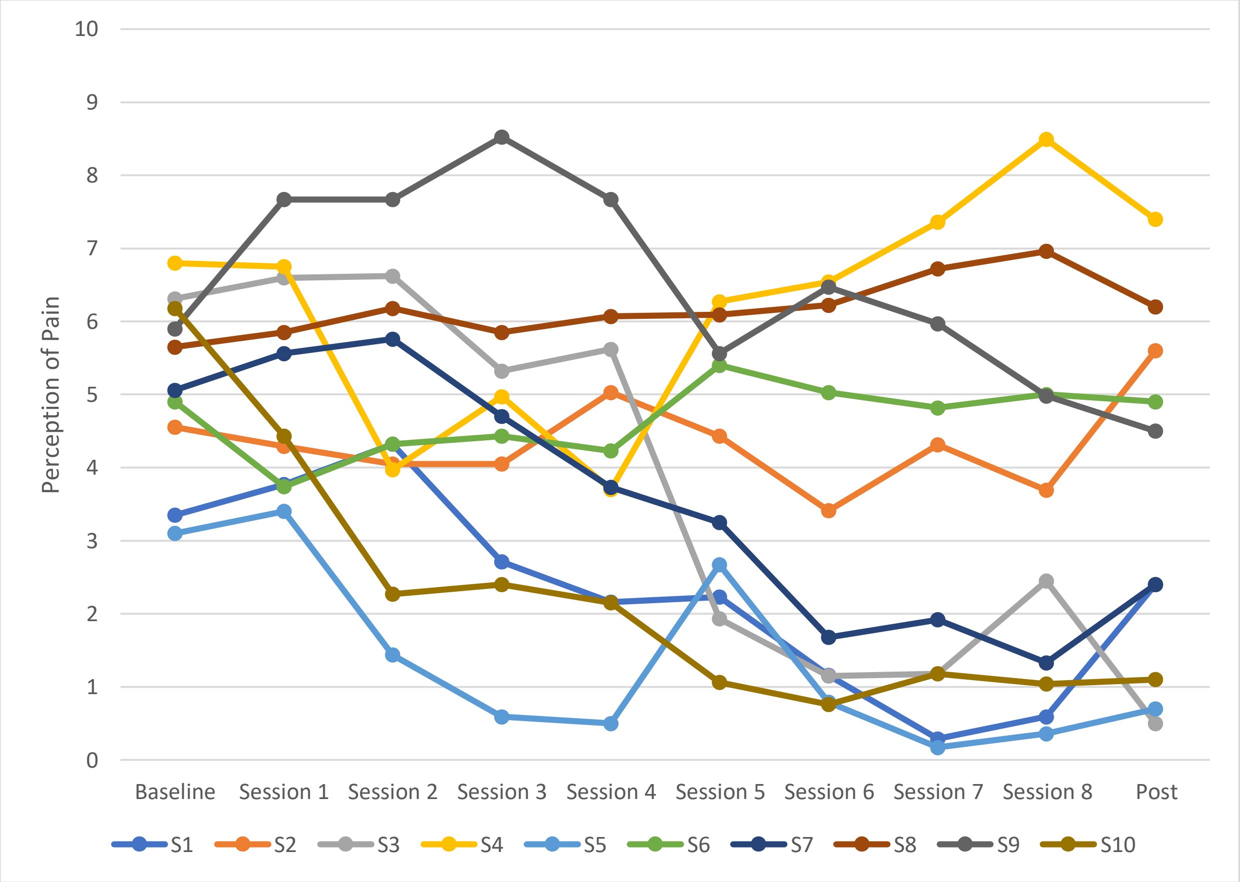
**Table 16**

*Participant Progression: Sets x Repetitions (Step Height in Inches)*

| | *Session* | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| *Participant* | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* |
| 1 | 3x5 (4) | 3x8 (4) | 3x8 (4) | 3x10 (4) | 3x5 (6) | 3x5 (6) | 3x8 (6) | 3x10 (6) |
| 2 | 3x5 (4) | 3x5 (4) | 3x5 (4) | 3x5 (4) | 3x8 (4) | 3x8 (4) | 3x8 (4) | 3x8 (4) |
| 3 | 3x5 (4) | 3x5 (4) | 3x5 (4) | 3x8 (4) | 3x10 (4) | 3x5 (6) | 3x5 (6) | 3x5 (6) |
| 4 | 3x5 (4) | 3x8 (4) | 3x8 (4) | 3x10 (4) | 3x5 (6) | 3x5 (6) | 3x5 (6) | 3x5 (6) |
| 5 | 3x5 (4) | 3x5 (4) | 3x8 (4) | 3x8 (4) | 3x8 (4) | 3x8 (4) | 3x10 (4) | 3x5 (6) |
| 6 | 3x5 (4) | 3x8 (4) | 3x10 (4) | 3x10 (4) | 3x5 (6) | 3x5 (6) | 3x8 (6) | 3x8 (6) |
| 7 | 3x5 (4) | 3x5 (4) | 3x5 (4) | 3x5 (4) | 3x8 (4) | 3x8 (4) | 3x10 (4) | 3x5 (6) |
| 8 | 3x5 (4) | 3x5 (4) | 3x5 (4) | 3x8 (4) | 3x8 (4) | 3x10 (4) | 3x10 (4) | 3x5 (6) |
| 9 | 3x5 (4) | 3x5 (4) | 3x5 (4) | 3x5 (4) | 3x8 (4) | 3x8 (4) | 3x10 (4) | 3x5 (6) |
| 10 | 3x5 (4) | 3x8 (4) | 3x10 (4) | 3x5 (6) | 3x8 (6) | 3x10 (6) | 3x5 (8) | 3x5 (8) |

**Figure 21**

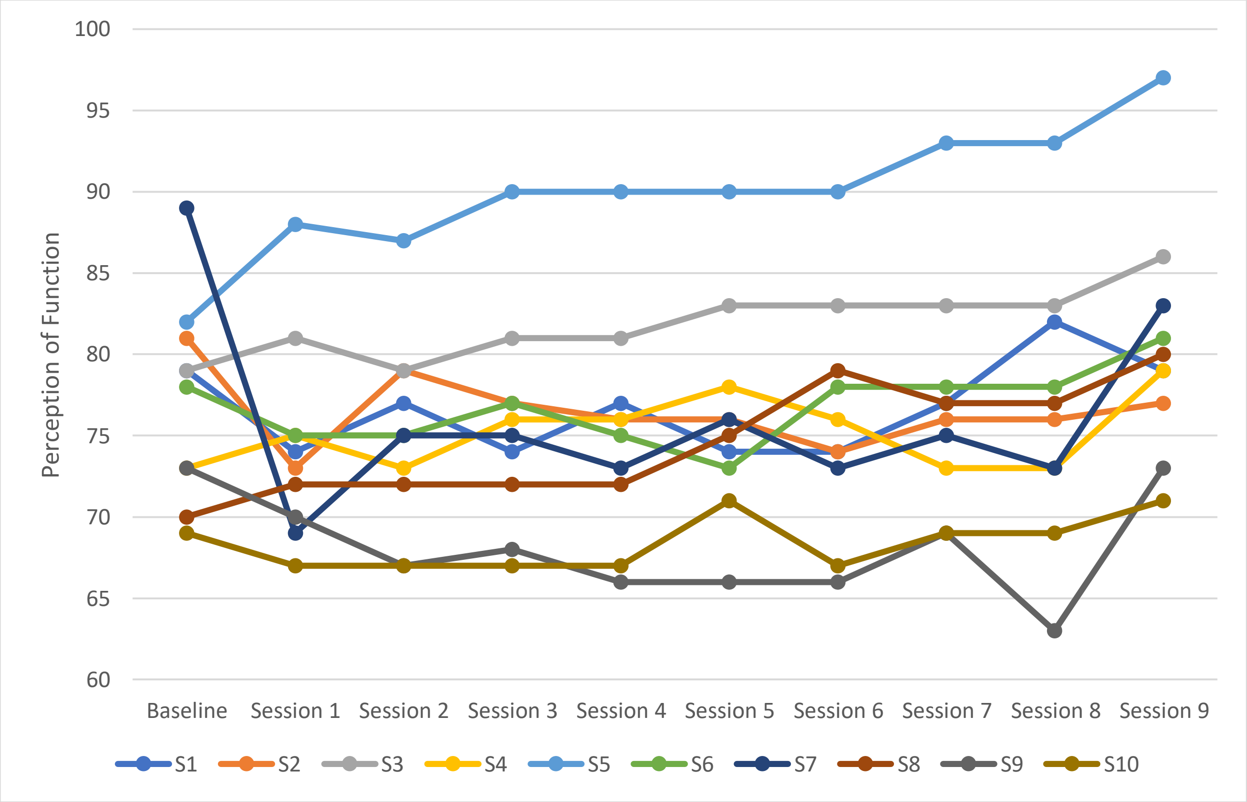
*Perception of Pain across Intervention Sessions*



*Note:* Each of the lines represents the data points for each of the participants in the intervention.

**Figure 22**

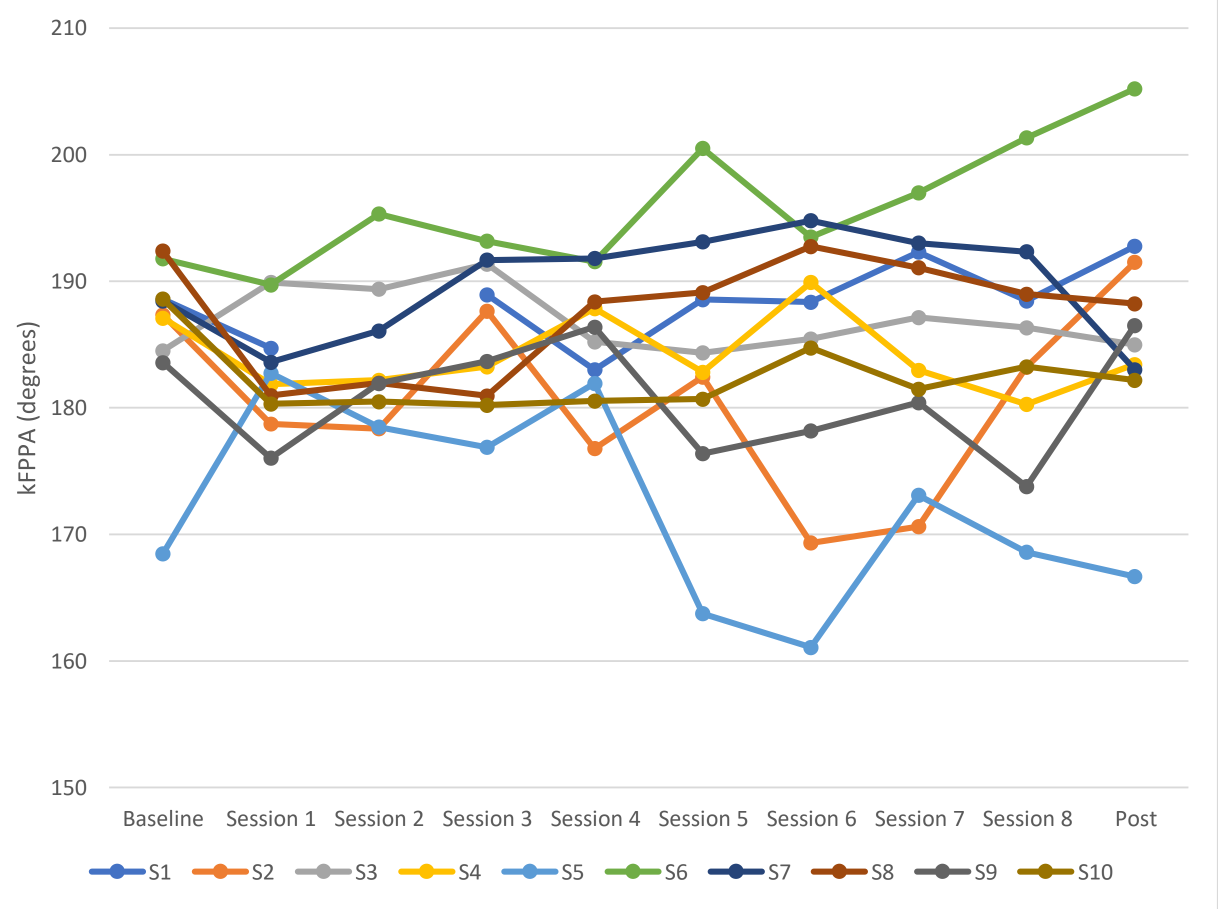
*Perception of Function across Intervention Sessions*



*Note:* Each of the lines represents the data points for each of the participants in the intervention.

**Figure 23**

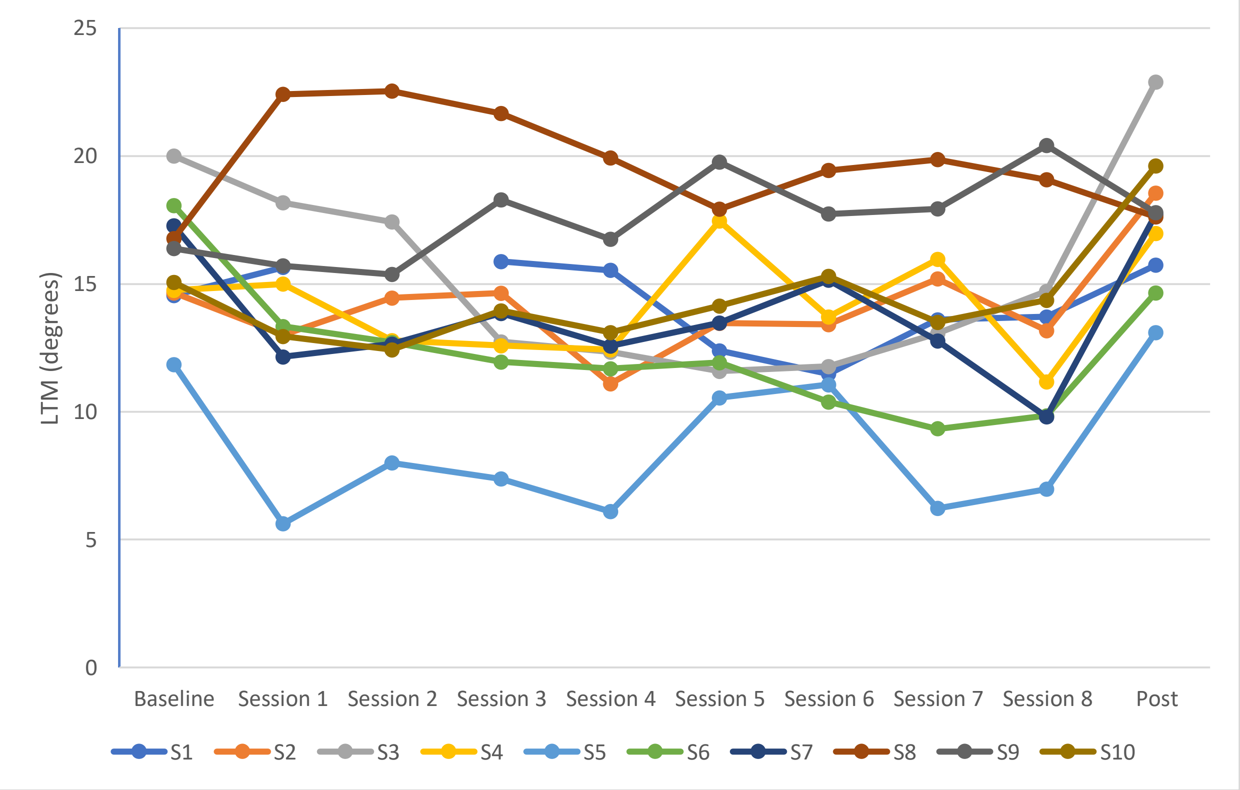
*kFPPA across Intervention Sessions*



*Note:* Each of the lines represents the data points for each of the participants in the intervention.

**Figure 24**

*LTM across Intervention Sessions*



*Note:* Each of the lines represents the data points for each of the participants in the intervention.

### *Minimal Clinically Important Difference (MCID) Results*

Five of the ten participants achieved a minimal clinically important difference in usual VAS score and/or AKPS score from baseline to post-intervention, which suggests the intervention had a 50% success rate in our sample.

### *Participant Input Survey Results*

A summary of the responses from the participant input survey can be found in Table 17. Almost all of the participants reported that the intervention scheduling, directions and cueing, set-up, and execution using technology were very easy.

**Table 17**

*Participant Input Survey Results*

| | *Very easy* | *Somewhat easy* | *Neither easy or difficult* | *Somewhat difficult* | *Very difficult* |
|---|---|---|---|---|---|
| Scheduling the sessions necessary for this intervention? | 9 | | 1 | | |
| Following the directions given to you to set up the intervention at home? | 10 | | | | |
| Following the cueing & feedback given to you during the intervention? | 10 | | | | |
| Setting up the equipment for the intervention? | 10 | | | | |
| Utilizing the technology used to complete the intervention? | 10 | | | | |

*Note:* n=10

## Discussion

We aimed to determine if the synchronous, tele-health squat retraining intervention aimed at changing faulty lower extremity movement patterns could change hip and knee strength, trunk, hip, and knee biomechanics (assessed in both 3D motion capture and 2D video), and participant's perceptions of pain and function in individuals with PFP. We hypothesized that the intervention would be effective in improving strength, biomechanics, and perceptions of pain and function in individuals with PFP.

### *Significant Findings*

The intervention used in this study improved the perception of pain in our sample. These findings are consistent with those of other studies that support the use of exercise-based therapy on changing the perception of pain in the short term (Collins et al., 2018). We also identified a significant increase in 2-D lateral trunk motion in our sample, suggesting that participants tended to be more upright with less lean during performance of the step-down following the intervention. We did not identify significant changes in our other outcome variables (perception of function, 3-D trunk and hip biomechanics, and 2-D knee biomechanics). Therefore, it appears that the improvement in the participants' perception of pain was due to other reasons independent of movement pattern or strength following the intervention.

The participants in this study varied greatly in the duration of symptoms associated with their PFP (median 45 months, range 2 – 240 months). Previous studies have reported that those with a longer duration of symptoms respond more favorably to exercise-based interventions (Lankhorst et al., 2015), which is consistent with what we found in our sample as a whole. In review of the trend lines for the change in perception of pain across the intervention sessions (Figure 24), it was noted that it appeared half of the sample had a more marked improvement in perception of pain compared to the other half. In comparison of the participants who exhibited a more marked improvement in perception of pain, the average duration of symptoms was 516.5 months (range 6.5-240 months) compared to an average duration of 262 months (range 2-120 months) in the remaining participants.

There also was a significant increase in 2-D lateral trunk motion following the intervention. Lower LTM values indicate that the participant was leaning over the stance limb, while larger values indicate more lean of the trunk away from the stance limb. While the intervention targeted motion at the knee, the participants may have adjusted the position of the trunk as a compensatory motion resulting from the cueing at the knee in the intervention. Ipsilateral trunk lean (or lateral trunk motion over the stance limb) is theorized to be a compensatory action to control contralateral pelvic drop and hip adduction of the stance limb during single-limb loadings tasks (Dierks et al., 2008; Souza & Powers, 2009). The intervention targeted improving motion at the knee, which in turn would influence hip position. It is possible that the change in position at the hip and/or the pelvis lead to the change in LTM. Further research into the role of pelvic control and how it may be used to enhance movement patterns in individuals with PFP is warranted given these findings.

In review of the trend lines for LTM in Figure 24, there appeared to be a noticeable increase in LTM at the post-intervention testing session compared to the intervention sessions for a majority of our sample. This could due to the differences in the execution of the step-down task between the intervention sessions and the testing sessions. During the baseline and testing sessions, the participant was instructed to perform the step-down at a cadence of 60 bpm for ease of post-processing. The participants were allowed to perform the step-downs during the intervention sessions at a self-selected pace, which could have influenced their movement pattern. In addition, the participants completed 3 sets of 5 repetitions of the step-down task from a 4-inch step height in the laboratory sessions. The participants varied in their progression during intervention sessions, but none of the participants remained at that phase of the progression up to the post-intervention testing session. Changes in step-height can lead to changes in lower extremity kinematics (Thorpe et al., 2021). The change in step height and number of repetitions may have attributed to differences in movement patterns as well.

Another consideration with these findings is that we utilized a 2-D measure for LTM. One limitation of 2-D measures is the inability to measure rotation in the transverse plane. Increased trunk rotation is a compensation that has been reported in females with PFP during performance of a similar task (Nakagawa et al., 2012). It is possible that motion in the transverse plan contributed to the 2-D measure of LTM calculated in this study.

### ***Non-significant Findings***

While not statistically significant, on average participants' perception of their function demonstrated slight improvement from baseline to post-intervention. This intervention focused solely on the performance of one task, the step-down task, which only encompasses one aspect of function. Comparatively, other studies that demonstrated improvements in self-reported function short-term included a wider range of exercises (Şahin et al. 2016; van Linschoten et al., 2009; Bolgla et al., 2016), which may have a larger impact on changing someone's perception of their overall function. However, the slight improvement identified in our sample is promising for this intervention to be coupled with other intervention strategies to improve self-reported function.

The intervention did not result in significant improvements in hip or knee strength or in 3-D trunk and hip biomechanics or 2-D knee biomechanics in our study. One potential explanation for the lack of change in biomechanics could be in part attributed to the age of our participants. The mean age of the participants in this study was 36.30 ± 6.48 years of age. Lack et al. (2014) reported that older individuals respond less favorably than younger individuals to exercise-based treatment interventions for PFP. Younger individuals may have a greater capacity for neuromuscular adaptations and strength gains than older individuals who are more fixed in their movement patterns (Lack et al., 2014).

