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RISK FACTORS FOR PATELLOFEMORAL PAIN SYNDROME

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March 7, 2012

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ABSTRACT

BACKGROUND AND PURPOSE: Patellofemoral pain syndrome (PFPS) is a common source of anterior knee in pain females. PFPS has been linked to severe pain, disability, and long-term consequences such as osteoarthritis. Three main mechanisms have been proposed as possible causes of PFPS: the top-down mechanism (a result of hip weakness), the bottom-up mechanism (a result of abnormal foot structure/mobility), and factors local to the knee (related to alignment and quadriceps strength). The purpose of this study was to compare hip strength and arch structure of young females with and without PFPS in order to detect risk factors for PFPS.

METHODS: Twenty-seven females aged 18-33 were recruited at the St. Catherine University campus: 12 case subjects with PFPS and 15 age-matched controls. A blinded examiner tested each subject for hip strength in all planes, core endurance using front and side planks, arch height and width in weight-bearing (WB) and non-weight-bearing (NWB), longitudinal arch angle, and ankle dorsiflexion (DF) range of motion (ROM). Arch height and width were used to calculate the foot mobility magnitude (FMM). Two-sample t-tests were used to determine significant differences between the two groups.

RESULTS: There were no significant differences when comparing BMI, dorsiflexion ROM, longitudinal arch angle, arch height and arch width difference in WB and NWB, FMM, core endurance, and hip strength between the cases and controls. Fair correlations were present between side plank endurance time and hip abduction, internal rotation, and external rotation hip strength. There were low and non-significant correlations between dorsiflexion flexibility and arch measurements.

CONCLUSION: The hypothesis that hip strength and arch structure are risk factors for PFPS was not supported in this study. The lack of significant results may be due to the low sample size or relatively mild cases of anterior knee pain within the case group. Alternatively, there may be other mechanisms that account for the development of PFPS in our sample population that have yet to be investigated.

The undersigned certify that they have read, and recommended approval of the research project entitled...

RISK FACTORS FOR PATELLOFEMORAL PAIN SYNDROME

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in partial fulfillment of the requirements for the Doctor of Physical Therapy Program

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Advisor final approval indicated by signature (see Appendix G)

Chapter I: INTRODUCTION

Patellofemoral pain syndrome (PFPS) is a common source of anterior knee pain in adolescents and young adults, particularly active females. Research has shown that it is one of the most common sports-related injuries.¹⁻³ According to Taunton,⁴ when investigating athletic injuries, the prevalence of PFPS was 1.5 times higher in females than males. Researchers have more recently found that PFPS is not just a problem for female athletes, but also occurs in sedentary females.¹ PFPS can cause severe pain, disability, and long-term consequences such as osteoarthritis, and as many as 70 to 90% of individuals with PFPS have chronic or recurring pain.⁵ A recent study by Davis et al.⁵ reported that five years after completing a rehab program 80% of patients still reported pain, and 70% had reduced their activity level.

Prevalence values of PFPS vary greatly.² It is hypothesized that the range is so vast due to the lack of epidemiological research on prevalence in this group.⁶ A review article by Oakes et al.² estimated up to 40% of patients seen in orthopedic and sports medicine centers for knee conditions are diagnosed with anterior knee pain from PFPS. The same study reported prevalence rates ranging from 3 to 40% as seen in other studies.² Boling et al.⁶ found the prevalence of PFPS in the United States Naval Academy classes 2009-2011 to be 13.5% with 15.3% prevalence in females and 12.3% in males. Epidemiological research has focused much more on the incidence of PFPS. Perhaps the most extensive review on PFPS incidence was completed by Oakes et al.² This review looked at ten articles published between 1984-2006 and found that the incidence of PFPS ranged from 8.75 to 17%.² Other studies have focused on specific population groups. In a two-year prospective study, Witrouw et al.⁷ reported a PFPS incidence of 10% amongst young female physical education students. A prospective cohort study by Thijs et al.⁸ found that 43% of Belgian Royal Military Academy recruits developed

PFPS over a 6-week training period. Thirty percent of these were male and 13% female, but the subject population was heavily composed of males (77%), thus skewing the data towards males.⁸

Three main mechanisms have been proposed as possible causes of PFPS: the top-down mechanism, the bottom-up mechanism, and factors local to the knee. According to the top-down mechanism, weakness of the hip musculature has been thought to contribute to abnormal lower-extremity mechanics. Without proximal stability, it is difficult to achieve distal mobility.