Another potential influence on this finding could be the combination of the inclusion into the intervention and the designed purpose of the intervention. Based on previous studies on individuals with PFP, we hypothesized that we would observe dynamic malalignment at the point of peak knee flexion during the step-down task in our sample (Powers et al., 2003; Powers et al., 2017; Nakagawa et al., 2012). Dynamic malalignment is characterized by excessive medial displacement of the knee in the frontal plane, and has been associated with 3-D hip adduction and hip internal rotation angles. The intervention was designed to use the PVC pipe as an external target to redirect movement of the knee and elicit motor learning to improve movement during the step-down. As described in Chapter 4, we saw a larger proportion of the sample we recruited from for this study exhibit a different movement pattern at the point of maximum knee flexion (Figure 16). In contrast to dynamic malalignment, the movement pattern observed more commonly in our sample was marked by a drop of the contralateral pelvis during single-leg support, leading to a shift of the center of mass away from the stance limb. This shift increases the distance from both the resultant ground reaction force vector and knee joint center, leading to an increase in varus moment at the knee (Powers, 2010).

In review of the 10 participants in our study, there was a lot of variation in the movement patterns exhibited during the baseline step-down task. We had one participant who exhibited dynamic malalignment, five who exhibited the other movement pattern described above, and four who exhibited a large degree of perturbation of the stance limb during the ascent and descent of the step-down task. We opted to use a movement screening rubric we adopted from Crossley et al. (2011). This assessment consisted of 5 sections: 1.) overall impression across the 5 trials (including ability to maintain balance, perform the movement slowly with minimal perturbations, etc.), 2.) trunk posture, 3.) the pelvis “in space”, 4.) hip joint, and 5.) knee joint. Only five of the participants were rated as fair or poor in the hip joint section, and four participants were rated as fair or poor in the knee joint section. In contrast, all ten participants were rated as fair or poor for the pelvis “in space” section. Given the variability in movement among the participants, and that approximately only half of the participants were rated as fair or poor for the hip and knee section of our scoring rubric, it is possible that the exercise intervention did not target the most influential segment for their movement pattern.

One of the challenges of this intervention was designing an exercise that was universal in nature but could be individualized in execution. We chose the external cueing of the knee position during the step-down based on the hypothesis that we would see participants exhibit dynamic malalignment. As we saw more participants from our recruitment pool demonstrate a different movement pattern, we opted to retain this approach to determine if it would improve knee alignment to a more neutral position during the step-down task. In retrospect, given the frequency of participants who were rated as fair or poor for their pelvic control during the movement, we may have elicited better results regarding motor learning and movement pattern had we targeted this segment rather than the knee. We did not assess pelvic angles at baseline and post-intervention as part of this study, however we do have that data for future analysis. This would determine if targeting the position of the knee during this task may have influenced pelvic position.

### ***Findings Relative to the Biopsychosocial Model***

As highlighted earlier, the rehabilitation process can be viewed as biopsychosocial in nature. The Biopsychosocial Model of Sport Injury Rehabilitation (Brewer et al., 2002) can be used to in part explain the findings of this study. The squat retraining intervention, as well as the various aspects of delivery of the intervention contribute to the rehabilitation environment, a social and contextual factor within the Biopsychosocial Model (Brewer et al., 2002). The squat retraining intervention was designed to address not only strength and biomechanics (an intermediate biopsychosocial outcome of a biological factor); but also, to change the participants' perception of pain and perception of function (cognitions, psychological factors).

The intervention resulted in a significant improvement in the perception of pain independent of changes in strength and biomechanics. This supports the notion that rehabilitation is in fact biopsychosocial in nature. Several aspects of the intervention delivery, including the tele-health format and individualized attention from the clinician/researcher, may be viewed as modifications to the rehabilitation environment focused on making the intervention more accessible and convenient for the participant. In the preliminary research on the use of tele-health for rehabilitation of musculoskeletal conditions, patients have cited the elimination of travel time and convenience as two main benefits of this format (Telforde et al., 2020). These modifications to the rehabilitation environment may have had an impact on the participant's cognitions, leading to a change in the perception of pain.

### ***Clinical Impact***

These findings suggest that doing step-down exercises in a supervised, tele-health format may be an effective intervention to use for changing the perception of pain in patients with PFP. The utilization of an easy to perform task, such as the step-down, is key since it is a task that a vast majority of PFP patients can perform and encounter in everyday life. The feasibility of a similar approach was tested in another study, who reported trends towards improvement in lower extremity biomechanics and perceived pain and function following the 6-week intervention (Salsich et al., 2018). Clinicians may consider utilizing this approach in addition to other treatment intervention proven to improve outcomes for patients with PFP, such as other exercise-based therapies.

This study is the first to our knowledge to utilize a synchronous, virtual tele-health movement retraining intervention for PFP. Our findings suggest that this approach may be beneficial for patients and may improve accessibility to rehabilitation for individuals with PFP.

Given the fact that early interventions have been linked to better outcomes for those with PFP, this could help improve long-term outcomes.

### *Limitations*

The main limitation of this study was the small sample size. Our recruitment was impacted by the COVID-19 pandemic and time constraints for completion of the study, which made it more challenging to include a larger sample size. Another limitation of this study was the lack of a control group, which makes it difficult to determine if this intervention is superior to taking a “wait and see” approach. The variability in movement patterns exhibited by our participants and the uniformity of the task targeting movement of the knee was another limitation of this study. Finally, another limitation was the lack of assessing long-term outcomes from the intervention. Due to time constraints, we only assessed short-term outcomes.

### *Future Research*

Future research is warranted with a larger sample to determine if any significant improvements may be achieved with this intervention approach, specifically in perhaps targeting different segments, such as the pelvis given its implication in both trunk and knee motion. In addition, it would be beneficial to examine if incorporating other exercises, such as hip and knee strengthening in a tele-health manner could further enhance outcomes in this population. We also only assessed short-term outcomes from this study, so further examination of the long-term outcomes associated with this intervention would be beneficial. Lastly, it would be of interest to examine the transferability of this movement retraining approach to other functional activities, such as running.

## Conclusion

The use of a tele-health movement retraining intervention resulted in decreased pain in our sample of participants with PFP with no changes in lower extremity strength and biomechanics. This suggests the improvement in pain observed in our sample may be attributed to biopsychosocial factors, such as the rehabilitation environment and accessibility to the intervention. Live, tele-health rehabilitation sessions are feasible and may be employed on a larger scale to increase accessibility to a larger population of individuals with PFP. This could expand the reach of early interventions for PFP to a larger population, thereby enhancing health outcomes for PFP.

# Chapter Six: Conclusion

## Exploration of PFP from a Biopsychosocial Perspective

The underpinning framework for this research project was the biopsychosocial model of sport injury rehabilitation (Brewer et al., 2002). The main objectives of this research project were:

1) to better understand how selected injury characteristics (i.e., duration of symptoms and location of pain), sociodemographic factors (i.e. gender and age), and intermediate biopsychosocial outcomes (i.e. hip and knee strength, trunk, hip and knee biomechanics) relate to participant's perceptions of pain and/or function in individuals with patellofemoral pain (PFP);
2) to assess how a squat retraining intervention changes a participant's hip and knee strength, trunk, hip and knee biomechanics and perceptions of pain and function in individuals with PFP.

Given the inconsistencies in the pathomechanical model of PFP (Powers et al., 2017), and the need to determine more effective rehabilitation strategies for patients with PFP, we proposed examining this condition from a different perspective. The biopsychosocial model of sport injury rehabilitation (Brewer et al., 2002), similar to the biopsychosocial model by (Waddell, 1987), consists of a dynamic core consisting of biological, psychological, and social and contextual factors. This conceptual framework may be beneficial to consider relative to PFP to help better identify and understand the interrelationships among biopsychosocial factors that may influence the rehabilitation process and recovery of PFP.

Within the scope of this study, we aimed to explore the nature of interrelationships of biopsychosocial factors commonly reported in individuals with PFP. Within the Biopsychosocial Model (Brewer et al., 2002), the perception of pain and perception of function were viewed as cognitions, which are considered psychological factors. In PFP research, pain severity and self-reported function are considered outcome measures influenced by physical factors within the pathomechanical model (Powers et al., 2017). However, these measures are influenced by a wide range of factors as highlighted in the Biopsychosocial Model (Brewer et al., 2002).

Our findings supported the relationship between duration of symptoms, painful location(s) (localized versus widespread), and participants' perception of their function. We assessed perception of function using the AKPS (Kujala, 1993), which asks the participant about a wide range of activities that they may perform on a daily basis. Longer symptom duration and more widespread pain had a negative impact on how a patient perceived their function. Theoretically, the longer someone experienced pain, the more aware they become of how their pain impacts their ability to function relative to their PFP, which is reflected by worse perception of function. Similarly, the experience of more widespread pain may lead to the perception that the "injury" is worse than expected. For this reason, participants may feel that their function is more impacted than if they only had localized pain.

Interestingly, neither duration of symptoms or painful location(s) significantly predicted perception of pain. We assessed participant's perception of pain using an NPRS (Katz & Melzack, 1999) and the VAS (Harrison et al., 1995), reflecting their usual pain over the past 7 days. While these are both reliable and responsive measures (Crossley et al., 2004; Alghadir et al., 2018), it is a one-dimensional measure that may not adequately capture the whole nature of how that participant perceives their pain. Additionally, there could be a wide range of other factors that may have a more profound influence on participant's perception of pain, including past experiences with injuries and resulting pain, different coping strategies, life stresses, or perhaps biological factors such as central sensitization (Sigmund et al., 2020).

Neither of the selected sociodemographic factors (gender or age) were related to participants' perception of pain or perception of function. It is plausible that other sociodemographic factors in this box of the Biopsychosocial Model (Brewer et al., 2002) may be more influential on PFP participants' perceptions of their pain and function. For example, this study was conducted during the COVID-19 pandemic. There may have been other factors outside of the design of this study, such as socioeconomic status during the shutdowns that occurred during the pandemic, that may have also influenced these patient perceptions. Additionally, other factors, such as access to health care, may be more likely to be related to the perception of pain and perception of function in individuals with PFP.

We also sought out to describe the relationship between hip and knee strength and trunk, hip and knee biomechanics (biological factors) and participant perceptions of pain and function. In the Biopsychosocial Model, biological factors and psychological factors are interrelated (Brewer et al., 2002). Our study focused on the predictive relationship of these selected biological factors on psychological factors, but not the relationship in the opposite direction. We did find a correlation between hip IR angle and participants' perception of pain, and between hip ABD strength, hip ER strength, knee EXT strength, LTM, and participants' perception of function. Only hip IR was identified as a significant predictor of perception of pain, and given the relatively small magnitude of this value and the large standard deviation, we question the clinical significance of this finding. Collectively, these findings did not support the expected relationship between these selected biological factors of strength and biomechanics and PFP participants' perception of pain and perception of function.

Our findings suggest that individuals with PFP perceive their pain and function independent of their hip and knee strength and movement pattern. Standard exercise therapy typically is focused on improving strength and movement patterns, however the literature is conflicting on if these changes actually occur (Collins et al., 2018; Earl-Boehm & Hoch, 2011; Şahin et al., 2016; Pairot de Fontenay et al., 2018). Furthermore, improvements in perception of pain and perception of function frequently occur in the absence of other physical changes (Şahin et al., 2016; Pairot de Fontenay et al., 2018). Our results support this by the lack of significant predictive relationships between strength and biomechanics and perception of pain and perception of function, as well as the improvement in perception of pain independent of changes in movement or strength following the intervention.

There are several other factors that may fall into the context of intermediate biopsychosocial outcomes that were not examined in this study, however, that may be related to how individuals with PFP perceive their pain and function. We chose to examine joint angles at a very specific point within a dynamic movement (Thorpe et al., 2021). There may be other aspects of movement that might be more impactful. Additionally, the measures of hip and knee strength in our study were not dynamic and may not be indicative of muscle function during movement. There may be other measures, such as pelvic position or stability of the femur during a loading task, that may be more predictive of perception of pain and perception of function in this population.

What these results do highlight is that perhaps the factors from the top of the Biopsychosocial Model (Brewer et al., 2002), such as injury characteristics, may be more influential on the perception of pain and perception of function in patients with PFP. It also supports the notion that pain severity and self-reported function are perhaps better recognized as cognitions, or psychological factors within the Biopsychosocial Model (Brewer et al., 2002). The experience of pain resulting from PFP is a result of a cumulation of biopsychosocial factors that as a whole shape the individual appraisal and interpretation of their knee pain. This is important for both researchers and clinicians to recognize, as there may be variation in how each individual with PFP presents clinically in regards to strength and movement. It appears that individuals with PFP may in fact alter their movement for a wide range of reasons, and this may or may not contribute to increased PFJ loading and nociception, leading to PFP. This could in part explain the inconsistencies in the literature surrounding the mechanisms within the pathomechanical model (Powers et al., 2017). The experience of pain may be better explained as the cumulation of a range of biopsychosocial factors, which could include how long they have had their pain, how widespread their pain is, how effective their management strategies have been, in addition to biological factors such as central sensitization, impaired muscle function, altered movement patterns, etc. These factors are all very individualized and there may not be a single profile of factors that best define those who have PFP.

The movement retraining intervention that was piloted in this study may be viewed as a modification of the rehabilitation environment within the Biopsychosocial Model (Brewer et al., 2002). This intervention was delivered live and virtually, providing the participants with an intervention to address their knee pain in the comfort of their own homes. In addition, we utilized externally focused cues when directing the participants' knee position during the step-down task in an attempt to elicit motor learning. While we did not see significant changes in the hip and knee strength and biomechanics to suggest that motor learning occurred, we did observe significant improvements in the perception of pain. This could in part be explained by our modification of the rehabilitation environment, considered a social/contextual factor within the Biopsychosocial Model (Brewer et al., 2002). While the intent of the intervention was to encourage motor learning to improve movement during a step-down task, there were several aspects of the intervention that may have also impacted the participant's perceptions. As mentioned, due to modifications that were needed due to the COVID-19 pandemic, these sessions were held online instead of in-person in the laboratory as originally intended. This change in environment from an unfamiliar place to their home, an environment that they are comfortable in, may have had implications their perception of their pain.

Additionally, the live interaction with a clinician who was working with them to address their knee pain may have also had an impact, creating a supportive environment where the participant felt comfortable sharing their experiences. Although not an aim of this study, several participants did offer up their perspectives on their knee pain and how they felt the intervention was influencing their knee pain. Interestingly, there were differing perspectives that emerged, including feeling "stronger" during other activities throughout the day as a result of doing the intervention, to others acknowledging that while the exercises may have increased their pain initially, overall, they felt that the "exercises were helping".

Overall, the Biopsychosocial Model (Brewer et al., 2002) is a good starting point as a conceptual framework for understanding PFP. Our findings do suggest that the experience of PFP may be very individual and is the cumulation of a wide range of factors, not simply the product of a set combination of muscle weakness and faulty movement pattern. It is important for future research to examine this condition within the context of a biopsychosocial framework, rather than solely a pathomechanical approach. More qualitative studies are needed to better understand the lived experiences of those with PFP, which could help develop and better define an inclusive model that is more specific to PFP and incorporates both the biopsychosocial and pathomechanical factors that influence the experience for those with this condition.

## Limitations

There were several limitations to this study that should be acknowledged. While we did find excellent agreement with SNAPPS (Dey et al., 2016) and the recommended clinical criteria (Willy et al., 2019) for diagnosing PFP, we relied only on SNAPPS score to define our sample with PFP. We had two participants in Study 2 who met the SNAPPS score cutoff, but did not meet the clinical criteria for PFP. Additional research should explore the alignment between SNAPPS and the clinical criteria for PFP.

Secondly, for Study 2 and 3, our sample sizes were relatively small. We had 38 participants in Study 2 and 10 in Study 3. We estimated our sample size for Study 2 and 3 based on previous studies (Nakagawa et al., 2011; Nakagawa et al., 2013). We did recruit the full 40 participants for Study 2, but had one participant who did not report for the data collection session in the lab, and we had issues with one participant's 3-D biomechanical data that we were unable to re-collect due to the COVID-19 pandemic onset. For Study 3, we had hoped to recruit 20 participants from Study 2 who displayed dynamic malalignment and had a VAS score of greater than 3. However, we did not see as many participants with dynamic malalignment as we had hypothesized we would, so we adjusted the inclusion criteria to use a movement assessment rubric (Crossley et al., 2011). This adjustment led to 17 eligible participants, with two reporting at follow-up that they no longer had knee pain and five who did not wish to continue into Study 3.

We focused solely on the step-down task for Study 2 and 3 given its applicability to activities of daily living, such as walking down stairs. There may be other dynamic tasks that may be better suited for identifying dynamic malalignment in individuals with PFP. Additionally, we standardized the step height for all participants at 4 inches. It is plausible that had we increased the step-height, we may have challenged the participants movement pattern more than the 4-inch height (Thorpe et al., 2021). In Study 3, we consistently observed an increase in perception of pain following an increase in step height during the intervention progression. This also seemed to make the task more difficult for the participants as well.

Another limitation was that in the lab sessions we used a metronome to standardize the movement cadence for our 3-D analysis. This may have had an impact on the participant's movement during the step-down, as it not only may have led to alterations in the preferred cadence of the movement, but also provided another attentional focus that may have interfered with focus on the step-down task performance.

## Impact on Clinical Practice

We hypothesized that the individuals with PFP in our study would demonstrate dynamic malalignment during performance of the step-down task. We did have some participants who displayed this movement pattern, however we also saw a larger portion of our sample display a different movement pattern at the point of maximum knee flexion during the step-down. This observation led to the decision to change the inclusion criteria into the intervention phase of this study. These findings may suggest that there isn't a "one shoe fits all" approach when it comes to movement patterns in individuals with PFP. More research is warranted to examine how movement patterns differ among those with PFP and to perhaps examine if a different assessment of movement is more indicative of pain and function. It appeared from our study that simply increasing activity levels may have had an impact on the perception of pain. Clinicians may want to design interventions focused on increasing activity levels and thereby perception of function rather than correcting biomechanics to improve alignment.

The movement retraining intervention performed in this study shows promise for treating patients with PFP. More research is needed to identify ways in which this intervention can be enhanced and paired with other exercises to enhance treatment outcomes. These same principles may be able to be applied to other novel tasks as well. The participants in this study reported that the live, tele-health approach was easy to follow and complete. This approach became vital during the COVID-19 pandemic but may be a means of providing access to rehabilitation for those who would normally face barriers, such as cost, transportation, or scheduling difficulties.

Our study also suggested that the role of the rehabilitation environment is one that should be leveraged when working with patients with PFP. The simple act of listening to a patient's experience with their knee pain might in itself serve a very important part of the healing process, and may help change how an individual with PFP perceives their condition. The importance of a good rapport with the clinician is something that can only serve to enhance outcomes for patients moving forward.

## Impact on PFP Research

There are several aspects of this study that are novel and contribute to the future research and clinical practice regarding PFP. We utilized SNAPPS (Dey et al., 2016) to identify PFP in our sample because it allowed us to recruit from a general population, capturing those who haven't sought medical attention or may have chosen self-management strategies to cope with their knee pain. This allows for inclusion of a broader sample in research to allow for a better understanding and more generalizability of the research findings. To our knowledge, this is the first study to utilize SNAPPS to identify individuals with PFP for inclusion. There was a 94% agreement between SNAPPS and the recommended clinical criteria for diagnosing PFP in Study 2. This supports the use of SNAPPS for larger scale survey research studies as well as for recruitment into laboratory-based studies.

One feature within SNAPPS that was of interest in our study was the knee pain maps to identify painful location(s). We utilized the heat map question within Qualtrics to build a knee pain map that allowed us to both get output regarding which regions of the knee were selected as well as descriptive visualizations that could be filtered to reflect responses to other items within the survey. While these visualizations were informative and aligned with patterns identified in previous studies, there is an opportunity for further development to create a more robust knee pain map tool within SNAPPS, similar to the one created by Boudreau et al. (2017).

The use of technology to enhance the availability of health care to a wider population is another topic that can be explored further in research. The execution of our intervention was easy for participants to complete in an online format. The outcomes we assessed were able to be captured digitally at each session, allowing us to gauge progress as the intervention was applied. This presents an exciting opportunity in PFP research to explore the capability of this type of intervention to reach an even broader population, as well as use other forms of technology to follow up on outcomes over a longer period of time.

## Directions for Future Research

Given our findings relative to the application of the Biopsychosocial Model of Sport Injury Rehabilitation (Brewer et al., 2002), there is a need for more qualitative research to understand the lived experiences of those with PFP to inform the application of a biopsychosocial framework to this condition. We selected variables to include in our study based on existing literature that has largely been anchored in a biomedical approach (Powers et al., 2017). During the clinical examination part of this study in particular, participants often wanted to share as much as possible about how their knee pain impacted the decisions they made on a daily basis. Some participants chose to accept their knee pain and simply coped with it as they went about their daily life and physical activity, while others had decided to avoid painful activities. Consistently it was noted that each participant's perception of the knee pain was very impactful in a personal way. This is important for researchers to recognize as future studies are designed. Not all PFP patients present alike – and their experience of PFP is a byproduct of a wide range of factors, including injury characteristics, potentially accessibility to health care, responsiveness to the rehabilitation environment, etc. Further qualitative work that captures the lived experiences of those with PFP is needed to help inform the best underpinning framework for evaluating and treating patients.

As previously identified, we observed a different movement pattern than we anticipated in our sample. We anticipated seeing more dynamic malalignment of the thigh and knee, but in reality, the movement of the hip, pelvis, and trunk appeared to be more impactful in our sample. Future studies examining biomechanics in individuals with PFP should include the pelvis and trunk to determine if movement of these segments is perhaps more significant to consider during tasks such as the step-down.

In addition to examining different lower extremity segments during performance of a dynamic task, it would be beneficial to look at other aspects of movement quality besides joint angles and moments. Many of the participants in our sample displayed a lot of perturbation of the knee as they descended and ascended during the step-down. Future studies could examine if this instability of the thigh during a step-down could be related to perception of pain and perception of function in this population.

Larger sample studies examining the effectiveness of novel movement retraining interventions are also warranted. While our study showed promise for a movement retraining for a step-down task, our relatively small sample size makes our findings more difficult to generalize to the larger population with PFP. Future studies may also consider comparing this approach to a control or other commonly utilized treatment approach.

Lastly, our study was the first to our knowledge to utilize a live, tele-health intervention with individuals with PFP. More research is warranted to determine the feasibility and effectiveness of this approach, utilizing other exercise-based therapies for PFP treatment. This approach may help overcome barriers that patients may face in seeking treatment for their knee pain by providing an opportunity to do so in the comfort of their own homes.

## Conclusion

Our results support that injury characteristics such as symptom duration and painful locations are related to how individuals with PFP perceive their function, which underscores the importance of early identification and treatment of PFP to minimize pain and preserve function. Our findings do not support a relationship between hip and knee strength and trunk, hip, and knee biomechanics and participant perceptions of pain and function. This suggests that the experience of PFP may be individual and there may not be a specific movement pattern or muscle weakness that is uniform to individuals with PFP. It is also plausible that other intermediate biopsychosocial outcomes may be related to the perception of pain and perception of function in individuals with PFP, such as range of motion or muscular endurance. The movement retraining intervention piloted in this study was effective at improving perception of pain, even though it did not lead to significant changes in strength or biomechanics. Further research is warranted to determine if modifications to this approach, such as increasing the duration or including other rehabilitation exercises could enhance other patient outcomes. While we identified some support for the application of the Biopsychosocial Model of Sport Injury Rehabilitation to PFP (Brewer et al., 2002), future work should be performed to develop a model that better depicts the complexity and individuality of this condition.

# References

Adams, N. (2006). Psychological, electromyographic, and neurochemical aspects of chronic low back pain: Can a biopsychosocial model be confirmed? *Journal of Musculoskeletal Pain, 14*(2), 33-44. https://doi.org/10.1300/J094v14n02_05

Alghadir, A. H., Anwer, S., Iqbal, A., & Iqbal, Z. A. (2018). Test-retest reliability, validity, and minimum detectable change of visual analog, numerical rating, and verbal rating scales for measurement of osteoarthritic knee pain. *Journal of pain research*, *11*, 851–856. https://doi.org/10.2147/JPR.S158847

Aminaka, N., Pietrosimone, B.G., Armstrong, C.W., Meszaros, A., & Gribble, P.A. (2011). Patellofemoral pain syndrome alters neuromuscular control and kinetics during stair ambulation. *Journal of Electromyography Kinesiology, 21*(4), 645-651. https://doi.org/10.1016/j.jelekin.2011.03.007

Anderson, K.O., Dowds, B.N., Pelletz, R.E., Edwards, T.W., & Peeters-Asdourian, C. (1995). Development and initial validation of a scale to measure self-efficacy beliefs in patients with chronic pain. *Pain, 63*(1), 77-84. https://doi.org/10.1016/0304-3959(95)00021-j

Aoyagi, Y., Ohnishi, E., Yamamoto, Y., Kado, N., Suzuki, T., Ohnishi, H., Hokimoto, N., Fukaya, N. (2019). Feedback protocol of 'fading knowledge of results' is effective for prolonging motor learning retention. *Journal of Physical Therapy Science, 31*(8): 687-691. https://dx.doi.org/10.1589%2Fjpts.31.687

Ardern, C.L., Kvist, J., & Webster, K.E. (2016). Psychological aspects of anterior cruciate ligament injuries. *Operative Techniques in Sports Medicine, 24*, 77-83. https://doi.org/10.1053/j.otsm.2015.09.006

Arendt-Nielsen, L., & Graven-Nielsen, T. (2011). Translational musculoskeletal pain research. *Best Practice & Research Clinical Rheumatology, 25*(2), 209-226. https://doi.org/10.1016/j.berh.2010.01.013

Arvinen-Barrow, M., Maresh, N., & Earl-Boehm, J. (2020). Functional outcomes and psychological benefits of active video gaming in the rehabilitation of lateral ankle sprains: A case report. *Journal of Sport Rehabilitation*, *29*(2), 213-224. https://doi.org/10.1123/jsr.2017-0135

Barton, C.J., Bonanno, D., Levinger, P., & Menz, H.B. (2010). Foot and ankle characteristics in patellofemoral pain syndrome: a case control and reliability study. *Journal of Orthopaedic & Sports Physical Therapy, 40*(5), 286-296. https://doi.org/10.2519/jospt.2010.3227

Barton, C.J., Levinger, P., Crossley, K.M., Webster, K.E., & Menz, H.B. (2012). The relationship between rearfoot, tibial, and hip kinematics in individuals with patellofemoral pain syndrome. *Clinical Biomechanics, 27*(7), 702-705. https://doi.org/10.1016/j.clinbiomech.2012.02.007

Barton, C.J., Levinger, P., Menz, H.B., & Webster, K.E (2009). Kinematic gait characteristics associated with patellofemoral pain syndrome: a systematic review. *Gait & Posture, 30*(4), 405-416. https://doi.org/10.1016/j.gaitpost.2009.07.109

Barton, C.J., Levinger, P., Webster, K.E., & Menz, H.B. (2011). Walking kinematics in individuals with patellofemoral pain syndrome: a case-control study. *Gait & Posture, 33*(2), 286-291. https://doi.org/10.1016/j.gaitpost.2010.11.022

Barton, C.J., Menz, H.B., & Crossley, K.M. (2011). Clinical predictors of foot orthoses efficacy in individuals with patellofemoral pain. *Medicine & Science in Sports & Exercise, 43*(9), 1603-1610. https://doi.org/10.1249/mss.0b013e318211c45d

Bauer, G.R., Braimoh, J., Scheim, A.I., & Dharma, C. (2017). Transgender-inclusive measures of sex/gender for population surveys: Mixed-methods evaluation and recommendations. *PLoS One, 12*(5), e0178043. https://doi.org/10.1371/journal.pone.0178043

Bazett-Jones, D.M., Cobb, S.C., Huddleston, W.E., O'Connor, K.M., Armstrong, B.S., & Earl-Boehm, J.E. (2013). Effect of patellofemoral pain on strength and mechanics after an exhaustive run. *Medicine & Science in Sports & Exercise, 45*(7), 1331-1339.

Beck, A.T., Ward, C.H., & Mendelson, M. (1961). An inventory for measuring depression. *Archives of General Psychiatry, 4*(6), 561-571.

Benjaminse, A., Welling, W., Otten, B., Gokeler, A. (2018). Transfer of improved movement technique after receiving verbal external focus and video instruction. *Knee Surgery, Sports Tramatology, Arthroscopy, 26*(3), 955-962. https://doi.org/10.1007/s00167-017-4671-y

Besier, T.F., Pal, S., Draper, C.E., Fredericson, M., Gold, G.E., Delp, S.L., & Beaupre, G.S. (2015). The role of cartilage stress in patellofemoral pain. *Medicine & Science in Sports & Exercise, 47*(11), 2416-2422. https://dx.doi.org/10.1249%2FMSS.0000000000000685

Biedert, R.M., & Gruhl, C. (1997). Axial computed tomography of the patellofemoral joint with and without quadriceps contraction. *Archives of Orthopedic and Trauma Surgery, 116*(1-2), 77-82. https://doi.org/10.1007/bf00434106

Binkley, J.M., Stratford, P.W., Lott, S.A., & Riddle, D.L. (1999). The Lower Extremity Functional Scale (LEFS): scale development, measurement properties, and clinical application. *Physical Therapy, 79*(4), 371-383.

Bolgla, L.A., Earl-Boehm, J.E., Emery, C., Hamstra-Wright, K., & Ferber, R. (2016). Pain, function, and strength outcomes for males and females with patellofemoral pain who participate in either a hip/core- or knee-based rehabilitation program. *International Journal of Sports Physical Therapy, 11*(6), 926-935.

Boling, M., & Padua, D. (2013). Relationship between hip strength and trunk, hip, and knee kinematics during a jump-landing task in individuals with patellofemoral pain. *International Journal of Sports Physical Therapy, 8*(5), 661-669.

Boling, M., Padua, D., Marshall, S., Guskiewicz, K., Pyne, S., & Beutler, A. (2010). Gender differences in the incidence and prevalence of patellofemoral pain syndrome. *Scandanivan Journal of Medicine & Science in Sports, 20*(5), 725-730. https://doi.org/10.1111/j.1600-0838.2009.00996.x

Boling, M.C, Padua, D.A., Marshall, S.W., Guskiewicz, K., Pyne, S., & Beutler, A. (2009). A prospective investigation of the biomechanical risk factors for patellofemoral pain syndrome: the Joint Undertaking to Monitor and Prevent ACL Injury (JUMP-ACL) cohort. *The American Journal of Sports Medicine, 37*(11), 2108-2116. https://doi.org/10.1177/0363546509337934

Boling, M.C., Nguyen, A., Padua, D.A., Cameron, K.L., Beutler, A., & Marshall, S.W. (2019). Gender-specific risk factor profiles for patellofemoral pain. *Clinical Journal of Sports Medicine, 31*(1), 49-56. https://doi.org/10.1097/jsm.0000000000000719

Boling, M.C., Padua, D.A., & Creighton, R.A. (2009). Concentric and eccentric torque of the hip musculature in individuals with and without patellofemoral pain. *Journal of Athletic*

*Training, 44*(1), 7-13. https://doi.org/10.4085/1062-6050-44.1.7

Boonstra, A.M., Stewart, R.E., Köke, A.J., Oosterwijk, R.F., Swaan, J.L., Schreuers, K.M., Schiphorst Preuper, H.R. (2016). Cut-off points for mild, moderate, and severe pain on the Numeric Rating Scale for pain in patients with chronic musculoskeletal pain: Variability and influence of sex and catastrophizing. *Frontiers in Psychology, 7*, 1466. https://dx.doi.org/10.3389%2Ffpsyg.2016.01466

Booth, M. (2000). Assessment of physical activity: an international perspective. *Research Quarterly for Exercise and Sport, 71*, 114-120. https://doi.org/10.1080/02701367.2000.11082794

Borsa, P.A., Lephart, S.M., & Irrgang, J.J. (1998). Sport-specificity of knee scoring systems to assess disability in anterior cruciate ligament-deficient athletes. *Journal of Sport Rehabilitation, 7*, 44-60.

Boudreau, S.A., Kamavuako, E.N., & Rathleff, M.S. (2017). Distribution and symmetrical patellofemoral pain patterns as revealed by high-resolution 3D body mapping: a cross-sectional study. *BMC Musculoskeletal Disorders, 18*(1), 160. https://doi.org/10.1186/s12891-017-1521-5

Boudreau, S.A., Royo, A.C., Matthews, M., Graven-Nielsen, T., Kamavuako, E.N., Slabaugh, G., Thorborg, K., Vicenzino, B., Rathleff, M.S. (2018). Distinct patterns of variation in the distribution of knee pain. *Nature, 8*, 16522. https://doi.org/10.1038/s41598-018-34950-2

Brašnić, J.R. (2003). Documentation of demographic data. *Psychological Reports, 93*, 151-152. https://doi.org/10.2466/pr0.2003.93.1.151

Brechter, J.H., & Powers, C.M. (2002a). Patellofemoral joint stress during stair ascent and descent in persons with and without patellofemoral pain. *Gait & Posture, 16*(2), 115-123. https://doi.org/10.1016/s0966-6362(02)00090-5

Brechter, J.H., & Powers, C.M. (2002b). Patellofemoral stress during walking in persons with and without patellofemoral pain. *Medicine & Science in Sports Exercise, 34*(10), 1582-1593. https://doi.org/10.1097/00005768-200210000-00009

Brewer, B.W., Andersen, M.B., & Van Raalte, J.L. (2002). Psychological Aspects of Sport Injury Rehabilitation: Toward a Biopsychosocial Approach. In D.L. Mostofsky & L.D. Zaichkowsky (Eds.), *Medical and Psychological Aspects of Sport and Exercise* (pp. 41-54). Morgantown, WV, USA: Fitness Information Technology, Inc.

Brewer, B.W., Cornelius, A.E., Van Raalte, J.C., Brickner, J.H., Sklar, J.H., Corsetti, J.R., Pohlman, M.H., Ditmar, T.D., & Emery, K. (2004). Rehabilitation adherence and anterior cruciate ligament reconstruction outcome. *Psychology, Health & Medicine, 9*(2), 163-175. https://doi.org/10.1080/13548500410001670690

Brewer, B.W., van Raalte, J.L., Petitpas, A.J., Sklar, J.H., Pohlman, M.H., Krushell, R.J., Ditmar, T.D., Daly, J.M., Weinstock, J. (2000). Preliminary psychometric evaluation of a measure of adherence to clinic-based sport injury rehabilitation. *Physical Therapy in Sport, 1*, 68-74. https://doi.org/10.1054/ptsp.2000.0019

Campbell, P., Bishop, A., Dunn, K.M., Main, C.J., Thomas, E., & Foster, N.E. (2013). Conceptual overlap of psychological constructs in low back pain. *Pain, 154*(9), 1783-1791. https://doi.org/10.1016/j.pain.2013.05.035

Carlson, V.R., Boden, B.P., & Sheehan, F.T. (2017). Patellofemoral kinematics and TT-TG distances in adolescent females with patellofemoral pain. *The American Journal of Sports Medicine, 45*(5), 1102-1109. https://dx.doi.org/10.1177%2F0363546516679139

Cavazzuti, L., Merlo, A., Orlandi, F., & Campanini, I. (2010). Delayed onset of electromyographic activity of vastus medialis obliquus relative to vastus lateralis in subjects with patellofemoral pain. *Gait & Posture, 32*(3), 290-295. https://doi.org/10.1016/j.gaitpost.2010.06.025

Chen, Y., & Powers, C.M. (2014). Comparison of three-dimensional patellofemoral joint reaction forces in persons with and without patellofemoral pain. *Journal of Applied Biomechanics, 30*(4), 493-500.

Chesworth, B.M., Culham, E., Tata, G.E., & Peat, M. (1989). Validation of outcome measures in patients with patellofemoral pain. *Journal of Orthopaedic & Sports Physical Therapy, 10*, 302-308. https://doi.org/10.2519/jospt.1989.10.8.302

Claudon, B., Poussel, M., Billon-Grumiller, C., Beyaert, C., & Paysant, J. (2012). Knee kinetic pattern during gait and anterior knee pain before and after rehabilitation in patients with patellofemoral pain syndrome. *Gait & Posture, 36*(1), 139-143. https://doi.org/10.1016/j.gaitpost.2012.02.003

Collins, N. J., Barton, C. J., van Middelkoop, M., Callaghan, M. J., Rathleff, M. S., Vicenzino, B. T., Davis, I.S., Powers, C.M., Macri, E.M., Hart, H.F., de Oliveira Silva, D., & Crossley, K. M. (2018). 2018 Consensus statement on exercise therapy and physical interventions (orthoses, taping and manual therapy) to treat patellofemoral pain: recommendations from the 5th International Patellofemoral Pain Research Retreat, Gold Coast, Australia, 2017. *British Journal of Sports Medicine, 52*(18), 1170-1178. http://dx.doi.org/10.1136/bjsports-2018-099397

Collins, N., Crossley, K., Beller, E., Darnell, R., McPoil, T., & Vincenzino, B. (2008). Foot orthoses and physiotherapy in the treatment of patellofemoral pain syndrome: randomised clinical trial. *BMJ, 337*, a1735. https://doi.org/10.1136/bmj.a1735

Collins, N.J., Bierma-Zeinstra, S.M., Crossley, K.M., van Linschoten R.L., Vicenzino, B., van Middelkoop, M. (2012). Prognostic factors for patellofemoral pain: a multicenter observational analysis. *British Journal of Sports Medicine,47*(4)*,* 227-33. https://doi.org/10.1136/bjsports-2012-091696

Collins, N.J., Crossley, K.M., Darnell, R., Vicenzino, B. (2010). Predictors of short and long term outcome in patellofemoral pain syndrome: a prospective longitudinal study. *BMC Musculoskeletal Disorders, 11,*11. https://doi.org/10.1186/1471-2474-11-11

Cowan, S.M., Crossley, K.M., & Bennell, K.L. (2009). Altered hip and trunk muscle function in individuals with patellofemoral pain. *British Journal of Sports Medicine, 43*(8), 584-588. https://doi.org/10.1136/bjsm.2008.053553

Crossley, K. M. (2014). Is patellofemoral osteoarthritis a common sequela of patellofemoral pain? *British Journal Sports Medicine, 48*(6), 409-410. http://dx.doi.org/10.1136/bjsports-2014-093445

Crossley, K. M., Stefanik, J. J., Selfe, J., Collins, N. J., Davis, I. S., Powers, C. M., McConnell, J., Vicenzino, B., Bazett-Jones, D.M., Esculier, J., Morrissey, D., & Callaghan, M. J. (2016). 2016 Patellofemoral pain consensus statement from the 4th International Patellofemoral Pain Research Retreat, Manchester. Part 1: Terminology, definitions, clinical examination, natural history, patellofemoral osteoarthritis and patient-reported outcome measures. *British Journal of Sports Medicine, 50*(14), 839-843. http://dx.doi.org/10.1136/bjsports-2016-096384

Crossley, K.M., Bennell, K.L., Cowan, S.M., & Green, S. (2004). Analysis of outcome measures for persons with patellofemoral pain: which are reliable and valid? *Archives of Physical*

*Medicine & Rehabilitation, 85*(5), 815-822. https://doi.org/10.1016/s0003-9993(03)00613-0

Crossley, K.M., Cowan, S.M., Bennell, K.L., & McConnell, J. (2004). Knee flexion during stair ambulation is altered in individuals with patellofemoral pain. *Journal of Orthopaedic Research, 22*(2), 267-274. https://doi.org/10.1016/j.orthres.2003.08.014

Crossley, K.M., Zhang, W., Schache, A.G., Bryant, A., Cowan, S.M. (2011). Performance on the single-leg squat task indicates hip abductor muscle function. *American Journal of Sports Medicine, 39*(4), 866-73. https://doi.org/10.1177/0363546510395456

Daniel, D.M., Stone, M.L, Riehl, B., & Moore, M. (1984). A measurement of lower limb function. The one leg hop for distance. *American Journal of Knee Surgery, 4*, 212-214.

de Moraes Vieira, E.B., de Góes Salvetti, M., Damiani, L.P., & de Mattos Pimenta, C.A. (2014). Self-efficacy and fear avoidance beliefs in chronic low back pain patients: coexistence and associated factors. *Pain Management Nursing, 15*(3), 593-602. https://doi.org/10.1016/j.pmn.2013.04.004

de Oliveira Silva, D., Briani, R.V., Pazzinatto, M.F., Ferrari, D., Aragão, F.A., & de Azevedo, F.M. (2015). Reduced knee flexion is a possible cause of increased loading rates in individuals with patellofemoral pain. *Clinical Biomechanics, 30*(9), 971-975. https://doi.org/10.1016/j.clinbiomech.2015.06.021

Décary, S., Frémont, P., Pelletier, B., Fallaha, M., Belzile, S., Martel-Pelletier, J., Pelletier, J., Feldman, D., Sylvestre, M., Vendittoli, P., Desmeules, F. (2018). Validity of combining history elements and physical examination tests to diagnose patellofemoral pain. *Archives of Physical Medicine and Rehabilitation, 99*(4), 607-614. https://doi.org/10.1016/j.apmr.2017.10.014

Devilly, G.J., & Borkovec, T.D. (2000). Psychometric properties of the credibility/expectancy questionnaire. *Journal of behavior therapy and experimental psychiatry, 31*, 73-86. https://doi.org/10.1016/S0005-7916(00)00012-4

Dey, P., Callaghan, M., Cook, N., Sephton, R., Sutton, C., Hough, E., James, J., Saqib, R., Selfe, J. (2016). A questionnaire to identify patellofemoral pain in the community: an exploration of measurement properties. *BMC Musculoskeletal Disorders, 17*, 237. https://doi.org/10.1186/s12891-016-1097-5

Dierks, T.A., Manal, K.T., Hamill, J., & Davis, I. (2011). Lower extremity kinematics in runners with patellofemoral pain during a prolonged run. *Medicine & Science in Sports & Exercise, 43*(4), 693-700. https://doi.org/10.1249/mss.0b013e3181f744f5

Dingenen, B., Malfait, B., Vanrenterghem, J., Verschueren, S.M., & Staes, F.F. (2014). The reliability and validity of the measurement of lateral trunk motion in two-dimensional video analysis during unipodal functional screening tests in elite female athletes. *Physical Therapy in Sport, 15*(2), 117-123. https://doi.org/10.1016/j.ptsp.2013.05.001

Domenech, J., Sanchis-Alfonso, V., & Espejo, B. (2014). Changes in catastrophizing and kinesiophobia are predictive of changes in disability and pain after treatment in patients with anterior knee pain. *Knee Surgery, Sports Traumatology, and Arthroscopy, 22*(10), 2295-2300. https://doi.org/10.1007/s00167-014-2968-7

Domenech, J., Sanchis-Alfonso, V., López, L., & Espejo, B. (2013). Influence of kinesiophobia and catastrophizing on pain and disability in anterior knee pain patients. *Knee Surgery, Sports Traumatology, and Arthroscopy, 21*(7), 1562-1568. https://doi.org/10.1007/s00167-012-2238-5

Dowling, G.J., Murley, G.S., Munteanu, S.E., Smith, M.M., Neal, B.S., Griffiths, I.B., Barton, C.J., & Collins, N.J. (2014). Dynamic foot function as a risk factor for lower limb overuse injury: a systematic review. *Journal of Foot and Ankle Research, 7*(1), 53. https://doi.org/10.1186/s13047-014-0053-6

Downie, W.W., Leatham, P.A., Rhind, V.M., Wright, V., Branco, J.A., & Anderson, J.A. (1978). Studies with pain rating scales. *Annals of the Rheumatic Diseases, 37*, 378-381. https://doi.org/10.1136/ard.37.4.378

Draper, C.E., Besier, T.F., Fredericson, M., Santos, J.M., Beaupre, G.S., Delp, S.L., & Gold, G.E. (2011). Differences in patellofemoral kinematics between weight-bearing and non-weight-bearing conditions in patients with patellofemoral pain. *Journal of Orthopaedic Research, 29*(3), 312-317. https://doi.org/10.1002/jor.21253

Draper, C.E., Besier, T.F., Santos, J.M., Jennings, F., Fredericson, M., Gold, G.E., Beaupre G.S., & Delp, S. (2009). Using real-time MRI to quantify altered joint kinematics in subjects with patellofemoral pain and to evaluate the effects of a patellar brace or sleeve on joint motion. *Journal of Orthopaedic Research, 27*(5), 571-577. https://doi.org/10.1002/jor.20790

Drew, B.T., Redmond, A.C., Smith, T.O., Penny, F., & Conaghan, P.G. (2016). Which patellofemoral joint imaging features are associated with patellofemoral pain? Systematic review and meta-analysis. *Osteoarthritis and Cartilage, 24*(2), 224-236. https://doi.org/10.1016/j.joca.2015.09.004

Earl-Boehm, J., Bazett-Jones, D., Thorpe, J., Bolgla, L., Emery, C., Hamstra-Wright, K., & Ferber, R. (2017). *Relationships among patient reported, demographic, and clinical baseline measurements in patellofemoral pain patients.* Paper presented at the International Patellofemoral Pain Research Retreat, Gold Coast, Australia.