Powers⁹ describes a medial collapse of the knee during weight-bearing that results from femoral adduction, tibial abduction (or a combination of both), as well as increased valgus at the knee, IR of the tibia, and excess foot pronation. An increased Q-angle is present at the tibiofemoral joint which creates increased contact pressure on the lateral patellofemoral joint.¹⁰ Lending support to this top-down theory, several studies have found weakness in the hip abductor and external rotator muscles,^{6,11-15} while others have found global weakness to be a possible fault.^{1,10}

According to the bottom-up mechanism, excessive or prolonged foot pronation during the stance phases of gait causes the tibia to excessively internally rotate and stay rotated as the knee is extended. This causes the femur to internally rotate to a greater extent than normal, in order to compensate so that the screw-home mechanism can be accomplished. This mechanism transfers the weight load from the muscles of the thigh to the cartilage and bones of the knee. Although the screw-home mechanism is still in place with this compensation, a greater Q-angle is created between the tibia and femur which may place excess stress and increased contact on the lateral patellofemoral joint. This theory is controversial as this compensation is seen in people with and without PFPS.¹⁰ This mechanism results in similar actions as the top-down mechanism, but originates from a different initial source of fault.

Many studies have hypothesized that increased navicular drop is a strong risk factor for PFPS because those with PFPS have a greater navicular drop between NWB and WB positions as compared to controls.¹⁶⁻¹⁸ Moderate and severe pes planus are also associated with a higher rate of anterior knee pain, almost double that of controls.¹⁹ In a case control study by Barton et al.,²⁰ the PFPS group showed significantly more foot pronation in relaxed standing compared to controls and a greater ROM in terms of navicular drop and drift, dorsal arch height, and longitudinal arch angle in weight-bearing activities.

Factors local to the knee are also a proposed mechanism for PFPS. Abnormal patellar alignment (lateral displacement or tilt), weak quadriceps musculature, and changes in Q-angle have been attributed to PFPS development.⁵ Q-angle is a measure of the acute angle between a line from the anterior superior iliac spine through mid patella and a line through mid patella and the tibial tuberosity in standing.²¹ An abnormal Q-angle reduces total contact area, which increases stress on the joint. As a result, a person may not be able to tolerate higher loads on the joint such as those associated with prolonged knee flexion or valgus stress, which may create pain depending on the intensity of the activity. Abnormal alignment is not always symptomatic,²² however, and weak quadriceps musculature can also be at fault. Tang et al.²³ found that during open-chain exercises, the vastus medialis obliquus/vastus lateralis strength ratio was smaller in the PFPS group when compared to controls.²³ When comparing eccentric and concentric ability of those muscles in the PFPS group, the contractile ability was less for concentric contractions. Finally, an abnormal Q-angle can create uneven contact pressures. The knee has very uniform pressure distribution under normal conditions. An increased or decreased Q-angle can cause non-uniform contact pressure, leading to knee pain.²⁴

This literature review will now discuss in greater detail the risk factors of hip strength, knee alignment, arch height, and foot structure. PFPS research would benefit from further exploration including the addition of core endurance and the exploration of a possible correlation with arch structure, which was done in this study. Findings from the current study will help strengthen the already vast knowledge base of the topic. The inclusion of foot structure measurements is imperative in order to further study this potential risk factor as previous studies have been inconclusive. Secondly, foot measurement methods have not been reliable in previous studies, thus the decision to use the foot mobility magnitude in this study, which has been shown to be both reliable and valid. This topic is of great importance in terms of better prevention of long-term detrimental consequences of PFPS, which is a very common disorder. Although factors local to the knee are thought to contribute to PFPS, this study did not include these in the analysis because other research has suggested that lower extremity alignment measures have poor reliability and validity.²⁵ The primary purpose of this study was to compare hip strength and arch structure of young females with and without PFPS in order to detect risk factors for PFPS. The secondary purpose of this study was to investigate correlations between hip strength/core endurance, and foot mobility.

Chapter II: REVIEW OF RELATED LITERATURE

HIP

As stated in the introduction, the top-down mechanism is one theoretical approach to explain abnormal mechanics in which altered movement patterns at a proximal joint require the more distal joints to compensate.

Proximal hip muscle weakness has been found to be associated with PFPS. A recent systematic review of six studies comparing hip strength between females with and without PFPS concluded there is strong evidence that females with PFPS demonstrate impaired strength of the hip abductors, hip extensors, and hip external rotators.¹⁵ In a study of 15 females with anterior knee pain and 15 age-matched female controls, Ireland et al.,¹⁴ reported that PFPS subjects demonstrated strength deficits of 26% in hip abduction and 36% in hip external rotation as compared to controls. Bolga et al.¹² reported similar results, in which 18 females diagnosed with PFPS produced 26% less hip abduction torque and 24% less external rotation torque than did their matched controls. Additionally, Baldon et al.¹¹ measured eccentric hip strength in females with PFPS and reported that, on average, the PFPS subjects demonstrated 28% lower eccentric hip abduction torque and 14% lower eccentric hip adduction torque, with no significant differences between groups in hip rotation. It has also been demonstrated that subjects with unilateral PFPS have a decreased mean force production of the external rotators³ and hip abductors^{1,3} on the affected side compared to the unaffected side.