Earl-Boehm, J.E., & Hoch, A.Z. (2011). A proximal strengthening program improves pain, function, and biomechanics in women with patellofemoral pain syndrome. *American Journal of Sports Medicine, 39*(1), 154-163. https://doi.org/10.1177/0363546510379967

Esculier, J.F,, Bouyer, L.J., Dubois, B., Fremont, P., Moore, L., McFayden, B., & Roy, J.S. (2018). Is combining gait retraining or an exercise programme with education better than education alone in treating runners with patellofemoral pain? A randomized clinical trial. *British Journal of Sports Medicine, 52*(10), 659-666. https://doi.org/10.1136/bjsports-2016-096988

Esculier, J.F., Roy, J., Bouyer, L.J. (2013). Psychometric evidence of self-reported questionnaires for patellofemoral pain syndrome: a systematic review. *Disability and Rehabilitation, 35*(26), 2181-2190. https://doi.org/10.3109/09638288.2013.774061

Esfandiarpour, F., Lebrun, C.M., Dhillon, S., & Boulanger, P. (2018). In-vivo patellar tracking in individuals with patellofemoral pain and healthy individuals. *Journal of Orthopaedic Research*. https://doi.org/10.1002/jor.23887

Fairbank, J.C., Couper, J., Davies, J.B., & O'Brien, J.P. (1980). The Oswestry low back pain disability questionnaire. *Physiotherapy, 66*(8), 271-273.

Farrokhi, S., Keyak, J.H., & Powers, C.M. (2011). Individuals with patellofemoral pain exhibit greater patellofemoral joint stress: a finite element analysis study. *Osteoarthritis & Cartilage, 19*(3), 287-294. https://doi.org/10.1016/j.joca.2010.12.001

Ferber, R., Bolgla, L., Earl-Boehm, J.E., Emery, C., & Hamstra-Wright, K. (2015). Strengthening of the hip and core versus knee muscles for the treatment of patellofemoral pain: a multicenter randomized controlled trial. *Journal of Athletic Training, 50*(4), 366-377. https://dx.doi.org/10.4085%2F1062-6050-49.3.70

Finnoff, J.T., Hall, M.M., Kyle, K., Krause, D.A., Lai, J., & Smith, J. (2011). Hip strength and knee pain in high school runners: a prospective study. *PM&R, 3*(9), 792-801. https://doi.org/10.1016/j.pmrj.2011.04.007

Frydenberg, E., & Lewis, R. (2004). *Coping Scale for Adults. Administrator's Manual* (Research Edition ed.). Melbourne: Australian Council for Educational Research.

Fujii, T., Matsudaira, K., & Oka, H. (2013). Factors associated with fear-avoidance beliefs about low back pain. *Journal of Orthopaedic Science, 18*(6), 909-915. https://doi.org/10.1007/s00776-013-0448-4

Fulkerson, J.P. (2002). Diagnosis and treatment of patients with patellofemoral pain. *The American Journal of Sports Medicine, 30*(3), 447-456. https://doi.org/10.1177/03635465020300032501

George, S.Z., & Beneciuk, J.M. (2015). Psychological predictors of recovery from low back pain: a prospective study. *BMC Musculoskeletal Disorders,* (16), 49. https://dx.doi.org/10.1186%2Fs12891-015-0509-2

Gerbino, P.G., Griffin, E.D., d'Hemecourt, P.A., Kim, T., Kocher, M.S., Zurakowski, D., & Micheli, L.J. (2006). Patellofemoral pain syndrome: evaluation of location and intensity of pain. *The Clinical Journal of Pain, 22*(2), 154-159. https://doi.org/10.1097/01.ajp.0000159583.31912.1d

Giles, L.S., Webster, K.E., McClelland, J.A., & Cook, J. (2015). Can ultrasound measurements of muscle thickness be used to measure the size of individual quadriceps muscles in people with patellofemoral pain? *Physical Therapy in Sport, 16*(1), 45-52. https://doi.org/10.1016/j.ptsp.2014.04.002

Glaviano, N. R., Kew, M., Hart, J. M., & Saliba, S. (2015). Demographic and epidemiological trends in patellofemoral pain. *International Journal of Sports Physical Therapy, 10*(3), 281-290.

Glaviano, N.R., Baellow, A., Saliba, S. (2019). Elevated fear avoidance affects lower extremity strength and squatting kinematics in women with patellofemoral pain. *Athletic Training & Sports Health Care, 11*(4), 192-200. https://doi.org/10.3928/19425864-20181029-01

Grabiner, M.D., Koh, T.J., & Draganich, L.F. (1994). Neuromechanics of the patellofemoral joint. *Medicine in Science & Sports in Exercise, 26*(1), 10-21.

Grood, E.S., & Suntay, W.J. (1983). A joint coordinate system for the clinical description of three-dimensional motions: application to the knee. *Journal of Biomechanical Engineering, 105*(2), 136-144.

Haefeli, M. & Elfering, A. (2006). Pain assessment. *European Spine Journal, (Suppl 1),* S17-24. https://doi.org/10.1007/s00586-005-1044-x

Halabchi, F., Mazaheri, R., & Seif-Barghi, T. (2013). Patellofemoral pain syndrome and modifiable intrinsic risk factors; how to assess and address? *Asian Journal of Sports Medicine, 4*(2), 85-100. https://doi.org/10.5812/asjsm.34488

Harrison, E., Quinney, H., Magee, D., Sheppard, M.S., & McQuarrie, A. (1995). Analysis of the outcome measures used in the study of patellofemoral pain syndrome. *Physiotherapy Canada, 47*, 264-272.

Hartigan, E., Lewek, M., & Snyder-Mackler, L. (2005). The Knee. In P. Levangie & C. Norkin (Eds.), *Joint Structure and Function: A Comprehensive Analysis* (5th ed., pp. 395-435). Philadelphia, PA: F.A. Davis Company.

Hefti, F., Müller, W., Jakob, R.P., & Stäubli, H.U. (1993). Evaluation of knee ligament injuries with the IKDC form. *Knee Surgery, Sports Traumatology, Arthroscopy, 1*, 226-234. https://doi.org/10.1007/bf01560215

Heintjes, E.M., Berger, M.Y., Bierma-Zeinstra, S.M., Bernsen, R., Verhaar, J.A., & Koes, B.W. (2003). Exercise therapy for patellofemoral pain syndrome. *Cochrane Database System Review*(4), CD003472. https://doi.org/10.1002/14651858.CD003472

Herbst, K.A., Barber Foss, K.D., Fader, L., Hewett, T.E., Witvrouw, E., Stanfield, D., & Myer, G.D. (2015). Hip strength is greater in athletes who subsequently develop patellofemoral pain. *The American Journal of Sports Medicine, 43*(11), 2747-2752. https://doi.org/10.1177/0363546515599628

Herrington, L. (2014). Knee valgus angle during single leg squat and landing in patellofemoral pain patients and controls. *The Knee, 21*(2), 514-517.

Hill, J.C., Dunn, K.M, Lewis, M., Mullis, R., Main, C.J., Foster, N.E., & Hay, E.M. (2008). A primary care back screening tool: identifying patient subgroups for initial treatment. *Arthritis and Rheumatism, 59*(5), 632-641. https://doi.org/10.1002/art.23563

Ho, K., Keyak, J.H., & Powers, C.M. (2014). Comparison of patella bone strain between females with and without patellofemoral pain: a finite element analysis study. *Journal of Biomechanics, 47*(1), 230-236. https://doi.org/10.1016/j.jbiomech.2013.09.010

Hollman, J.H., Galardi, C.M., Lin, I., Voth, B.C., & Whitmarsh, C.L. (2014). Frontal and transverse plane hip kinematics and gluteus maximus recruitment correlate with frontal plane knee kinematics during single-leg squat tests in women. *Clinical Biomechanics, 29*(4), 468-474.

Hott, A., Brox, J.I., Pripp, A.H., Juel, N.G., Liavaag, S. (2020). Predictors of pain, function, and change in patellofemoral pain. *American Journal of Sports Medicine, 48*(2):351-358. https://doi.org/10.1177/0363546519889623

Huberti, H.H., & Hayes, W.C. (1984). Patellofemoral contact pressures. The influence of q-angle and tendofemoral contact. *The Journal of Bone & Joint Surgery, 66*(5), 715-724.

Hudson, Z., & Darthuy, E. (2009). Iliotibial band tightness and patellofemoral pain syndrome: a case-control study. *Manual Therapy, 14*(2), 147-151. https://doi.org/10.1016/j.math.2007.12.009

Insall, J., Goldberg, V., & Salvati, E. (1972). Recurrent dislocation and the high-riding patella. *Clinical Orthopaedics and Related Research, 88*, 67-69. https://doi.org/10.1097/00003086-197210000-00012

Ireland, M.L., Willson, J.D., Ballantyne, B.T., & Davis, I.M. (2003). Hip strength in females with and without patellofemoral pain. *Journal of Orthopaedic & Sports Physical Therapy, 33*(11), 671-676. https://doi.org/10.2519/jospt.2003.33.11.671

Irrgang, J.J., Snyder-Mackler, L., Wainner, R.S., Fu, F.H., & Harner, C.D. (1998). Development of a patient-reported measure of function of the knee. *The Journal of Bone and Joint Surgery. American volume, 80*, 1132-1145. https://doi.org/10.2106/00004623-199808000-00006

Jaramillo, J., Worrell, T.W., & Ingersoll, C.D. (1994). Hip isometric strength following knee surgery. *Journal of Orthopaedic & Sports Physical Therapy, 20*(3), 160-166.

Jensen, R., Hystad, T., & Baerheim, A. (2005). Knee function and pain related to psychological variables in patients with long-tern patellofemoral pain syndrome. *Journal of Orthopaedic & Sports Physical Therapy, 35*(9), 594-600. https://doi.org/10.2519/jospt.2005.35.9.594

Jonsson, T., Althoff, B., Peterson, L., & Renström, P. (1982). Clinical diagnosis of ruptures of the anterior cruciate ligament: A comparative study of the Lachman test and the anterior drawer sign. *American Journal of Sports Medicine, 10*, 100-102. https://doi.org/10.1177/036354658201000207

Kang, S., Choung, S., Park, J., Jeon, H., & Kwon, O. (2014). The relationship between length of the iliotibial band and patellar position in Asians. *The Knee, 21*(6), 1135-1138. https://doi.org/10.1016/j.knee.2014.09.005

Kase, K., Wallis, J., & Tsuyoshi, K. (2003). *Clinical therapeutic applications of the kinesio taping method* (3rd ed.): Kinesio USA.

Katz, J., & Melzack, R. (1999). Measurement of pain. *Surgical Clinics of North America, 79*, 231-252.

Kaya, D., Citaker, S., Kerimoglu, U., Atay, O.A., Nyland, J., Callaghan, M., Yakut, Y., Yüksel, I., & Doral, M.N. (2011). Women with patellofemoral pain syndrome have quadriceps femoris volume and strength deficiency. *Knee Surgery, Sports Traumatology, Arthroscopy, 19*(2), 242-247.

Kessler, R.C., Green, J.G., Gruber, M.J., Sampson, N.A., Bromet, E., Cuitan, M., Furukawa, T.A., Gureje, O., Hinkov, H., Hu, C., Lara, C., Lee, S., Mneimneh, Z., Myer, L., Oakley-Browne, M., Posada-Villa, J., Sager, R., Viana, M.C., Zaslavsky, A. (2010). Screening for serious mental illness in the general population with the K6 screening scale: results from the WHO World Mental Health (WMH) survey initiative. *International Journal of Methods in Psychiatric Research, 19*, 4-22. https://doi.org/10.1002/mpr.310

Kroenke, K., Spitzer, R.L., & Williams, J.B. (2001). The PHQ-9: validity of a brief depression severity measure. *Journal of General Internal Medicine, 16*(9), 606-613. https://doi.org/10.1046/j.1525-1497.2001.016009606.x

Kujala, U.M., Jaakkola, L.H., Koskinen, S.K., Taimela, S., Hurme, M., & Nelimarkka, O. (1993). Scoring of patellofemoral disorders. *Arthroscopy: The Journal of Arthroscopic & Related Surgery, 9*(2), 159-163. https://doi.org/10.1016/S0749-8063(05)80366-4

Kurt, E.E., Buyukturan, O., Erdem, H.R., Tuncay, F., & Sezgin, H. (2016). Short-term effects of kinesio tape on joint position sense, isokinetic measurements, and clinical parameters in patellofemoral pain syndrome. *Journal of Physical Therapy Science, 28*(7), 2034-2040. https://doi.org/10.1589/jpts.28.2034

Kvist, J., Ek, A., Sporrstedt, K., & Good, L. (2005). Fear of re-injury: a hindrance for returning to sports after anterior cruciate ligament reconstruction. *Knee Surgery, Sports Traumatology, Arthroscopy, 13*(5), 393-397. https://doi.org/10.1007/s00167-004-0591-8

Lack, S., Barton, C., Vicenzino, D., & Morrissey, D. (2014). Outcome predictors for conservative patellofemoral pain management: a systematic review and meta-analysis. *Sports Medicine, 44*(12), 1703-1716. https://doi.org/10.1007/s40279-014-0231-5

Lankhorst, N.E., Bierma-Zeinstra, S.M, & van Middelkoop, M. (2012). Risk factors for patellofemoral pain syndrome: A systematic review. *Journal of Orthopaedic & Sports Physical Therapy.* (Vol. 42, pp. 81-94). https://www.jospt.org/doi/10.2519/jospt.2012.3803

Lankhorst, N.E., van Middelkoop, M., Crossley, K.M., Bierma-Zeinstra, S.M., Oei, E.H., Vicenzino B., Collins, N.J. (2016). Factors that predict a poor outcome 5-8 years after the diagnosis of patellofemoral pain: a multicenter observational analysis. *British Journal of Sports Medicine, 50*, 881-886. https://doi.org/10.1136/bjsports-2015-094664

Lankhorst, N.E., van Middelkoop, M., van Trier, Y.D., van Linschoten, R., Koes, B.W., Verhaar, J.A., & Bierma-Zeinstra, S.M. (2015). Can we predict which patients with patellofemoral pain are more likely to benefit from exercise therapy? A secondary exploratory analysis of a randomized controlled trial. Journal of Orthopaedic & Sports Physical Therapy, 45(3), 183-189. https://doi.org/10.2519/jospt.2015.5583

Lee, T.Q., Yang, B.Y., Sandusky, M.D., & McMahon, P.J. (2001). The effects of tibial rotation on the patellofemoral joint: assessment of the changes in in situ strain in the peripatellar retinaculum and the patellofemoral contact pressures and areas. *Journal of Rehabilitation Research and Development, 38*(5), 463-469.

Levinger, P., & Gilleard, W. (2004). An evaluation of the rearfoot posture in inidividuals with patellofemoral pain syndrome. *Journal of Sports Science & Medicine, 3*(1), 8-14.

Liao, T., Yang, N., Ho, K., Farrokhi, S., & Powers, C.M. (2015). Femur rotation increases patella cartilage stress in females with patellofemoral pain. *Medicine & Science in Sports & Exercise, 47*(9), 1775-1780. https://doi.org/10.1249/mss.0000000000000617

Lobenhoffer, P., Posel, P., Witt, S., Piehler, J., & Wirth, C.J. (1987). Distal femoral fixation of the iliotibial tract. *Archives of orthopaedic and traumatic surgery, 106*(5), 285-290. https://doi.org/10.1007/bf00454335

Long-Rossi, F., & Salsich, G.B (2010). Pain and hip lateral rotator muscle strength contribute to functional status in females with patellofemoral pain. *Physiotherapy Research International., 15*(1), 57-64. https://dx.doi.org/10.1002%2Fpri.449

Lorenz, A., Muller, O., Kohler, P., Wünschel, M., Wülker, N., & Leichthle, U. (2012). The influence of asymmetric quadriceps loading on patellar tracking - an in vitro study. *The Knee, 19*(6), 818-822. https://doi.org/10.1016/j.knee.2012.04.011

Lorenz, D.S., Reiman, M.P., & Walker, J.C. (2010). Periodization: current review and suggested implementation for athletic rehabilitation. *Sports Health, 2*(6), 509-518. https://doi.org/10.1177/1941738110375910

Lovibond, S., & Lovibond, P. (1995). *Manual for the Depression Anxiety Stress Scales*. Sydney: Psychology Foundation.

Maclachlan, L.R., Matthews, M., Hodges, P.W., Collins, N.J., & Vicenzino, B. (2018). The psychological features of patellofemoral pain: a cross-sectional study. *Scandinavian Journal of Pain, 18*(2), 261-271. https://doi.org/10.1515/sjpain-2018-0025

Maddison, R., Prapavessis, H., & Clatworthy, M. (2006). Modeling and rehabilitation following anterior cruciate ligament reconstruction. *Annals of Behavioral Medicine, 31*(1), 89-98. https://doi.org/10.1207/s15324796abm3101_13

Magalhães, E., Fukuda, T.Y., Sacramento, S.N., Forgas, A., Cohen, M., & Abdalla, R.J. (2010). A comparison of hip strength between sedentary females with and without patellofemoral pain syndrome. *Journal of Orthopaedic & Sports Physical Therapy, 40*(10), 641-647. https://www.jospt.org/doi/10.2519/jospt.2010.3120

Maly, M.R., Costigan, P.A., & Olney, S.J. (2006). Role of kinematics and kinetics on performance and disability in people with medial compartment knee osteoarthritis. *Clinical Biomechanics, 21*(10), 1051-1059. https://doi.org/10.1016/j.clinbiomech.2006.06.010

Meira, E.P., & Brumitt, J. (2011). Influence of the hip on patients with patellofemoral pain syndrome: a systematic review. *Sports Health, 3*(5), 455-465.

Merican, A.M., Sanghavi, S., Iranpour, F., & Amis, A.A. (2009). The structural properties of the lateral retinaculum and capsular complex of the knee. *Journal of Biomechanics, 42*(14), 2323-2329. https://dx.doi.org/10.1016%2Fj.jbiomech.2009.06.049

Miller, R.P., Kori, S.H., & Todd, D.D. (1991). The Tampa Scale: a measure of kinesiophobia. *The Clinical Journal of Pain, 7*(1), 51.

Mitchell, T., O'Sullivan, P.B., Smith, A., Burnett, A.F., Straker, L., Thornton, J., & Rudd, C.J. (2009). Biopsychosocial factors are associated with low back pain in female nursing students: a cross-sectional study. *International Journal of Nursing Studies, 46*(5), 678-688. https://doi.org/10.1016/j.ijnurstu.2008.11.004

Mizner, R.L., Petterson, S.C., Clements, K.E., Zeni, J.A., Irrgang, J.J., & Snyder-Mackler, L. (2011). Measuring functional improvement after total knee arthroplasty requires both performance-based and patient-report assessments: a longitudinal analysis of outcomes. *Journal of Arthroplasty, 26*(5), 728-737. https://doi.org/10.1016/j.arth.2010.06.004

Møller, B.N., Krebs, B., & Jurik, A.G. (1986). Patellar height and patellofemoral congruence. *Archives of orthopaedic and traumatic surgery, 104*(6), 380-381. https://doi.org/10.1007/bf00454436

Moss-Morris, R., Weiman, J., Petrie, K., Horne, R., Cameron, L., & Buick, D. (2002). The revised illness perception questionnaire (IPQ-R). *Psychology & Health, 17*, 1-16. https://doi.org/10.1080/08870440290001494

Nakagawa, T.H., Baldon, R., Muniz, T.B., & Serrão, F.V. (2011). Relationship among eccentric hip and knee torques, symptom severity and functional capacity in females with patellofemoral pain syndrome. *Physical Therapy in Sport, 12*(3), 133-139. https://doi.org/10.1016/j.ptsp.2011.04.004

Nakagawa, T.H., Moriya, É.T., Maciel, C.D., & Serrão, F.V. (2012). Frontal plane biomechanics in males and females with and without patellofemoral pain. *Medicine & Science in Sports & Exercise, 44*(9), 1747-1755.

Nakagawa, T.H., Serrão, F.V., Maciel, C.D., & Powers, C.M. (2013). Hip and knee kinematics are associated with pain and self-reported functional status in males and females with patellofemoral pain. *International Journal of Sports Medicine, 34*(11), 997-1002. https://doi.org/10.1055/s-0033-1334966

Neal, B.S., Barton, C.J., Gallie, R., O'Halloran, P., & Morrissey, D. (2016). Runners with patellofemoral pain have altered biomechanics which targeted interventions can modify: A systematic review and meta-analysis. *Gait & Posture, 45*, 69-82.

Neumann, D. (2010). Kinesiology of the hip: a focus on muscular actions. *Journal of Orthopaedic & Sports Physical Therapy, 40*(2), 82-94. https://www.jospt.org/doi/10.2519/jospt.2010.3025

Nicholas, M.K. (2007). The pain self-efficacy questionnaire: taking pain into account. *European Journal of Pain, 11*, 153-163. https://doi.org/10.1016/j.ejpain.2005.12.008

Noehren, B., Scholz, J., & Davis, I. (2011). The effect of real-time gait retraining on hip kinematics, pain and function in subjects with patellofemoral pain syndrome. *British Journal of Sports Medicine, 45*(9), 691-696. https://doi.org/10.1136/bjsm.2009.069112

Noehren, B., Shuping, L., Jones, A., Akers, D.A., Bush, H.M., & Sluka, K.A. (2016). Somatosensory and biomechanical abnormalities in females with patellofemoral pain. *Clinical Journal of Pain, 32*(10), 915-919. https://doi.org/10.1097/ajp.0000000000000331

Ota, S., Nakashima, T., Morisaka, A., Ida, K., & Kawamura, M. (2008). Comparison of patellar mobility in female adults with and without patellofemoral pain. *Journal of Orthopaedic*

*& Sports Physical Therapy, 38*(7), 396-402.
https://doi.org/10.2519/jospt.2008.2585

Pairot de Fontenay, B., Esculier, J.F., Bouyer, L., & Roys, J.S. (2018). Hip kinematics during functional tasks in females with patellofemoral pain: Modification following rehabilitation and correlation with clinical improvement. *Physical Therapy in Sport, 32*(7), 7-14.
https://doi.org/10.1016/j.ptsp.2018.03.001

Pal, S., Besier, T.F., Beaupre, G.S., Fredericson, M., Delp, S.L., & Gold, G.E. (2013). Patellar maltracking is prevalent among patellofemoral pain subjects with patella alta: an upright, weightbearing MRI study. *Journal of Orthopaedic Research, 31*(3), 448-457.
https://doi.org/10.1002/jor.22256

Pal, S., Draper, C.E., Fredericson, M., Gold, G.E., Delp, S.L., Beaupre, G.S., & Besier, T.F. (2011). Patellar maltracking correlates with vastus medialis activation delay in patellofemoral pain patients. *The American Journal of Sports Medicine, 39*(3), 590-598.
https://doi.org/10.1177/0363546510384233

Panhale, V.P., Gurav, R.S., & Nahar, S.K. (2016). Association of physical performance and fear-avoidance beliefs in adults with chronic low back pain. *Annuals of Medical & Health Sciences Research, 6*(6), 375-379.
https://dx.doi.org/10.4103%2Famhsr.amhsr_331_15

Paoloni, M., Mangone, M., Fratocchi, G., Murgia, M., Saraceni, V.M., & Santilli, V. (2010). Kinematic and kinetic features of normal level walking in patellofemoral pain syndrome: more than a sagittal plane alteration. *Journal of Biomechanics, 43*(9), 1794-1798.
https://doi.org/10.1016/j.jbiomech.2010.02.013

Pappas, E., & Wong-Tom, W.M. (2012). Prospective predictors of patellofemoral pain syndrome: A systematic review with meta-analysis. *Sports Health, 4*(2), 115-120.
https://doi.org/10.1177/1941738111432097

Pattyn, E., Verdonk, P., Steyaert, A., Vanden Bossche, L., Van den Broecke, W., Thijs, Y., & Witvrouw, E. (2011). Vastus medialis obliquus atrophy: does it exist in patellofemoral pain syndrome? *The American Journal of Sports Medicine, 39*(7), 1450-1455. https://doi.org/10.1177/0363546511401183

Peacock, S., & Watson, P. (2003). The psychology of chronic pain. *British Journal of Anaesthesia, 8*(5), 147-150.

Petersen, W., Ellermann, A., Rembitzki, I.V., Scheffler, S., Herbort, M., Brüggemann, G.P., Best, R., Zantop, T., Liebau, C. (2016). Evaluating the potential synergistic benefit of a realignment brace on patients receiving exercise therapy for patellofemoral pain syndrome: a randomized clinical trial. *Archives of Orthopaedic and Trauma Surgery, 136*(7), 975-982. https://doi.org/10.1007/s00402-016-2464-2

Pincus, T., Kent, P., Bronfort, G., Loisel, P., Pransky, G., & Hartvigsen, J. (2013). Twenty-five years with the biopsychosocial model of low back pain- is it time to celebrate? A report from the twelfth international forum for primary care research on low back pain. *Spine, 38*(24), 2118-2123. https://doi.org/10.1097/brs.0b013e3182a8c5d6

Piper, B.F., Dibble, S.L., Dood, M.J., Weiss, M.C., Slaughter, R.E., & Paul, S.M. (1998). The revised Piper Fatigue Scale: psychometric evaluation in women with breast cancer. *Oncology Nursing Forum, 25*(4), 677-684.

Piva, S.R., Fitzgerald, G.K., Wisniewski, S., & Delitto, A. (2009). Predictors of pain and function outcome after rehabilitation in patients with patellofemoral pain syndrome. *Journal of Rehabilitation Medicine, 41*(8), 604-612. https://doi.org/10.2340/16501977-0372

Piva, S.R., Fitzgerald, K., Irrgang, J.J., Jones, J., Hando, B.R., Browder, D.A., & Childs, J.D. (2006). Reliability of measures of impairments associated with patellofemoral pain syndrome. *BMC Musculoskeletal Disorders, 7*, 33. https://dx.doi.org/10.1186%2F1471-2474-7-33

Piva, S.R., Goodnite, E.A., & Childs, J.D. (2005). Strength around the hip and flexibility of soft tissues in individuals with and without patellofemoral pain syndrome. *Journal of Orthopaedic & Sports Physical Therapy, 35*(12), 793-801. https://www.jospt.org/doi/10.2519/jospt.2005.35.12.793

Podlog, L., & Eklund, R.C. (2007). The psychosocial aspects of a return to sport following serious injury: A review of the literature from a self-determination perspective. *Psychology of Sport and Exercise, 8*(4), 535-566. https://doi.org/10.1016/j.psychsport.2006.07.008

Powers, C. M., Witvrouw, E., Davis, I. S., & Crossley, K. M. (2017). Evidence-based framework for a pathomechanical model of patellofemoral pain: 2017 patellofemoral pain consensus statement from the 4th International Patellofemoral Pain Research Retreat, Manchester, UK: part 3. *British Journal of Sports Medicine, 51*(24), 1713-1723. http://dx.doi.org/10.1136/bjsports-2017-098717

Powers, C.M, Heino, J.G., Rao, S., & Perry, J. (1999). The influence of patellofemoral pain on lower limb loading during gait. *Clinical Biomechanics, 14*(10), 722-728. https://doi.org/10.1016/s0268-0033(99)00019-4

Powers, C.M. (2003). The influence of altered lower-extremity kinematics on patellofemoral joint dysfunction: A theoretical perspective. *Journal of Orthopaedic & Sports Physical Therapy, 33*(11), 639-646. https://doi.org/10.2519/jospt.2003.33.11.639

Powers, C.M. (2010). The influence of abnormal hip mechanics on knee injury: a biomechanical perspective. *The Journal of Orthopaedic and Sports Physical Therapy, 40*(2), 42. https://www.jospt.org/doi/10.2519/jospt.2010.3337

Powers, C.M., Chen, P., Reischl, S.F., & Perry, J. (2002). Comparison of foot pronation and lower extremity rotation in persons with and without patellofemoral pain. *Foot & Ankle International, 23*(7), 634-640. https://doi.org/10.1177/107110070202300709

Powers, C.M., Maffucci, R., & Hampton, S. (1995). Rearfoot posture in subjects with patellofemoral pain. *Journal of Orthopaedic & Sports Physical Therapy, 22*(4), 155-160. https://doi.org/10.2519/jospt.1995.22.4.155

Powers, C.M., Ward, S.R., Fredericson, M., Guillet, M., & Shellock, F.G. (2003). Patellofemoral kinematics during weight-bearing and non-weight-bearing knee extension in persons with lateral subluxation of the patella: a preliminary study. *Journal of Orthopaedic & Sports Physical Therapy, 33*(11), 677-685. https://doi.org/10.2519/jospt.2003.33.11.677

Price, A.J., Jones, J., & Allum, R. (2000). Chronic traumatic anterior knee pain. *Injury, 31*(5), 373-378. https://doi.org/10.1016/s0020-1383(00)00006-1

Prins, M.R., & van der Wurff, P. (2009). Females with patellofemoral pain syndrome have weak hip muscles: a systematic review. *Australian Journal of Physiotherapy, 55*(1), 9-15. https://doi.org/10.1016/S0004-9514(09)70055-8

Priore, L.B., Azevedo, F.M., Pazzinatto, M.F., Ferreira, A.S., Hart, H.F., Barton, C., & de Oliveira Silva, D. (2019). Influence of kinesiophobia and pain catastrophism on objective function in women with patellofemoral pain. *Physical Therapy in Sport, 35*, 116-121. https://doi.org/10.1016/j.ptsp.2018.11.013

Rabin, A., Kozol, Z., Moran, U., Efergan, A., Geffen, Y., & Finestone, A.S. (2014). Factors associated with visually assessed quality of movement during a lateral step-down test among individuals with patellofemoral pain. *Journal of Orthopaedic & Sports Physical Therapy, 44*(12), 937-946. https://www.jospt.org/doi/10.2519/jospt.2014.5507

Rathleff, M.S., Rathleff, C.R., Crossley, K.M., & Barton, C.J. (2014). Is hip strength a risk factor for patellofemoral pain? A systematic review and meta-analysis. *British Journal of Sports Medicine, 48*(11), 1088. http://dx.doi.org/10.1136/bjsports-2013-093305

Rathleff, M.S., Roos, E.M., Olesen, J.L., Rasmussen, S., & Arendt-Nielsen, L. (2013). Lower mechanical pressure pain thresholds in female adolescents with patellofemoral pain syndrome. *The Journal of Orthopaedic and Sports Physical Therapy, 43*(6), 414. https://doi.org/10.2519/jospt.2013.4383

Roland, M., & Morris, R. (1983). A study of the natural history of back pain. Part I: development of a reliable and sensitive measure of disability in low-back pain. *Spine, 8*, 141-144. https://doi.org/10.1097/00007632-198303000-00004

Roos, E.M, & Lohmander, L.S. (2003). The Knee injury and Osteoarthritis Outcome Score (KOOS): from joint injury to osteoarthritis. *Health and Quality of Life Outcomes, 3*(1), 64. https://doi.org/10.1186/1477-7525-1-64

Roper, J.L., Harding, E.M., Doerfler, D., Dexter, J.G., Kravitz, L., Dufek, J.S., & Mermier, C.M. (2016). The effects of gait retraining in runners with patellofemoral pain: A randomized trial. *Clinical Biomechanics, 35*, 14-22. https://doi.org/10.1016/j.clinbiomech.2016.03.010

Şahin, M., Ayhan, F.F., Borman, P., & Atasoy, H. (2016). The effect of hip and knee exercises on pain, function, and strength in patients with patellofemoral pain syndrome: a randomized controlled trial. *Turkish Journal of Medical Sciences, 46*(2), 265-277. https://doi.org/10.3906/sag-1409-66

Saito, M., & Nishida, Y. (2015). Effects of fear-avoidance beliefs on low back pain in Japanese nurses. *Physiotherapy, 101*, e1317-e1318. https://doi.org/10.1016/j.physio.2015.03.1241

Salsich, G.B., & Perman, W.H. (2007). Patellofemoral joint contact area is influenced by tibiofemoral rotation alignment in individuals who have patellofemoral pain. *Journal of Orthopaedic & Sports Physical Therapy, 37*(9), 521-8. https://doi.org/10.2519/jospt.2007.37.9.521

Salsich, G.B., & Perman, W.H. (2013). Tibiofemoral and patellofemoral mechanics are altered at small knee flexion angles in people with patellofemoral pain. *Journal of Science and Medicine in Sport, 16*(1), 13-17. https://doi.org/10.1016/j.jsams.2012.04.003

Salsich, G.B., Brechter, J.H., Farwell, D., & Powers, C.M. (2002). The effects of patellar taping on knee kinetics, kinematics, and vastus lateralis muscle activity during stair ambulation in individuals with patellofemoral pain. *Journal of Orthopaedic & Sports Physical Therapy, 32*(1), 3-10. https://doi.org/10.2519/jospt.2002.32.1.3

Salsich, G.B., Yemm, B., Steger-May, K., Lang, C.E., & Van Dillen, L.R. (2018). A feasibility study of a novel, task-specific movement training intervention for women with patellofemoral pain. *Clinical Rehabilitation, 32*(2), 179-190. https://doi.org/10.1177/0269215517723055

Santi, G., & Pietrantoni, L. (2013). Psychology of sport injury rehabilitation: a review of models and interventions. *Journal of Human Sport and Exercise, 8*(4), 1029-1044. https://doi.org/10.4100/jhse.2013.84.13

Saragiotto, B.T., de Almeida, M.O., & Yamato, T.P., Maher, C.G. (2016). Multidisciplinary biopsychosocial rehabilitation for nonspecific chronic low back pain. *Physical Therapy & Rehabilitation Journal, 96*(6), 759-763. https://doi.org/10.2522/ptj.20150359

Schwane, B.G., Goerger, B.M., Goto, S., Blackburn, J.T., Aguilar, A.J., & Padua, D.A. (2015). Trunk and lower extremity kinematics during stair descent in women with or without patellofemoral pain. *Journal of Athletic Training, 50*(7), 704-712. https://doi.org/10.4085/1062-6050-49.3.100

Sheehan, F.T., Borotikar, B.S., Behnam, A.J., & Alter, K.E. (2012). Alterations in vivo knee joint kinematics following a femoral nerve branch block of the vastus medialis: implications for patellofemoral pain syndrome. *Clinical Biomechanics, 27*(6), 525-531. https://doi.org/10.1016/j.clinbiomech.2011.12.012

Sigmund, K.J., Bement, M.K., & Earl-Boehm, J.E. Exploring the pain in patellofemoral pain: a systematic review and meta-analysis examining signs of central sensitization. *Journal of Athletic Training, 56*(8), 887-901. https://doi.org/10.4085/1062-6050-0190.20

Sinclair, J.K., Selfe, J., Taylor, P.J., Shore, H.F., & Richards, J.D. (2016). Influence of a knee brace intervention on perceived pain and patellofemoral loading in recreational athletes. *Clinical Biomechanics, 37*, 7-12. https://doi.org/10.1016/j.clinbiomech.2016.05.002

Smith, B. E., Selfe, J., Thacker, D., Hendrick, P., Bateman, M., Moffatt, F., Rathleff, M.S., Smith, T.O., & Logan, P. (2018). Incidence and prevalence of patellofemoral pain: A systematic review and meta-analysis. *PLoS One, 13*(1), e0190892. https://doi.org/10.1371/journal.pone.0190892

Smith, B.E, Moffatt, F., Hendrick, P., Bateman, M., Rathleff, M. S., Selfe, J., Smith, T.O., & Logan, P. (2018). The experience of living with patellofemoral pain-loss, confusion and fear-avoidance: a UK qualitative study. *BMJ Open, 8*(1), e018624. http://dx.doi.org/10.1136/bmjopen-2017-018624

Smith, B.E., Hendrick, P., Bateman, M., Moffatt, F., Rathleff, M.S., Selfe, J., Smith, T.O., Logan, P. (2019). A loaded self-managed exercise programme for patellofemoral pain: a mixed methods feasibility study. *BMC Musculoskeletal Disorders, 20*, 129. https://doi.org/10.1186/s12891-019-2516-1

Smith, B.E., Hendrick, P., Smith, T.O., Bateman, M., Mofatt, F., Rathleff, M.S., Selfe, J., Logan, P. (2017). Should exercises be painful in the management of chronic musculoskeletal pain? A systematic review and meta-analysis. *British Journal of Sports Medicine, 51*(23), 1679-1687. http://dx.doi.org/10.1136/bjsports-2016-097383

Souza, R.B., & Powers, C.M. (2009). Predictors of hip internal rotation during running: an evaluation of hip strength and femoral structure in women with and without patellofemoral pain. *The American Journal of Sports Medicine, 37*(3), 579-587. https://doi.org/10.1177/0363546508326711

Souza, R.B., Draper, C.E., Fredericson, M., & Powers, C.M. (2010). Femur rotation and patellofemoral joint kinematics: a weight-bearing magnetic resonance imaging analysis. *Journal of Orthopaedic & Sports Physical Therapy, 40*(5), 277-285. https://doi.org/10.2519/jospt.2010.3215

Speilberger, C.D., Gorsuch, R.L., & Lushene, R. (1970). *The State-Trait Anxiety Inventory (STAI)*. Palo Alto, CA: Consulting Psychologists Press.

Stathopulu, E., & Baildum, E. (2003). Anterior knee pain: a long-term follow-up. *Rheumatology, 42*(2), 380-382. https://doi.org/10.1093/rheumatology/keg093

Sternberg, W. (2007). Pain. In D. Pargman (Ed.), *Psychological Bases of Sport Injuries* (3 ed., pp. 305-318). Morgantown, WV: Fitness Information Technology.

Strand, L.I., Moe-Nilssen, R., & Ljunggren, A.E. (2002). Back Performance Scale for the assessment of mobility-related activities in people with back pain. *Physical Therapy, 82*, 1213-1223.

Stratford, P., Gill, C., Westaway, M., & Binkley, J. (1995). Assessing disability and change on individual patients: a report of a patient specific measure. *Physiotherapy Canada, 47*, 258-263.

Stratford, P.W., & Kennedy, D.M. (2006). Performance measures were necessary to obtain a complete picture of osteoarthritic patients. *Journal of Clinical Epidemiology, 59*(2), 160-167. https://doi.org/10.1016/j.jclinepi.2005.07.012

Sullivan, M., Bishop, S., & Pivik, J. (1995). The pain catastrophising scale: development and validation. *Psychological Assessment, 7*, 524-532. https://psycnet.apa.org/doi/10.1037/1040-3590.7.4.524

Symonds, T.L., Burton, A.K., Tillotson, K.M., & Maine, C.J. (1996). Do attitudes and beliefs influence work loss due to low back trouble? *Occupational Medicine, 46*, 25-32. https://doi.org/10.1093/occmed/46.1.25

Tenforde, A.S., Borgstrom, H., Polich, G., Steere, H., Davis, I.S., Cotton, K., O'Donnell, M., Silver, J.K. (2020). Outpatient physical, occupational, and speech therapy synchronous telemedicine: a survey study of patient satisfaction with virtual visits during the COVID-19 pandemic. *American Journal of Physical Medicine & Rehabilitation, 99*(11), 977-981. https://dx.doi.org/10.1097%2FPHM.0000000000001571

Teng, H.L., & Powers, C.M. (2016). Hip-extensor strength, trunk posture, and use of the knee-extensor muscles during running. *Journal of Athletic Training, 51*(7), 519-524. https://doi.org/10.4085/1062-6050-51.8.05

Teng, H.L., Chen, Y.J., & Powers, C.M. (2014). Predictors of patellar alignment during weight bearing: an examination of patellar height and trochlear geometry. *The Knee, 21*(1), 142-146. https://doi.org/10.1016/j.knee.2013.08.011

Terry, G.C., Hughston, J.C., & Norwood, L.A. (1986). The anatomy of the iliopatellar band and iliotibial tract. *The American Journal of Sports Medicine, 14*(1), 39-45. https://doi.org/10.1177/036354658601400108

Thijs, Y., Pattyn, E., Van Tiggelen, D., Rombaut, L., & Witvrouw, E. (2011). Is hip muscle weakness a predisposing factor for patellofemoral pain in female novice runners? A prospective study. *The American Journal of Sports Medicine, 39*(9), 1877-1882. https://doi.org/10.1177/0363546511407617

Thomeer, J., Sheehan, F., & Jackson, J. (2017). Normalized patellofemoral joint reaction force is greater in individuals with patellofemoral pain. *Journal of Biomechanics, 26*(60), 238-242. http://dx.doi.org/10.1016/j.jbiomech.2017.06.024

Thorpe, J.L., Dey, P., & Earl-Boehm, J.E. (2019). *The Prevalence of Patellofemoral Pain in the Community.* Paper presented at the National Athletic Trainers' Association Annual Meeting, Las Vegas, NV, USA.

Thorpe, J.L., Oblak, P., Earl-Boehm, J.E. (2021). The influence of step direction and step height on lower extremity joint kinematics during step-down tasks. *Athletic Training & Sports Health Care, 13*(4), e212–e220. https://doi.org/10.3928/19425864-20201027-01

Uboldi, F.M., Ferrua, P., Tradati, D., Zedde, P., Richards, J., Manunta, A., & Berruto, M. (2018). Use of an elastomeric knee brace in patellofemoral pain syndrome: Short-term results. *Joints, 6*(2), 85-89. https://dx.doi.org/10.1055%2Fs-0038-1661339

Van Cant, J., Declève, P., Garnier, A., Roy, J.S. (2021). Influence of symptom frequency and severity on hip abductor strength and endurance in individuals with patellofemoral pain. *Physical Therapy in Sport, 49,* 83-89. https://doi.org/10.1016/j.ptsp.2021.02.001

Van Cant, J., Pineux, C., Pitance, L., & Feipel, V. (2014). Hip muscle strength and endurance in females with patellofemoral pain: a systematic review with meta-analysis. *International Journal of Sports Physical Therapy, 9*(5), 564-582.

van Linschoten, R., van Middelkoop, M., Berger, M.Y., Heintjes, E.M., Verhaar, J.A., Willemsen, S.P., Koes, B.W., & Bierma-Zeinstra, S.M. (2009). Supervised exercise therapy versus usual care for patellofemoral pain syndrome: an open label randomised controlled trial. *BMJ, 339*, b4074. https://doi.org/10.1136/bmj.b4074

Van Tiggelen, D., Cowan, S., Coorevits, P., Duvigneaud, N., & Witvrouw, E. (2009). Delayed vastus medialis obliquus to vastus lateralis onset timing contributes to the development of patellofemoral pain in previously healthy men: a prospective study. *The American Journal of Sports Medicine, 37*(6), 1099-1105. https://doi.org/10.1177/0363546508331135

Waddell, G. (1987). 1987 Volvo award in clinical sciences. A new clinical model for the treatment of low-back pain. *Spine, 12*(7), 632-644. https://doi.org/10.1097/00007632-198709000-00002

Waddell, G., & Burton, A. (2004). *Concepts of rehabilitation for the management of common health problems*. Norwich, UK: The Stationary Office.

Waddell, G., Newton, M., Henderson, I., Somerville, D., & Main, C.J. (1993). A Fear-Avoidance Beliefs Questionnaire (FABQ) and the role of fear-avoidance beliefs in chronic low back pain and disability. *Pain, 52*(2), 157-168. https://doi.org/10.1016/0304-3959(93)90127-b

Whyte, E.F., Moran, K., Shortt, C.P., & Marshall, B. (2010). The influence of reduced hamstring length on patellofemoral joint stress during squatting in healthy male adults. *Gait & Posture, 31*(1), 47-51. https://doi.org/10.1016/j.gaitpost.2009.08.243

Williamson, A., & Hoggart, B. (2004). Pain: a review of three commonly used pain rating scales. *Journal of Clinical Nursing, 14*, 798-804. https://doi.org/10.1111/j.1365-2702.2005.01121.x

Willson, J.D., & Davis, I.S. (2008). Utility of the frontal plane projection angle in females with patellofemoral pain. *Journal of Orthopaedic & Sports Physical Therapy, 38*(10), 606-615.