Willson et al.²⁶ evaluated the association between hip and knee joint kinematics with the timing of the gluteus maximus and medius in female runners with and without PFPS. Pearson correlation coefficients were used to quantify gluteal muscle activation with running kinematics. Runners with PFPS exhibited delayed ($p=0.028$, effect size= 0.76) and shorter ($p=0.01$, effect

size= 0.88) gluteus medius contractions compared to the female control group. Consequently, greater hip adduction and internal rotation was also correlated with this late contraction. Therefore, neuromuscular differences appeared to exist in females with PFPS pain during running. Target interventions to help this population may warrant earlier activation of the gluteal muscles in order to avoid altered hip and knee mechanics.²⁶

Some authors suggest that the weakness found in PFPS is actually a global problem causing dynamic instability in the knee rather than weakness in specific muscles. Magalhaes et al.¹ studied hip strength in 50 sedentary female subjects with both unilateral and bilateral PFPS. In those with unilateral PFPS, there was a 15-20% strength deficit in the hip abductors, hip flexors, hip external rotators and hip extensors on the affected side when compared to matched controls. Subjects with bilateral PFPS were found to have significant weakness in all six hip muscle groups when compared to matched controls. Cichanowski et al.³ also reported that female athletes presenting with PFPS demonstrated hip weakness in all hip muscle groups (except hip adduction) when compared with age- and sport-matched controls.

What remains unclear is whether hip weakness is a predisposing factor or a consequence of the development of PFPS. A 2011 prospective study by Thijs et al.²⁷ reported that isometric hip muscle strength may not be a predisposing factor for the development of PFPS. This study measured the isometric strength of the hip flexors, extensors, abductors, adductors, and external and internal rotators in 77 healthy female novice runners prior to the start of a 10-week running training program. Sixteen of the runners developed PFPS over the 10-week period, but there were no significant differences in hip strength between the runners who did and did not develop PFPS. Furthermore, logistic regression analysis found that the assessed hip muscle group's strength was not an intrinsic risk factor for the development of PFPS.²⁷

As a result of proximal hip muscle weakness, several studies^{12,13,28,29} hypothesized that subjects with PFPS would display altered lower extremity kinematics during functional weight-bearing activities. Willson et al.²⁸ reported that kinematic measures taken in 40 females during dynamic activities revealed that the PFPS group performed running, squatting, and single leg hops with an average of 4.3° greater knee external rotation, 3.5° greater hip adduction, and 3.9° decreased hip internal rotation compared to the pain-free control group. Decreased hip internal rotation movement in the PFPS group was an unexpected finding due to the number of studies that have found decreased hip external rotation strength in those with PFPS.^{1,3,11,12,14} Dierks et al.¹³ reported that while both the PFPS group and the controls demonstrated a decrease in hip abduction and external rotation strength following a prolonged run, the PFPS group displayed significantly lower hip abduction strength compared to the control group, as evidenced by the level of association between the hip abduction strength and hip adduction angle. Because of the larger decrease in hip strength displayed by the PFPS group, this may suggest an important link between hip core endurance and its influence on patellofemoral pain. However, Bolga et al.¹² found that the PFPS group did not display any altered lower extremity kinematics in hip internal rotation, hip adduction, or valgus of the knee during stair descent when compared to controls as previously hypothesized. The authors theorized that this finding may be due to the relatively low-demand task performed by the subjects. Souza et al.²⁹ found differences in hip function in female subjects with PFPS compared to pain-free controls. Specifically, the PFPS group demonstrated a higher amount of hip internal rotation in all tasks evaluated and decreased hip abduction and extension strength when compared to the pain-free control group. These findings are consistent with earlier findings by Powers⁹ linking internal femoral rotation to PFPS.²⁹

If this top-down mechanism is in fact the cause of PFPS, then strengthening the hip musculature in PFPS patients should result in a decrease in pain and a normalization of their mechanics. Only one study, to date, has examined this in a randomized controlled clinical trial. Fukada et al.³⁰ demonstrated that after four weeks of a combined hip and knee strengthening program, sedentary females with PFPS experienced a decrease in pain while descending stairs compared to a group performing only knee strengthening exercises and a third group performing no exercise. The two exercise groups both demonstrated an increase in function (as measured by the Lower Extremity Functional Scale and Anterior Knee Pain Scale), and decreased pain with ascending stairs compared to the control (no exercise) group. Although no significant differences were found between groups regarding function, the combined exercise group demonstrated improvement greater than the minimal clinically important difference (MCID) for all outcome measures.³⁰

Although not a randomized controlled trial, a cohort study by Ferber et al.³¹ investigated the relationship between hip abductor strengthening and changes in strength, pain, and biomechanics in runners with PFPS. This study used a three-week protocol for hip abductor muscle strengthening and found that the PFPS group demonstrated increased strength, less pain, reduced stride-to-stride knee-joint variability compared with baseline measurements. There was no change, however, in peak genu valgum angle.³¹

KNEE

As previously stated, the cause of PFPS is multifaceted, with its etiology unclear. Along with proximal and distal factors contributing to PFPS, research has also focused on how local knee factors play a role in the development of PFPS. In a review article describing the various

factors contributing to PFPS, Thomee et al.³² describes three local factors that contribute to knee pain, including malalignment of the lower extremity (with regard to the Q-angle), muscle imbalance in the lower extremity, and overuse within the knee joint itself. Although these factors have been shown to contribute to PFPS, there is inconsistency in the literature regarding the degree of involvement of these factors.

Malalignment of the knee joint has widely been considered the most common etiological factor contributing to PFPS.²⁵ However, clinical studies have not agreed upon the significance of their findings when comparing alignment characteristics of individuals with PFPS and controls, especially with regard to the Q-angle.²¹ Messier et al.³³ demonstrated that 16 individuals with PFPS had significantly larger Q-angles than 20 age- and gender-matched controls. Additionally, Haim et al.³⁴ prospectively studied soldiers' knee pain, and reported that an anomalous Q-angle of greater than 20 degrees significantly correlated with anterior knee pain.³⁴ Conversely, Thomee et al.²¹ found no significant difference between patients with PFPS and controls in regards to Q-angle. Likewise, a prospective study done by Witvrouw et al.⁷ did not find any significant baseline differences in Q-angle between the subjects who went on to develop PFPS and those who did not.

In a clinical commentary, Wilson²⁵ suggests that patellar malalignment (including Q-angle) in PFPS patients is just speculation, and not rooted in evidence. He claims that most evidence for this speculation has been largely based upon alignment measures that have poor reliability and/or validity. Wilson suggests that in order for the debate to progress, valid, reliable, and accurate measurements of patellar alignment are required. Therefore, concentrating on developing said measurements should commence before claims of association are made.²⁵

Muscle imbalance in the lower extremity has also been shown to contribute to PFPS. Strength deficits of the quadriceps muscles have frequently been associated with PFPS.^{21,35} In a study by Callaghan and Oldham,³⁵ 57 patients with PFPS of one lower extremity, had extensor torque of the quadriceps compared between the painful leg and the pain-free leg. They found significant differences in quadriceps muscle strength and cross-sectional area between PFPS subjects' painful and pain-free lower extremity. Additionally, Thomee et al.²¹ compared quadriceps muscle strength in young women with PFPS and healthy controls, and found a 17% strength differentiation. Since this was a case control study design, cause could not be determined. The pain could have inhibited strength measurements, PFPS may have led to lower extremity weakness due to disuse atrophy, or the strength imbalance may have predisposed the knee to PFPS. In addition to deficits in muscle strength, Messier³³ also found that those with PFPS were deficient in knee extension endurance when compared to healthy controls.³³

With specific reference to lower extremity weakness, Witvrouw et al.⁷ found a difference in the reflex response times of the vastus medialis obliquus (VMO) and vastus lateralis (VL) muscles in the group with PFPS as compared to those without. In order to be considered a PFPS patient in this study, the subject had to have a characteristic history and symptoms of PFPS for more than 6 weeks. The group with PFPS showed significantly faster reflex response time in both the VMO and VL when compared with the control group. In addition to the faster reflex time, those with PFPS nearly had an equal firing sequence of the two muscles, while those without PFPS demonstrated a distinctly earlier reflex response time of the VMO compared to the VL. The authors in the study did not expand upon why these timing issues may relate to PFPS.⁷

Overactivity/overuse at the knee joint has also been shown to be a contributor to