Willy, R.W., & Davis, I.S. (2011). The effect of a hip-strengthening program on mechanics during running and during a single-leg squat. *Journal of Orthopaedic & Sports Physical Therapy, 41*(9), 625-632. https://doi.org/10.2519/jospt.2011.3470

Willy, R.W., Hoglund, L.T., Barton, C.J., Bolgla, L.A., Scalzitti, D.A., Logerstedt, D.S., Lynch, A.D., Snyder-Mackler, L., McDonough, C.M. (2019). Patellofemoral pain. *Journal of Orthopaedic & Sports Physical Therapy, 49*(9), CPG1-CPG95. https://doi.org/10.2519/jospt.2019.0302

Willy, R.W., Scholz, J.P., & Davis, I.S. (2012). Mirror gait retraining for the treatment of patellofemoral pain in female runners. *Clinical Biomechanics, 27*(10), 1045-1051. https://doi.org/10.1016/j.clinbiomech.2012.07.011

Wirtz, A.D., Willson, J.D., Kernozek, T.W., & Hong, D.A. (2012). Patellofemoral joint stress during running in females with and without patellofemoral pain. *The Knee, 19*(5), 703-708. https://doi.org/10.1016/j.knee.2011.09.006

Witoński, D., & Góraj, B. (1999). Patellar motion analyzed by kinematic and dynamic axial magnetic resonance imaging in patients with anterior knee pain syndrome. *Archives of Orthopaedic and Trauma Surgery, 119*(1-2), 46-49. https://doi.org/10.1007/s004020050353

Witvrouw, E., Callaghan, M. J., Stefanik, J. J., Noehren, B., Bazett-Jones, D. M., Willson, J. D., Earl-Boehm, J.E., Davis, I.S., Powers, C.M., McConnell, J., & Crossley, K. M. (2014). Patellofemoral pain: consensus statement from the 3rd International Patellofemoral Pain Research Retreat held in Vancouver, September 2013. *British Journal of Sports Medicine, 48*, 411-414. http://dx.doi.org/10.1136/bjsports-2014-093450

Witvrouw, E., Lysens, R., Bellemans, J., Cambier, D., & Vanderstraeten, G. (2000). Intrinsic risk factors for the development of anterior knee pain in an athletic population. A two-year prospective study. *The American Journal of Sports Medicine, 28*(4), 480-489. https://doi.org/10.1177/03635465000280040701

Witvrouw, E., Werner, S., Mikkelsen, C., Vanden Berghe, L., & Cerulli, G. (2005). Clinical classification of patellofemoral pain syndrome: guidelines for non-operative treatment. *Knee Surgery, Sports Traumatology, Arthroscopy, 13*(2), 122-130. https://doi.org/10.1007/s00167-004-0577-6

Wyndow, N., De Jong, A., Rial, K., Tucker, K., Collins, N., Vincenzino, B., Russell, T., & Crossley, K. (2016). The relationship of foot and ankle mobility to the frontal plane projection angle in asymptomatic adults. *Journal of Foot and Ankle Research, 25*(9), 3. https://doi.org/10.1186/s13047-016-0134-9

Yip, S.L., & Ng, G.Y. (2006). Biofeedback supplementation to physiotherapy exercise programme for rehabilitation of patellofemoral pain syndrome: a randomized controlled pilot study. *Clinical Rehabilitation, 20*(12), 1050-1057. https://doi.org/10.1177/0269215506071259

Zigmond, A.S., & Snaith, R.P. (1983). The hospital anxiety and depression scale. *Acta Psychiatrica Scandinavica, 67*, 361-370. https://doi.org/10.1111/j.1600-0447.1983.tb09716.x

# Appendix A

## Qualtrics Survey consisting of SNAPPS, MSGM, NPRS, & AKPS

**University of Wisconsin - Milwaukee**

**Consent to Participate in Online Survey Research**

**Study Title:** Injury Characteristics & Sociodemographic Factors Associated with Perceptions of Pain and Function in Individuals with Patellofemoral Pain

**Person Responsible for Research:** Jennifer Thorpe, MS, ATC (Doctoral student, University of Wisconsin-Milwaukee) & Jennifer Earl-Boehm, Ph.D, ATC (Faculty, University of Wisconsin-Milwaukee)

**Study Description:** The purpose of this research study is to determine the relationships between injury characteristics and sociodemographic factors with patient perceptions of pain and function in those experiencing patellofemoral pain, or chronic knee pain centered around the knee cap. We are recruiting participants residing in the United States between the ages of 18-45 to participate in this study. In order to participate in this study, you must be able to read and understand English and be able to use a computer or electronic device. If you agree to participate, you will be asked to complete four online surveys that will take approximately 15-20 minutes to complete. The questions you will be asked include basic demographic information as well as information regarding your knees and relative medical history regarding any recent knee pain.

**Risks / Benefits:** Risks to participants are considered minimal. All responses are voluntary. Collection of data and survey responses using the internet involves the same risks that a person would encounter in everyday use of the internet, such as breach of confidentiality. While the researchers have taken every reasonable step to protect your confidentiality, there is always the possibility of interception or hacking of the data by third parties that is not under the control of the research team. You will be asked upon completion of the survey if you wish to be contacted about other upcoming research regarding knee pain. Sharing your personal information for us to contact you is completely voluntary and you will only be contacted about other research opportunities if you elect to share this information.

There will be no costs for participating. There are no benefits to you other than to further research.

**Limits to Confidentiality:** Identifying information such as your name, email address, and the Internet Protocol (IP) address of this computer will not be automatically provided to the researcher. If you elect to share your personal information to be contacted about future research opportunities, you may do so voluntarily upon completion of the online surveys. Data will be retained on the Qualtrics website server for two years and will be deleted by the research staff after this time. However, data may exist on backups or server logs beyond the timeframe of this research project. Data transferred from the survey site will be saved on a password protected computer indefinitely. Only Jennifer Thorpe and Jennifer Earl-Boehm will have access to the data collected by this study. However, the Institutional Review Board at UW-Milwaukee or appropriate federal agencies like the Office for Human Research Protections may review this study's records.

**Voluntary Participation:** Your participation in this study is voluntary. You may choose not to answer any of the questions or withdraw from this study at any time without penalty. Your decision will not change any present or future relationship with the University of Wisconsin Milwaukee.

**Who do I contact for questions about the study:** For more information about the study or study procedures, contact Jennifer Thorpe at jln@uwm.edu.

**Who do I contact for questions about my rights or complaints towards my treatment as a research subject?** Contact the UWM IRB at (414) 229-3173 or irbinfo@uwm.edu.

**Research Subject's Consent to Participate in Research:** By entering this survey, you are indicating that you have read the consent form, you are 18 or older and that you voluntarily agree to participate in this research study.

Thank you!

Please select the state or United States territory that you currently reside in.

State or Territory (1)

▼ Alabama (AL) (1) ... None, currently reside outside of the US (57)

Survey Instrument for Natural History, Aetiology, and Prevelence of Patellofemoral Pain Studies

The following survey will ask you a series of questions about your age and knee pain. Please answer each question honestly and accurately.

Are you over 18 years of age?

○ Yes (1)

○ No (2)

Are you under 45 years of age?

○ Yes (1)

○ No (2)

How old are you? (years)

________________________________________________________________

Have you ever been to a doctor because of knee problems? (Please choose only one).

○ Yes (1)

○ No (2)

Have you had pain or problems in the last year in or around the knee? (Please choose only one)

○ Yes (1)

○ No (2)

In which knee have you had pain or problems? (Please choose only one of the options listed below)

○ Left knee only (1)

○ Right knee only (2)

○ Both knees (3)

Have you ever had surgery to your knee? (Including arthroscopy, scope surgery, camera in your knee) (Please choose only one option)

○ No (1)

○ Yes, Left knee only (2)

○ Yes, Right knee only (3)

○ Yes, Both knees (4)

Have you ever had a knee cap that has gone out of place (dislocated)? (Please choose only one option)

○ No (1)

○ Yes, Left knee only (2)

○ Yes, Right knee only (3)

○ Yes, Both knees (4)

Since your knee problem started, does your knee ever swell up? (Please choose only one option)

○ No (1)

○ Yes, Left knee only (2)

○ Yes, Right knee only (3)

○ Yes, Both knees (4)

Have you ever had pain and discomfort for more than one month? (Please chose only one option)

○ No (1)

○ Yes, Left knee only (2)

○ Yes, Right knee only (3)

○ Yes, Both knees (4)

How long have you had pain and discomfort in your knee? Please report in number of months.

________________________________________________________________

Because of your knee problems would you suffer from pain or difficulty with sitting for a long time? (Please choose only one option)

○ No (1)

○ Yes, Left knee (2)

○ Yes, Right knee (3)

○ Yes, Both knees (4)

Because of your knee problems would you suffer from pain or difficulty with going ***up*** stairs? (Please choose only one option)

○ No (1)

○ Yes, Left knee (2)

○ Yes, Right knee (3)

○ Yes, Both knees (4)

Because of your knee problems would you suffer from pain or difficulty with going ***down*** stairs? (Please choose only one option)

○ No (1)

○ Yes, Left knee (2)

○ Yes, Right knee (3)

○ Yes, Both knees (4)

Because of your knee problems would you suffer from pain or difficulty with squatting? (Please choose only one option)

- ○ No (1)
- ○ Yes, Left knee (2)
- ○ Yes, Right knee (3)
- ○ Yes, Both knees (4)

Because of your knee problems would you suffer from pain or difficulty with standing for long periods? (Please choose only one option)

○ No (1)

○ Yes, Left knee (2)

○ Yes, Right knee (3)

○ Yes, Both knees (4)

Because of your knee problems would you suffer from pain or difficulty with walking on a level surface? (Please choose only one option)

○ No (1)

○ Yes, Left knee (2)

○ Yes, Right knee (3)

○ Yes, Both knees (4)

Because of your knee problems would you suffer from pain or difficulty with getting up out of a chair? (Please choose only one option)

○ No (1)

○ Yes, Left knee (2)

○ Yes, Right knee (3)

○ Yes, Both knees (4)

Because of your knee problems would you suffer from pain or difficulty with kneeling? (Please choose only one option)

○ No (1)

○ Yes, Left knee (2)

○ Yes, Right knee (3)

○ Yes, Both knees (4)

Because of your knee problems would you suffer from pain or difficulty with walking on uneven surfaces? (Please choose only one option)

○ No (1)

○ Yes, Left knee (2)

○ Yes, Right knee (3)

○ Yes, Both knees (4)

Because of your knee problems would you suffer from pain or difficulty with walking ***down*** slopes? (Please choose only one option)

○ No (1)

○ Yes, Left knee (2)

○ Yes, Right knee (3)

○ Yes, Both knees (4)

Because of your knee problems would you suffer from pain or difficulty with walking ***up*** slopes? (Please choose only one option)

○ No (1)

○ Yes, Left knee (2)

○ Yes, Right knee (3)

○ Yes, Both knees (4)

Because of your knee problems would you suffer from pain or difficulty with hopping? (Please choose only one option)

○ No (1)

○ Yes, Left knee (2)

○ Yes, Right knee (3)

○ Yes, Both knees (4)

Because of your knee problems would you suffer from pain or difficulty with jumping? (Please choose only one option)

○ No (1)

○ Yes, Left knee (2)

○ Yes, Right knee (3)

○ Yes, Both knees (4)

Because of your knee problems would you suffer from pain or difficulty with running? (Please choose only one option)

○ No (1)

○ Yes, Left knee (2)

○ Yes, Right knee (3)

○ Yes, Both knees (4)

We are now going to ask you some questions about each knee, starting with your right knee.

Thinking about your right knee, what do you consider is your main problem with your knee? (Please choose only one option)

○ Pain or discomfort (1)

○ Locking (2)

○ Giving way or feeling like it will give way (3)

○ No problem in this knee (4)

Thinking about your right knee, did your current knee problem come on: (Please choose only one option)

○ Because of sudden injury e.g. twist, fall or accident that you needed to see a doctor about (1)

○ Gradually over a period of time (2)

○ Neither gradually nor because of a sudden injury (3)

○ Not sure, can't remember (4)

○ No problem in this knee (5)

Now we are going to ask you some questions about your left knee.

Thinking about your left knee, what do you consider your main problem with your knee? (Please choose only one option)

○ Pain or discomfort (1)

○ Locking (2)

○ Giving way or feeling like it will give way (3)

○ No problem in this knee (4)

Thinking about your left knee, did your current knee problem come on (Please choose only one option)

○ Because of a sudden injury e.g. twist, fall or accident that you needed to see a doctor about (1)

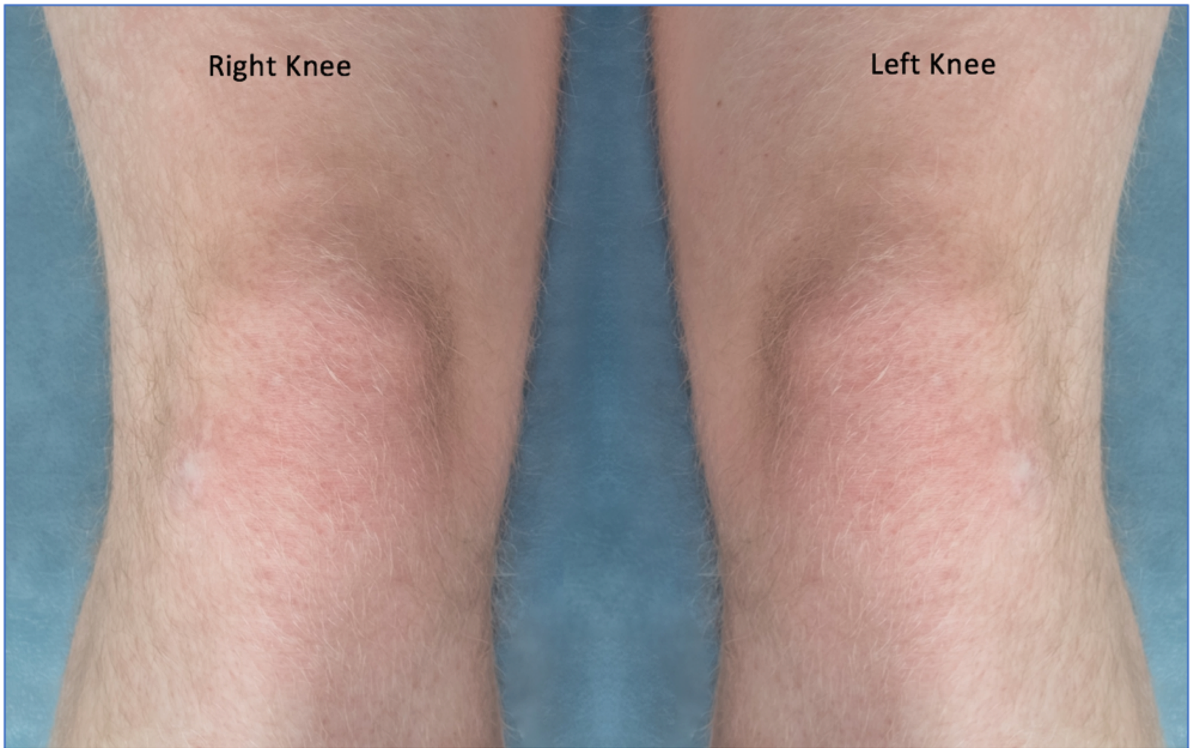
○ Gradually over a period of time (2)

○ Neither gradually nor because of a sudden injury (3)

○ Not sure, can't remember (4)

○ No problem in this knee (5)

Please take a moment to think about where you get your knee pain. We would like you to imagine that this is a picture of your knees. Please click to mark where you feel your knee pain on this photograph. You can use several clicks if needed. When you have finished, please click on the double arrows at the bottom right of the page.



If you feel pain in the back of your knee, please select the box that corresponds to the knee you are experiencing pain. If you do not have pain in the back of your knee, select none.

☐ Right Knee (1)

☐ Left Knee (2)

☐ None (3)

Considering both your knees which would you say is the knee that gives you the most problems?

- ○ Always right (1)
- ○ Usually right (2)
- ○ Right and left equally (3)
- ○ Usually left (4)
- ○ Always left (5)

Multidimensional Sex/Gender Measure

Next, you will be asked a series of questions regarding your sex and gender identity.

What sex were you assigned at birth, meaning on your original birth certificate?

○ Male (1)

○ Female (2)

Which best describes your current gender identity?

○ Male (1)

○ Female (2)

○ Indigenous or other cultural gender minority identity (e.g. two-spirit) (3)

○ Something else (e.g. gender fluid, non-binary) (4)

Numerical Pain Rating Scale

The next question will ask you to rate the severity of your pain over the past 7 days. Please rate the average intensity of your knee pain over the past week on a scale of 0 (indicating no pain) to 10 (worst pain imaginable) using the scale pictured below.

| | 0 = No pain 10 = Worst possible pain |
|---|---|
| | 0 1 2 3 4 5 6 7 8 9 10 |
| (11) | |

The following section will ask you to select the response that best corresponds to your knee symptoms.

Limp: Do you walk with a limp (or have difficulty with ambulating?)

- ○ None (1)
- ○ Slight or periodical (2)
- ○ Constant (3)

Support: Are you able to support (ability to bear weight on the involved limb or limbs)?

○ Full support without pain (1)

○ Painful (2)

○ Weight bearing is impossible (3)

Walk: Are you able to walk?

○ Unlimited (1)

○ More than 2 km (1.2 miles) (2)

○ 1-2 km (0.6-1.2 miles) (3)

○ Unable (4)

Stairs: Are you able to navigate stairs?

○ No difficulty (1)

○ Slight pain when descending (2)

○ Pain both when descending and ascending (3)

○ Unable (4)

Squatting: Are you able to squat?

- ○ No difficulty (1)
- ○ Repeated squatting painful (2)
- ○ Painful each time (4)
- ○ Possible with partial weight bearing (5)
- ○ Unable (6)

Running: Are you able to run?

- ○ No difficulty (1)
- ○ Pain after more than 2km (1.2 miles) (2)
- ○ Slight pain from the start (3)
- ○ Severe pain (4)
- ○ Unable (5)

Jumping: Are you able to jump?

- ○ No difficulty (1)
- ○ Slight difficulty (2)
- ○ Constant pain (3)

○ Unable (4)

Prolonged sitting with the knees flexed: Are you able to sit for long periods of time with your knees bent?

- ○ No difficulty (1)
- ○ Pain after exercise (2)
- ○ Constant pain (3)
- ○ Pain forces to extend knees temporarily (4)
- ○ Unable (5)

Pain: Which of the following best describes your knee pain?

- ○ None (1)
- ○ Slight and occasional (2)
- ○ Interferes with sleep (3)
- ○ Occasionally severe (4)
- ○ Constant and severe (5)

Swelling: Which of the following best describes swelling in your knee?

- ○ None (1)
- ○ After severe exertion (2)
- ○ After daily activities (3)
- ○ Every evening (4)

○ Constant (5)

Abnormal painful kneecap movements or subluxations: Which of the following best describes any episodes of the kneecap moving out of place?

○ None (1)

○ Occasionally in sports activities (2)

○ Occasionally in daily activities (3)

○ At least one documented dislocation (4)

○ More than two dislocations (5)

Atrophy of the thigh: Do you notice that your thigh muscle is smaller in size on the leg where you are experiencing knee pain?

○ None (1)

○ Slight (2)

○ Severe (3)

Flexion deficiency: Do you experience any difficulty or limitation in bending your knee?

○ None (1)

○ Slight (2)

○ Severe (3)

Would you be interested in being contacted by our research team regarding participation in other studies regarding your knee pain?

○ Yes (4)

○ No (5)

Do you reside in southeastern Wisconsin, within driving distance of Milwaukee?

○ Yes (1)

○ No (2)

Please provide your contact information below for our research team to contact you.

○ First name: (1) ________________________________________________

○ Phone number (with area code): (2) ________________________________________________

○ Email address: (3) ________________________________________________

Thank you for your information. Someone from our research team will contact you regarding other research study opportunities.

Thank you for your time.

# Appendix B

## Screening Survey in Qualtrics Including SNAPPS & Exclusion Criteria

Thank you for your interest in participating in our study about knee pain. In the following survey, you will be asked several questions about your knee pain. These questions will help the researchers to determine if you are eligible to participate in the study. Please answer all questions completely and truthfully. At the end of the survey, you will be asked to share your contact information so we can confirm your responses and contact you if you are eligible to schedule a session in the lab.

Questions about this study can be directed to Jenny Thorpe (jln@uwm.edu) University of Wisconsin-Milwaukee, Department of Kinesiology - Integrated Health Care & Promotion Unit This research study has been approved by the University of Wisconsin-Milwaukee Institutional Review Board for the Protection of Human Subjects (IRB # approved on )

Survey Instrument for Natural History, Aetiology, and Prevelence of Patellofemoral Pain Studies

Are you over 18 years of age?

○ Yes (1)

○ No (2)

Are you under 40 years of age?

○ Yes (1)

○ No (2)

How old are you? (years)

________________________________________________________________

Have you ever been to a doctor because of knee problems? (Please choose only one).

○ Yes (1)

○ No (2)

Have you had pain or problems in the last year in or around the knee? (Please choose only one)

○ Yes (1)

○ No (2)

In which knee have you had pain or problems? (Please choose only one of the options listed below)

○ Left knee only (1)

○ Right knee only (2)

○ Both knees (3)

Have you ever had surgery to your knee? (Including arthroscopy, scope surgery, camera in your knee) (Please choose only one option)

○ No (1)

○ Yes, Left knee only (2)

○ Yes, Right knee only (3)

○ Yes, Both knees (4)

Have you ever had a knee cap that has gone out of place (dislocated)? (Please choose only one option)

○ No (1)

○ Yes, Left knee only (2)

○ Yes, Right knee only (3)

○ Yes, Both knees (4)

Since your knee problem started, does your knee ever swell up? (Please choose only one option)

○ No (1)

○ Yes, Left knee only (2)

○ Yes, Right knee only (3)

○ Yes, Both knees (4)

Have you ever had pain and discomfort for more than one month? (Please chose only one option)

○ No (1)

○ Yes, Left knee only (2)

○ Yes, Right knee only (3)

○ Yes, Both knees (4)

Because of your knee problems would you suffer from pain or difficulty with sitting for a long time? (Please choose only one option)

○ No (1)

○ Yes, Left knee (2)

○ Yes, Right knee (3)

○ Yes, Both knees (4)

Because of your knee problems would you suffer from pain or difficulty with going ***up*** stairs? (Please choose only one option)

○ No (1)

○ Yes, Left knee (2)

○ Yes, Right knee (3)

○ Yes, Both knees (4)

Because of your knee problems would you suffer from pain or difficulty with going ***down*** stairs? (Please choose only one option)

○ No (1)

○ Yes, Left knee (2)

○ Yes, Right knee (3)

○ Yes, Both knees (4)

Because of your knee problems would you suffer from pain or difficulty with squatting? (Please choose only one option)

○ No (1)

○ Yes, Left knee (2)

○ Yes, Right knee (3)

○ Yes, Both knees (4)

Because of your knee problems would you suffer from pain or difficulty with standing for long periods? (Please choose only one option)

○ No (1)

○ Yes, Left knee (2)

○ Yes, Right knee (3)

○ Yes, Both knees (4)

Because of your knee problems would you suffer from pain or difficulty with walking on a level surface? (Please choose only one option)

- ○ No (1)
- ○ Yes, Left knee (2)
- ○ Yes, Right knee (3)
- ○ Yes, Both knees (4)

Because of your knee problems would you suffer from pain or difficulty with getting up out of a chair? (Please choose only one option)

- ○ No (1)
- ○ Yes, Left knee (2)
- ○ Yes, Right knee (3)
- ○ Yes, Both knees (4)

Because of your knee problems would you suffer from pain or difficulty with kneeling? (Please choose only one option)

- ○ No (1)
- ○ Yes, Left knee (2)
- ○ Yes, Right knee (3)
- ○ Yes, Both knees (4)

Because of your knee problems would you suffer from pain or difficulty with walking on uneven surfaces? (Please choose only one option)

- ○ No (1)
- ○ Yes, Left knee (2)
- ○ Yes, Right knee (3)
- ○ Yes, Both knees (4)

Because of your knee problems would you suffer from pain or difficulty with walking ***down*** slopes? (Please choose only one option)

○ No  (1)

○ Yes, Left knee  (2)

○ Yes, Right knee  (3)

○ Yes, Both knees  (4)

Because of your knee problems would you suffer from pain or difficulty with walking ***up*** slopes? (Please choose only one option)

○ No  (1)

○ Yes, Left knee  (2)

○ Yes, Right knee  (3)

○ Yes, Both knees  (4)

Because of your knee problems would you suffer from pain or difficulty with hopping? (Please choose only one option)

○ No  (1)

○ Yes, Left knee  (2)

○ Yes, Right knee  (3)

○ Yes, Both knees  (4)

Because of your knee problems would you suffer from pain or difficulty with jumping? (Please choose only one option)

○ No (1)

○ Yes, Left knee (2)

○ Yes, Right knee (3)

○ Yes, Both knees (4)

Because of your knee problems would you suffer from pain or difficulty with running? (Please choose only one option)

○ No (1)

○ Yes, Left knee (2)

○ Yes, Right knee (3)

○ Yes, Both knees (4)

We are now going to ask you some questions about each knee, starting with your right knee.

Thinking about your right knee, what do you consider is your main problem with your knee? (Please choose only one option)

○ Pain or discomfort (1)

○ Locking (2)

○ Giving way or feeling like it will give way (3)

○ No problem in this knee (4)

Thinking about your right knee, did your current knee problem come on: (Please choose only one option)

○ Because of sudden injury e.g. twist, fall or accident that you needed to see a doctor about (1)

○ Gradually over a period of time (2)

○ Neither gradually nor because of a sudden injury (3)

○ Not sure, can't remember (4)

○ No problem in this knee (5)

Now we are going to ask you some questions about your left knee.

Thinking about your left knee, what do you consider your main problem with your knee? (Please choose only one option)

○ Pain or discomfort (1)

○ Locking (2)

○ Giving way or feeling like it will give way (3)

○ No problem in this knee (4)

Thinking about your left knee, did your current knee problem come on (Please choose only one option)

○ Because of a sudden injury e.g. twist, fall or accident that you needed to see a doctor about (1)

○ Gradually over a period of time (2)

○ Neither gradually nor because of a sudden injury (3)

○ Not sure, can't remember (4)

○ No problem in this knee (5)

Please take a moment to think about where you get your knee pain. We would like you to imagine that this is a picture of your knees. Please click to mark where you feel your knee pain on this Diagram. You can use several clicks if needed. When you have finished, please click on the double arrows at the bottom right of the page.

If you feel pain in the back of your knee, please select the box that corresponds to the knee you are experiencing pain. If you do not have pain in the back of your knee, select none.

☐ Right Knee (1)

☐ Left Knee (2)

☐ None (3)

Considering both your knees which would you say is the knee that gives you the most problems?

○ Always right (1)

○ Usually right (2)

○ Right and left equally (3)

○ Usually left (4)

○ Always left (5)

Next we are going to ask a series of questions about relevant medical history to determine your eligibility for participation in our study.

Do you currently have an injury to your meniscus in your knee or any of the cartilage within the knee joint?

○ Yes (1)

○ No (2)

Do you currently have an injury to any of the ligaments of the knee (including anterior cruciate ligament (ACL), posterior cruciate ligament (PCL), medial collateral ligament (MCL), or lateral collateral ligament (LCL))?

○ Yes (1)

○ No (2)

Are you currently diagnosed with Osgood-Schlatter, Sinding-Larsen-Johansson syndrome, osteoarthritis of the knee?

- ○ Yes (1)
- ○ No (2)

Do you currently have effusion (major swelling) of your knee joint?

- ○ Yes (1)
- ○ No (2)

Do you currently experience pain in the knee caused by an injury to your hip or lower back?

- ○ Yes (1)
- ○ No (2)

Have you had surgery to your lower extremity (hip, knee, ankle, or foot) in the past 24 months?

- ○ Yes (5)
- ○ No (6)

Have you experienced any neurological or vestibular disorder in the past six months that may affect your ability to balance?

○ Yes (1)

○ No (2)

Are you currently pregnant?

○ Yes (4)

○ No (5)

Thank you for your time! You are eligible to participate in our study. Please fill in the information below to confirm your contact information so we can schedule your session in the lab.

○ Name (1) ________________________________________________

○ Email (2) ________________________________________________

○ Phone (3) ________________________________________________

Thank you for your interest in our study. Unfortunately, you do not meet the eligibility criteria for participation. Thank you for your time!

# Appendix C

## Informed Consent Form

| | |
|---|---|
| **Study title** | The Use of a Squat Retraining Intervention for Patellofemoral Pain |
| **Researchers** | Jennifer Thorpe, MS, ATC & Erin Lally, MS, ATC, & Jennifer Earl-Boehm, PhD, ATC, FNATA<br>Department of Kinesiology - Integrated Health Care & Promotion Unit |

We're inviting you to participate in a research study. Participation is completely voluntary. If you agree to participate now, you can always change your mind later. There are no negative consequences, whatever you decide.

## Overview

**Purpose:** The purpose of this research study is to investigate if your hip and knee muscle strength and how you move during a step-down task relate to how you rate your pain severity and function, as well as assess the outcomes of an exercise program focused on the step-down task.

A second purpose is to investigate the accuracy of a video method of analyzing the quality of movement during a stepdown task.

**Procedures:** As part of your involvement in this study, you will be asked to participate in an online session for a brief telehealth clinical examination of your involved knee(s). You will also be asked to report to the lab for a session to complete surveys about your knee pain and symptoms, muscle strength testing of your hip and knee muscles, and video-recording of your movement during a set of step-down exercises. If have a certain movement pattern during the step-down exercises, you will advance to the exercise program of our study, which takes place over the span of two weeks. After the exercise program is complete, we will re-test your knee pain and symptoms, muscle strength, and movement during the step-down exercises like we did in the first session of this study.

**Time Commitment:** The online session will take approximately 20 minutes. The first visit to our lab will take approximately 40-70 minutes to complete all the measures. If you move on to the exercise program, those sessions will include 8 sessions over the span of 2 weeks (4 sessions per week), with each exercise session lasting approximately 20-30 minutes. The final re-testing session will take approximately 60-90 minutes to complete.

**Primary risks:** It is possible you may experience some mild muscle soreness or increased knee pain from your participation in this study.

**Benefits:** You will learn more about your knee pain, your hip and knee muscle strength, and how you move during a step-down task. You will also help researchers better understand how muscle strength and movement relate to pain severity and function, as well as understand how our exercise program affects those with patellofemoral pain.

## What is the purpose of this study?

We want to better understand how knee pain severity and your symptoms are related to your hip and knee strength and how you move during a step-down task, and assess the outcomes of an exercise-based program using the step-down task.

## What will I do?

During our online session:

- We will conduct a brief clinical examination on your painful knee(s). You will be asked some questions and instructed through some prompts by research personnel who are also licensed athletic trainers to allow us to better classify your knee pain. (10 minutes).

During our first in-person testing session:

- You'll complete two surveys - one will ask about your knee pain, and the other will ask about your symptoms from your knee pain. (10 minutes).
- We'll measure your height and weight. (5 minutes).
- We'll ask you to complete a brief warm-up consisting of walking at a self-selected moderate pace on a treadmill (10 minutes).
- We'll perform a series of muscle strength tests to assess your hip and knee strength (12 minutes).
- We'll apply reflective stickers to your joints to allow us to record your movement during the step-down task (10 minutes).
- We'll show you the step-down task and allow you to practice it (10 minutes).
- We'll record you performing the step-down task, completing 3 sets of 5 repetitions. (15 minutes).
- We'll remove the reflective stickers and allow you to change out of the lab clothing. (5 minutes).
- We'll ask you to complete a brief survey about your knee pain after the muscle testing and step-down task. (1-2 minutes)

After review of your data from the testing session, we will assess if you have a certain movement pattern that might be changed with the exercise program for our study. If you do not have a certain movement pattern your involvement in the study is complete.

If you move on to the exercise program, you will be asked to do the following:

- Take an exercise kit home with you including all the materials needed to complete the exercise sessions (which will need to be returned to the lab).
- Attend 8 online virtual tele-rehabilitation sessions over the span of 2 weeks, each session lasts 20-30 minutes.

At each online exercise session you will:

- complete two brief surveys about your knee pain and symptoms. (5 minutes)
- complete a brief dynamic warm-up consisting of leg swings, walking/marching in place, etc. (5 minutes).
- be instructed in how to set up the adjustable step, rehab device, camera view on your device and how to apply the stickers to your chest/shoulder, hip, knee, and ankle area (10 minutes).
- be taught the step-down exercise for that session, and allow you time to practice (5 minutes).
- be recorded performing the step-down exercises for that session (10 minutes).
- complete a brief survey about your knee pain after the step-down exercises. (1-2 minutes)

After the virtual tele-rehabilitation sessions are complete, you will be asked to return to our lab for another testing session, where you will be asked to repeat the steps from the first testing session listed above and return the exercise kit materials that were loaned to you.

## Risks

| **Possible risks** | **How we're minimizing these risks** |
|---|---|
| Muscle soreness and/or muscle cramping | The muscle testing for this study only requires a maximal effort for 5 seconds at a time. We will provide generous rest intervals in between these testing efforts to decrease the likelihood of muscle soreness. In addition, you will be asked to perform warm-up repetitions for each motion of the strength tests to allow you to ramp up your effort, decreasing the likelihood of a muscle cramp. |
| Risk of losing balance or falling during the step-down task | The step-down task included in this study requires you to perform the movement while balancing on one foot. The initial step height is set at a height of 4in for the first testing session, and you will be asked to perform the motion at a set rate of speed to ensure a slow, controlled motion to improve your ability to balance. Prior to the performance of this task, you will be properly instructed in how to perform the task safely and what to do if you should lose your balance. If you advance to the exercise portion of the study, you will need to meet specific criteria in order to progress in step height as part of the exercise program for your own safety. |
| Breach of confidentiality (your data being seen by someone who shouldn't have access to it) | ● All identifying information is removed and replaced with a study ID.<br>● We'll remove all identifiers once data collection is complete.<br>● We'll store all electronic data on a password-protected, encrypted computer. |

| | |
|---|---|
| | ● We'll store all paper data in a locked filing cabinet in a locked office.<br>● We'll keep your identifying information separate from your research data, but we'll be able to link it to you by using a study ID. We will destroy this link after we finish collecting and analyzing the data. |
| Online screening data being hacked or intercepted | ● This is a risk you experience any time you provide information online. We're using a secure system to collect this data, but we can't completely eliminate this risk. |
| Potential increase in knee pain | The step-down task and exercises used in this study are designed to mimic walking down stairs, a task that many adults perform on a daily basis. You are free to discontinue the step-down task at any point during the study if you are uncomfortable performing the task. |

There may be risks we don't know about yet. Throughout the study, we'll tell you if we learn anything that might affect your decision to participate.

## Other Study Information

| | |
|---|---|
| **Possible benefits** | ● The researcher will explain the clinical examination findings with you, allowing you to better understand your knee pain.<br>● You will be provided information about your hip and knee strength and your movement during the step-down task.<br>● The results of this study will help clinicians and patients with patellofemoral pain better understand how muscle strength and movement relate to pain severity and symptoms.<br>● The results will also help researchers better recommend exercises for clinicians to treat patients with patellofemoral pain. |
| **Estimated number of participants** | 45 participants are needed to complete the first data collection, and 30 participants are needed to move on to the exercise program of this study. |
| **How long will it take?** | 90 minutes or up to 7 hours total (spread out over the course of several weeks) |
| **Costs** | You'll pay for your own transportation and parking. |
| **Compensation** | **You will receive a $10 gift card for your participation in this study. If you advance to the exercise phase of this study, you will receive an additional $50 gift card upon completion of all 8 exercise sessions and the re-testing session, as well as returning the exercise kit materials loaned to you. Due to UWM policy and IRS regulations, we may have to collect your** |

| | |
|---|---|
| | **name, address, social security / tax ID number, and signature to give you this compensation.** |
| **Future research** | De-identified (all identifying information removed) data may be shared with other researchers and may be used for further analysis of the data. You won't be told specific details about these future research studies. |
| **Recordings / Photographs** | We will record / photograph you. The recordings / photographs will be used for measurement of your joint angles during the step-down task and exercises.<br>The recording / photography is necessary to this research. If you do not want to be recorded / photographed, you should not be in this study.<br>These video recordings and photographs may be used in future presentations and/or publications, but your face will not be included. |
| **Removal from the study** | In order for our data to be useful, it is important that you attend every exercise session, if applicable. If you miss a session and can't reschedule, we'll have to take you out of the study. |
| **Alternative Care** | An alternative to participating in this study is to seek medical care for your knee pain from an outside health care provider. |
| **Funding Source** | UWM College of Health Sciences, Office of Research Programs & Wisconsin Athletic Trainers' Association |

## What if I am harmed because I was in this study?

If you're harmed from being in this study, let us know. If it's an emergency, get help from 911 or your doctor right away and tell us afterward. We can help you find resources if you need psychological help. You or your insurance will have to pay for all costs of any treatment you need.

## Confidentiality and Data Security

We'll collect the following identifying information for the research: your name, email address, and phone number. This information is necessary so that we can contact you to schedule sessions in the lab.

| | |
|---|---|
| **Where will data be stored?** | On our computers in the lab at UWM |
| **How long will it be kept?** | Indefinitely |

| Who can see my data? | Why? | Type of data |
|---|---|---|

| | | |
|---|---|---|
| The researchers | To conduct the study and analyze the data | We will keep your survey results, height, weight, age, gender, clinical examination findings, muscle strength results, and videos of your step-down task to allow us to analyze our findings. These findings will be coded with your name removed and labeled with a study ID. |
| The IRB (Institutional Review Board) at UWM<br>The Office for Human Research Protections (OHRP) or other federal agencies | To ensure we're following laws and ethical guidelines | We will keep your survey results, height, weight, age, gender, clinical examination findings, muscle strength results, and videos of your step-down task to allow us to analyze our findings. These findings will be coded with your name removed and labeled with a study ID. |
| Anyone (public) | If we share our findings in publications or presentations | Aggregate (grouped) data will be used to share our findings with the public. |

**Contact information:**

| | | |
|---|---|---|
| **For questions about the research** | Jennifer Thorpe<br>Jennifer Earl-Boehm<br>Erin Lally | jln@uwm.edu<br>jearl@uwm.edu<br>Emlally@uwm.edu |
| **For questions about your rights as a research participant** | IRB (Institutional Review Board; provides ethics oversight) | 414-229-3173 /<br>irbinfo@uwm.edu |
| **For complaints or problems** | Jennifer Thorpe<br>Jennifer Earl-Boehm<br>Erin Lally | jln@uwm.edu<br>jearl@uwm.edu<br>Emlally@uwm.edu |
| | IRB | 414-229-3173 /<br>irbinfo@uwm.edu |

## Signatures

If you have had all your questions answered and would like to participate in this study, sign on the lines below. Remember, your participation is completely voluntary, and you're free to withdraw from the study at any time.

Name of Participant (print)

Signature of Participant Date

Name of Researcher obtaining consent (print)

Signature of Researcher obtaining consent Date

## Appendix D

## Virtual Clinical Examination Flow & Script

***Virtual Consent and Clinical Exam***
Schedule a time to meet with participant in Zoom.
Review the involvement in the study, address questions, and have the participant virtually consent (note date and time).

***Clinical Exam***:

1. Ask the participant to confirm which knee(s) is the involved knee. If they reply both, note which one is the most painful. (Note SNAPPS scores too in case of bilateral pain – make sure the knee you are examining meets the SNAPPS criteria)

2. Ask the participant "How long have you experienced symptoms in the involved knee"?

3. Palpation: "I am going to show you a slide with an image of two knees. I will guide you through the image with animations to highlight the region of the knee I will ask you to touch. I would like for you to press on your knee in the following locations with enough force to indent the skin in the view of your camera so I can verify you are pressing on the correct location. As you press on each of the locations, I will ask you if you experience any tenderness with the pressure from your fingers. We will start with your knees straight out in front of you as you are seated."

- **Patella (medial and lateral borders and facets, inferior pole, superior border/quad tendon)**
  "Start at the bottom middle edge of your kneecap. Press around the outside, including the edges, going around in a circle. Next press down along the middle of the knee cap, hitting all of the front of the knee cap, and let me know if you feel tenderness with that pressure of your fingers."
- **Patellar tendon**
  "Next, I want you to start at the bottom middle edge of your kneecap, and follow along down the tendon underneath the kneecap. Press down along the middle, and each side of the tendon."
- **Gerdy's tubercle**
  "Now, starting from the tendon we just pressed on, I would like you to move your fingers towards the outside of your knee from the tendon. You should feel a small bony bump on the bone. Press down on this bump.
- **Distal IT band**
  "Moving up from the bump we just pressed on, I want you to follow up the side of your knee and just past your knee cap along the outside of your knee. You should feel a band of tissue, this is your IT band. Press along this band until you are just past the knee as illustrated in this picture."
- **Pes anserine**
  "Now we will go back to the tendon below the kneecap that we pressed on earlier. Move your fingers over towards the inside of your knee, feeling for a soft plateau on the bone. Press on this plateau area as illustrated in the picture.
- **Lateral joint line**
  "Next I will ask you to bend your knee so it is at a 60-90 degree angle. Starting on the knee cap, I would like you to move just outside of the middle of the kneecap until you feel the divot between the thigh bone and the shin bone. Starting at the point nearest to the kneecap, press on this divot moving to the outside of your knee."
- **Medial joint line**
  "Now we will do the same thing on the inside of the knee. Start on the knee cap, move your fingers just inside of the middle of the kneecap until you feel the divot between the thigh bone and the shin bone. Starting at the point nearest to the kneecap, press on the divot moving to the outside of the knee.
    - If tender, confirm where by asking and visually observing where they are pointing.
    - Also use my own knee to demonstrate if they are having trouble finding the landmarks.

4. Effusion: Ask them if they notice any swelling of their knee. Ask them to position the camera so I can see their knees side by side to look for any visible signs of swelling.

5. *Presence of retropatellar or peripatellar pain*: Ask the participant:
   - "Do you experience knee pain during or after any activity?" If yes, "Where do you experience that pain?"
   - "Do you experience knee pain with prolonged sitting?" If yes, "Where do you experience that pain?"
   - "Do you experience knee pain with walking up or down stairs?" If yes, "Do you experience pain when walking up stairs? What about walking down stairs? Where do you experience your pain?"

- “Do you experience knee pain with kneeling?” If yes, “Where do you experience your pain?”
- “Please perform a double leg squat. Does this cause you any pain?” If yes, “Where do you experience your pain?”
- *Palpation of medial and lateral facets – this is noted during the palpation part of the exam.*
- *Step-down from a 20cm height – I have the participant step down from the stairs in the lab to determine if this is painful.*

6. Rehabilitation/Treatment history: “Have you completed any rehabilitation or treatment for your knee pain?” If so, what did you do? When/how long ago did you do this? How often? Was it helpful?

7. Current physical activity level: “What is your current physical activity level? What activities do you do, and how often per week, for how long?”

8. Complete COVID-19 screening using the UWM Symptom Check website (have pulled up ahead of meeting.

9. Confirm/schedule for lab session. Give directions on where to park, where to meet, mask reminder, and to contact me if they are ill or unable to attend. Remind them about COVID screening 24 hours before arriving on campus and confirm how we will complete the screening. Ask about shoe size to help have shoes ready for arrival. Answer any questions they may have.

# Appendix E

# Clinical Examination Form

**Clinical Examination** **Participant Code:**

Involved knee(s): Right Left Both

Duration of current symptoms: ___________

Point tenderness:

________________________________________________________________________________

____________________________________________________________________________

Effusion of knee joint: Y N

Presence of retropatellar and/or peripatellar pain:

| | | |
|---|---|---|
| ● During or after activity | Y | N |
| ● Prolonged sitting | Y | N |
| ● Navigating stairs | Y | N |
| ● Kneeling | Y | N |
| ● Double Leg Squatting | Y | N |
| ● Palpation of patellar facets | Y | N |
| ● Step-down from a 20-cm box | Y | N |

Current or past treatment or rehabilitation for knee pain: ______________________________

______________________________________________________________________________

Current physical activity level: _____________________________________________________

______________________________________________________________________________

# Appendix F

## VAS for In-person Testing

## **VISUAL ANALOG SCALE**

Participant Code: ______Session: ________Date: ___________

*Place a vertical line on the scale below, indicating how much pain you experienced, on average, during the past week.*

________________________________________________

No pain Severe pain

## **VISUAL ANALOG SCALE**

Participant Code: ______Session: ________Date: ____________

*Place a vertical line on the scale below, indicating how much pain you are currently experiencing.*

________________________________________________

No pain Severe pain

## **VISUAL ANALOG SCALE**

Participant Code: ______Session: ________Date: ____________

*Place a vertical line on the scale below, indicating how much pain you are currently experiencing.*

________________________________________________

No pain Severe pain

# Appendix G

## AKPS for In-person Testing

**Participant Code: __________ Session:__________ Date:______________**

**The following section will ask you to select the response that best corresponds to your knee symptoms. If you are experiencing pain in both knees, please select the response that best describes the worse knee.**

**Limp: Do you walk with a limp (or have difficulty with ambulating)?**

☐ None
☐ Slight or periodical
☐ Constant

**Support: Are you able to support (ability to bear weight on the involved limb or limbs)?**

☐ Full support without pain
☐ Painful
☐ Weight bearing is impossible

**Walk: Are you able to walk?**

☐ Unlimited
☐ More than 1 mile
☐ Between ½ mile and 1 mile
☐ Unable

**Stairs: Are you able to navigate stairs?**

☐ No difficulty
☐ Slight pain when descending
☐ Pain both when descending and ascending
☐ Unable

**Squatting: Are you able to squat?**

☐ No difficulty
☐ Repeated squatting painful
☐ Painful each time
☐ Possible with partial weight bearing
☐ Unable

**Running: Are you able to run?**

☐ No difficulty
☐ Pain after more than 1 mile
☐ Slight pain from the start
☐ Severe pain
☐ Unable

**Jumping: Are you able to jump?**

- ☐ No difficulty
- ☐ Slight difficulty
- ☐ Constant pain
- ☐ Unable

**Prolonged sitting with the knees flexed: Are you able to sit for long periods of time with your knees bent?**

- ☐ No difficulty
- ☐ Pain after exercise
- ☐ Constant pain
- ☐ Pain forces to extend knees temporarily
- ☐ Unable

**Pain: Which of the following best describes your knee pain?**

- ☐ None
- ☐ Slight and occasional
- ☐ Interferes with sleep
- ☐ Occasionally severe
- ☐ Constant and severe

**Swelling: Which of the following best describes swelling in your knee?**

- ☐ None
- ☐ After severe exertion
- ☐ After daily activities
- ☐ Every evening
- ☐ Constant

**Abnormal painful kneecap movements or subluxations: Which of the following best describes any episodes of the kneecap moving out of place?**

- ☐ None
- ☐ Occasionally in sports activities
- ☐ Occasionally in daily activities
- ☐ At least one documented dislocation
- ☐ More than two dislocations

**Atrophy of the thigh: Do you notice that your thigh muscle is smaller in size on the leg where you are experiencing knee pain?**

- ☐ None
- ☐ Slight
- ☐ Severe

**Flexion deficiency: Do you experience any difficulty or limitation in bending your knee?**

- ☐ None
- ☐ Slight
- ☐ Severe

# Appendix H

## Data Collection Form

Participant ID: Date:

Session:

Involved limb:

Dominant limb:

Weight:

Height:

Pain with step-down: Y N

| | Trial #1 | Trial #2 | Trial #3 | Trial #4 | Trial #5 |
|---|---|---|---|---|---|
| Hip ABD | | | | | |
| Hip EXT | | | | | |
| Hip ER | | | | | |
| Knee EXT | | | | | |

# Appendix I

## Step-down Assessment for Screening into Intervention Phase

Participant ID: _____________ Date: ____________

SDS Movement Assessment (adapted from Crossley et al. 2011)

**Criterion:**

1. **Overall impression across the 5 trials**
    - Participant maintains balance: Y N
    - Movement is performed smoothly, minimal perturbations: Y N
    - Depth of movement, touches heel to floor: Y N
    - Speed of movement, stays with pace of metronome: Y N
2. **Trunk posture**
    - Trunk/thoracic lateral deviation or shift: Y N
    - Trunk/thoracic rotation: Y N
    - Trunk/thoracic lateral flexion: Y N
    - Trunk/thoracic forward flexion: Y N
3. **The pelvis "in space"**
    - Pelvic shunt or lateral deviation Y N
    - Pelvic rotation Y N
    - Pelvic tilt Y N
4. **Hip joint**
    - Hip adduction Y N
    - Hip (femoral) internal rotation Y N
5. **Knee joint**
    - Apparent knee valgus Y N
    - Knee position relative to foot position Y N

**Final rating:**

☐ Good: *Participant has all Y's for 4 of the 5 criteria for all 5 reps.*

☐ Poor: *Participant did not meet all of the requirements for at least 1 criterion for all trials.*

☐ Fair: *Participant can not be rated as good or poor.*

## Appendix J

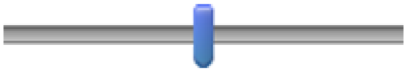
## Qualtrics VAS for Usual Pain and Pre-session

Please enter in your participant ID number. (If you are unsure, please ask the researcher for this number).

______________________________________________________

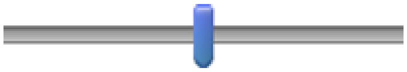
Place the slider on the scale below, indicating how much pain you experienced, on average, during the past week.

| | No pain | Severe pain |
|---|---|---|
| | 0 | 10 |



Place the slider on the scale below, indicating how much pain you are currently experiencing.

| | No pain | Severe pain |
|---|---|---|
| | 0 | 10 |



# Appendix K

## Qualtrics AKPS Version

Please enter in your participant ID number. (If you are unsure, please contact the researcher for this number).

________________________________________________________________

The following section will ask you to select the response that best corresponds to your knee symptoms. If you are experiencing pain in both knees, please select the response that best describes the worse knee.

Limp: Do you walk with a limp (or have difficulty with ambulating)?

○ None (4)

○ Slight or periodical (5)

○ Constant (6)

Support: Are you able to support (ability to bear weight on the involved limb or limbs)?

○ Full support without pain (1)

○ Painful (2)

○ Weight bearing impossible (3)

Walking: Are you able to walk?

- ○ Unlimited (1)
- ○ More than 1 mile (2)
- ○ Between a 1/2 mile and 1 mile (3)
- ○ Unable (4)

Stairs: Are you able to navigate stairs?

- ○ No difficulty (1)
- ○ Slight pain when descending (2)
- ○ Pain both when descending and ascending (3)
- ○ Unable (4)

Squatting: Are you able to squat?

- ○ No difficulty (1)
- ○ Repeated squatting painful (2)
- ○ Painful each time (3)
- ○ Possible with partial weight bearing (4)
- ○ Unable (5)

Running: Are you able to run?

○ No difficulty (1)

○ Pain after more than 1 mile (2)

○ Slight pain from the start (3)

○ Severe pain (4)

○ Unable (5)

Jumping: Are you able to jump?

○ No difficulty (1)

○ Slight difficulty (2)

○ Constant pain (3)

○ Unable (4)

Prolonged sitting with the knees flexed: Are you able to sit for long periods of time with the knees bent?

○ No difficulty (1)

○ Pain after exercise (2)

○ Constant pain (3)

○ Pain forces to extend knees temporarily (4)

○ Unable (5)

Pain: Which of the following best describes your knee pain?

- ○ None (1)
- ○ Slight and occasional (2)
- ○ Interferes with sleep (3)
- ○ Occasionally severe (4)
- ○ Constant and severe (5)

Swelling: Which of the following best describes swelling in your knee?

- ○ None (1)
- ○ After severe exertion (2)
- ○ After daily activities (3)
- ○ Every evening (4)
- ○ Constant (5)

Abnormal painful kneecap (patellar) movements (subluxations): Which of the following best describes any episodes of the knee cap moving out of place?

○ None (1)

○ Occasionally in sports activities (2)

○ Occasionally in daily activities (3)

○ At least one documented dislocation (4)

○ More than two dislocations (5)

Atrophy of thigh: Do you notice that your thigh muscle is smaller in size on the leg where you are experiencing knee pain?

○ None (1)

○ Slight (2)

○ Severe (3)

Flexion deficiency: Do you experience any difficulty or limitation in bending your knee?

○ None (1)

○ Slight (2)

○ Severe (3)

# Appendix L

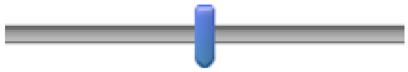
## Qualtrics VAS Post-session

Please enter in your participant ID number. (If you are unsure, please ask the researcher for this number).

________________________________________________________

Place the slider on the scale below, indicating how much pain you are currently experiencing.

| | No pain | Severe pain |
|---|---|---|
| | 0 | 10 |



## Appendix M

## Qualtrics Patient Input Survey

Please enter your participant ID. (If you are unsure of your participant ID, please ask the researcher).

________________________________________________________________

Please answer the following questions below.

| | Very easy (1) | Somewhat easy (2) | Neither easy or difficult (3) | Somewhat difficult (4) | Very difficult (5) |
|---|---|---|---|---|---|
| scheduling the sessions necessary for this intervention? (1) | ○ | ○ | ○ | ○ | ○ |
| Following the directions given to you to set up the intervention at home? (2) | ○ | ○ | ○ | ○ | ○ |
| Following the cueing and feedback given to you during the intervention? (3) | ○ | ○ | ○ | ○ | ○ |
| Setting-up the equipment for the intervention? (4) | ○ | ○ | ○ | ○ | ○ |
| Using the technology used to complete the intervention? (5) | ○ | ○ | ○ | ○ | ○ |

## Curriculum Vitae

# JENNIFER THORPE, MS, LAT, CSCS

## EDUCATION

- University of Wisconsin-Milwaukee 2011-Present
    - Candidate for PhD: Health Sciences
- University of Illinois, Urbana, IL 2004-2006
    - Master of Science: Kinesiology
- University of Wisconsin-Milwaukee, Milwaukee, WI
    - Bachelor of Science: Kinesiology/Athletic Training 2000-2004

## PROFESSIONAL EXPERIENCE

**Assistant Professor in Health and Human Performance** 2012-Present

*Concordia University Wisconsin, Mequon, WI*

| | |
|---|---|
| HHP 115 | Medical Terminology for the Health Professions |
| HHP 272 | Introduction to Athletic Training |
| HHP 289 | Seminar in Athletic Training |
| HHP 292 | Athletic Training Practicum II |
| HHP 301/302 | Rehabilitation of Athletic Injuries |
| MSAT 303/304 | Therapeutic Modalities |
| HHP 330 | Manual Muscle Testing |
| HHP 392 | Athletic Training Practicum VI |
| HHP 403 | Advanced Injury Management |
| HHP 491 | Athletic Training Practicum |
| MSAT 501 | Manual Based Examination & Treatment |
| MSAT 571 | Advanced Practice in Athletic Training |

**Instructor in Health and Human Performance** 2010-2012

*Concordia University Wisconsin, Mequon, WI*

| | |
|---|---|
| HHP 115 | Medical Terminology for the Health Professions |
| HHP 272 | Introduction to Athletic Training |
| HHP 289 | Seminar in Athletic Training |

| | |
|---|---|
| HHP 292 | Athletic Training Practicum II |
| HHP 301/302 | Rehabilitation of Athletic Injuries |
| HHP 330 | Manual Muscle Testing |
| HHP 403 | Advanced Injury Management |
| HHP 491 | Athletic Training Practicum V |

**Adjunct Instructor in Health and Human Performance** 2006-2010

*Concordia University Wisconsin, Mequon, WI*

| | |
|---|---|
| HHP 272/273 | Introduction to Athletic Training |
| HHP 292 | Athletic Training Practicum II |
| HHP 330 | Manual Muscle Testing |
| HHP 491 | Athletic Training Practicum V |
| HHP 492 | Athletic Training Practicum VI |

**Clinical Education Coordinator** 2010-Present

*Concordia University Wisconsin, Mequon, WI*

- Coordinate and establish athletic training clinical experiences both on and off campus for all students in the Athletic Training Program (ATP)
- Training of all preceptors involved with the ATP
- Ensure that all athletic training clinical experiences meet the expectations of the Commission on Accreditation of Athletic Training Education (CAATE)
- Serve as academic advisor to students enrolled in the ATP
- CAATE Athletic Training Student Supervision during clinical practice in the athletic training room

**Associate Head Athletic Trainer** 2007-2010

*Concordia University Wisconsin, Mequon, WI*

- Provide athletic training coverage for various teams
    - Men's Soccer
    - Men's Basketball
    - Track and Field
- Provide athletic training services to students, faculty, and staff during clinical hours.
- Maintain and oversee budgets and supplies for athletic training facility.

- Develop a staff schedule providing athletic training services to all athletic practices and events.
- CAATE Athletic Training Student Supervision

**Staff Athletic Trainer** 2006-2007

*Concordia University Wisconsin, Mequon, WI*

- Provide athletic training coverage for various teams
    - Men's Soccer
    - Men's Basketball
    - Track and Field
- Provide athletic training services to students, faculty, and staff during clinical hours.
- CAATE Athletic Training Student Supervision

**Teaching Assistant in Kinesiology and Community Health** 2004-2006

*University of Illinois, Urbana, IL*

| | |
|---|---|
| KIN 120 | Injuries in Sport |
| KIN 320 | Advanced Assessment of Athletic Injuries-Upper Extremity |
| KIN 325 | Advanced Assessment of Athletic Injuries-Lower Extremity |

**Graduate Assistant Athletic Trainer** 2004-2006

*SportWell Clinic, McKinley Health Center, Urbana, IL*

- Provide athletic training services to students, faculty, and staff with athletic injuries.
- Educate and design exercise programs for students, faculty, and staff.
- Perform body compositions and personal fitness assessments.

## PROFESSIONAL PREPARATION

- Certified Graston Technician- M1 & M2 2012-Present
    - Graston Technique Instructor 2013-Present

- Licensed Athletic Trainer in Wisconsin 2006-Present

- Licensed Athletic Trainer in Illinois 2004-2006

- American Heart Association Healthcare Provider CPR 2005-Present

- Certified Strength and Conditioning Specialist 2006-Present

- Certified Athletic Trainer- National Athletic Trainers' Association 2004-Present

- American Red Cross CPR/AED for the Professional Rescuer 2000-2005

## PROFESSIONAL DEVELOPMENT & MEMBERSHIPS

- International Patellofemoral Research Retreat and Clinical Symposium Oct. 2019
    - Milwaukee, WI

- National Athletic Trainers' Association Annual Meeting June 2019
    - Las Vegas, NV

- Commission on the Accreditation of Athletic Training Education Accreditation Conference Oct. 2018
    - Tampa Bay, FL

- Wisconsin Athletic Trainers' Association Annual Meeting April 2018
    - Wisconsin Dells, WI

- Great Lakes Athletic Trainers' Association Annual Meeting March 2018
    - Wheeling, IL

- Wisconsin Athletic Trainers' Association Strategic Planning Summit Jan. 2018
    - Madison, WI

- Wisconsin Athletic Trainers' Association Annual Meeting April 2017
    - Wisconsin Dells, WI

- National Athletic Trainers' Association Annual Meeting June 2016
    - Baltimore, MD

- National Athletic Trainers' Association Annual Meeting June 2015
    - St. Louis, MO

- Wisconsin Athletic Trainers' Association Annual Meeting April 2015
    - Milwaukee, WI

- Wisconsin Athletic Trainers' Association Strategic Planning Retreat Oct. 2014

- National Athletic Trainers' Association Annual Meeting June 2013
    - Las Vegas, NV

- Wisconsin Athletic Trainers' Association Annual Meeting
    - Wisconsin Dells, WI April 2013

- National Athletic Trainers' Association Educators' Conference Jan. 2013
    - Dallas, TX

- National Athletic Trainers' Association Educators' Conference Feb. 2011
    - Washington DC

- National Athletic Trainers' Association Clinical Instructor Educator Course Feb. 2011
    - Washington DC

- Wisconsin Athletic Trainers' Association National Conference on Revenue & the Business of Athletic Training Nov. 2010
    - Milwaukee, WI

- Medical College of Wisconsin Annual Sports Symposium March 2010
    - Milwaukee, WI

- National Athletic Trainers' Association Annual Meeting June 2008
    - St. Louis, MO

- National Athletic Trainers' Association Annual Meeting June 2007
    - Anaheim, CA

- National Athletic Trainers' Association Annual Meeting June 2006
    - Atlanta, GA

- National Athletic Trainers' Association Annual Meeting June 2005
    - Indianapolis, IN

- Member- National Strength and Conditioning Association 2006-Present
- Member- National Athletic Trainers’ Association 2001-Present
- Member- Great Lakes Athletic Trainers’ Association 2001-Present
- Member- Wisconsin Athletic Trainers’ Association 2001-Present

## PROFESSIONAL SERVICE

- Served as a moderator for the 2015 Wisconsin Athletic Trainers’ Association Annual Meeting in Milwaukee, WI. 2015
- Wisconsin Athletic Trainers’ Association Secretary 2014-2018
- Served as a moderator for the 2008 National Athletic Trainers’ Association Annual Meeting in St. Louis, MO 2008
- Served as a moderator for the 2007 National Athletic Trainers’ Association Annual Meeting in Anaheim, CA. 2007
- Volunteered as a model and examiner for the NATABOC examination. 2004-2006

## PUBLICATIONS

Thorpe JL, Oblak P, Earl-Boehm JE (2020). The influence of step direction and step height on lower extremity kinematics during step-downs. *Athletic Training and Sports Health Care* 13(4):e212–e220.

Thorpe JL and Ebersole KT (2008). The influence of lower extremity strength on the star excursion balance test. *Journal of Strength and Conditioning Research* 42:1429-1433.

## PROFESSIONAL PRESENTATIONS

Thorpe JL, Dey P, Earl-Boehm JE (2019). The prevalence of patellofemoral pain in the community. *International Patellofemoral Research Retreat, October 2019.*

Thorpe JL, Dey P, Earl-Boehm JE (2019). The prevalence of patellofemoral pain in the community. *National Athletic Trainers' Association Annual Meeting, June 2019.*
Thorpe JL. Introduction to the Graston Technique. *Wisconsin Athletic Trainers' Association Annual Meeting, April 2019.*

Thorpe JL, Earl-Boehm JE, Dey P, Selfe, J (2018). The prevalence of patellofemoral pain in southeastern Wisconsin using the Survey instrument for Natural history, Aeitology, and Prevalence of Patellofemoral pain Studies (SNAPPS). *University of Wisconsin College of Health Sciences Research Symposium, May 2018.*

Thorpe JL and Earl-Boehm JE (2018). Lower extremity strength and kinematics in adolescents with patellofemoral pain. *Wisconsin Athletic Trainers' Association Annual Meeting, April 2018.*

Bazett-Jones D and Thorpe JL (2018). Knee valgus: Looking beyond the knee. *Great Lakes Athletic Trainers' Association Annual Meeting, March 2018.*
Thorpe JL, O'Connor MA, Arvinen-Barrow M, Earl-Boehm JE, Truebenbach C (2016). Does hip strength predict performance on the Landing Error Scoring System in collegiate athletes? *National Athletic Trainers' Association Annual Meeting, June 2016.*

Thorpe JL, Arvinen-Barrow M, Earl-Boehm JE (2015). Does hip strength predict performance on the Landing Error Scoring System in collegiate athletes? *University of Wisconsin-Milwaukee College of Health Sciences Fall Research Symposium, December 2015.*

Thorpe JL, Earl-Boehm JE, Oblak PA (2012). Hip and knee joint kinematics during lateral- and front-single leg stepdowns. *Concordia University Fall Faculty Research Forum, October 2012.*

Thorpe JL, Earl-Boehm JE, Oblak PA (2012). Hip and knee joint kinematics during lateral- and front-single leg stepdowns. *National Athletic Trainers' Association Annual Meeting, June 2012.*

Thorpe JL, Earl-Boehm JE, Oblak PA (2012). Hip and knee joint kinematics during lateral- and front-single leg stepdowns. *University of Wisconsin-Milwaukee College of Health Sciences Spring Research Symposium, May 2012.*

Thorpe JL and Ebersole KT (2007). The relationship between lower extremity strength, limb dominance, and SEBT reach performance. *National Athletic Trainers' Association Annual Meeting, June 2007.*

## GRANTS

Wisconsin Athletic Trainers' Association Research Grant, awarded in Fall 2019 for the study, *The Use of a Squat Retraining Intervention for Patellofemoral Pain.*

University of Wisconsin-Milwaukee College of Health Sciences Graduate School Research Grant, awarded in Fall of 2019 for the study, *The Use of a Squat Retraining Intervention for Patellofemoral Pain.*

University of Wisconsin-Milwaukee College of Health Sciences Graduate School Research Grant, awarded in Spring 2012 for the study, *Lower Extremity Strength and Kinematics in Female Adolescents with Patellofemoral Pain.*

Wisconsin Athletic Trainers' Association Research Grant, awarded in Spring 2012 for the study, *Lower Extremity Strength and Kinematics in Female Adolescents with Patellofemoral Pain.*

## AWARDS

University of Wisconsin-Milwaukee College of Health Sciences Fall Research Symposium, December, 2015: Graduate Student Research Competition, 2nd place

University of Wisconsin-Milwaukee College of Health Sciences Spring Research Symposium, May, 2012: Graduate Student Research Competition, 2nd place