PFPS.^{21,36,37} After finding insignificant results regarding mechanical abnormalities associated with PFPS in adolescents, Fairbank et al.³⁷ concluded that the unremitting overload of the joint is the cause of PFPS. Furthermore, Thomee et al.²¹ surveyed patients with PFPS and found that their highest level of pain (as measured by the Visual Analog Scale) was linked to increased physical activity. In addition, all patients described a brief period of overuse/increased physical activity level that lead to their PFPS.²¹

FOOT

Research has suggested that there are characteristics of the foot which may predispose individuals to PFPS. One theory on the biomechanics that lead to PFPS is known as the bottom-up mechanism. The bottom-up approach hypothesizes that PFPS may be acquired due to biomechanical faults in the lower extremity that either increase or decrease the Q-angle, placing additional stress and increased contact forces on the patellofemoral joint.¹⁰

Many studies have looked at static and dynamic foot characteristics in those with PFPS because abnormal foot mechanics are suspected to contribute to knee pain by influencing the Q-angle. These studies have looked at excessive and/or prolonged subtalar pronation during weight-bearing activities, rearfoot eversion/inversion in static and dynamic movement, arch height, and midfoot mobility in individuals with PFPS.^{1,8,10,38,39}

Tiberio⁴⁰ expounds on this hypothesis by giving a theoretical explanation on how faulty foot mechanics may negatively impact the patellofemoral joint. He suggests that because the tibia normally externally rotates in relation to the femur in order to achieve full extension during mid-stance, an overly pronated foot (or one that fails to re-supinate in the gait cycle) may consequently reduce the amount of relative tibial external rotation needed for the screw-home mechanism. If the tibia cannot externally rotate to a sufficient degree, the femur will have to

internally rotate to a greater degree in order to complete the screw-home mechanism and achieve sufficient knee extension for mid- and terminal-stance. Excessive internal rotation of the femur consequently increases the Q-angle, and an increased Q-angle has been linked to patellofemoral pain in a number of individuals.^{1,38}

A number of studies have identified excessive pronation, or a decreased arch height, as a potential factor in the development of PFPS. A large retrospective, cross-sectional analysis performed by the Israel Defense Force, looked at the relationship between the degree of pes planus in their adolescent military recruits and the development of anterior knee pain. Recruits with longitudinal plantar arches classified as either “moderate” or “severe” pes planus showed a significantly higher chance of developing anterior knee pain than recruits with mild pes planus measurements. However, a significant weakness of this study was the absence of a standardized measure for arch classification; the determination of arch height was based on the examiner’s subjective classification.²¹ Although the results from this study cannot be generalized to other clinical populations, this evidence supports a possible relationship between the mechanics of the foot/ankle and knee.²¹

Other studies have looked at dynamic aspects of the gait cycle in order to determine distal factors affecting patellofemoral mechanics. A prospective study by Thijs et al.⁸ used a footscan pressure plate to compare gait-related intrinsic factors between a control and experimental group. Logistic regression analysis revealed that those who developed PFPS had increased stance time on the lateral aspect of their feet and shifted their weight from lateral to medial more slowly. Three consequences of these biomechanical changes that may have predisposed these subjects to PFPS were decreased shock absorption in the feet, decreased tibial internal rotation, and increased Q-angle.⁸

It is important to note that the bottom-up theory assumes that motion at the foot is influencing motion at the femur. Current literature is inconsistent with regards to the strength of this relationship, however.³⁹ It has also been suggested that tibial and femoral rotation are independent of each other, and are not related as directly as might be assumed. Additionally, although tibial rotation is closely linked in response to subtalar movement, the ratio of this coupling is not identical between individuals and may fluctuate based on gait speed.³⁹

Ratios comparing the relationship between foot eversion and tibial internal rotation among individuals with PFPS and healthy controls have been shown to be similar. This finding provides some evidence that there may not be a direct link between PFPS and foot mechanics.¹⁰ In a study performed by Powers,⁴¹ the magnitude and timing of femoral, tibial, and foot rotation was compared in subjects with PFPS and in those without pain during regular chosen walking speeds. The two groups showed no significant differences between excessive or prolonged pronation nor excessive internal tibial torsion. However, a small but significant difference between the groups' magnitude and timing of peak femoral rotation was noted.⁴¹ Contrary to Tiberio's theory (that individuals with PFPS may internally rotate their femur to a greater extent in order to achieve the screw-home mechanism), Powers found that more than half of the pain-free controls exhibited greater than the mean peak femoral internal rotation whereas only half of the individuals with PFPS portrayed this lower extremity characteristic.⁴¹ Powers found no statistically significant difference between the magnitude of peak tibial internal rotation between the PFPS or comparison groups. This data represents a prime example of the difficulty in determining the risk factors for developing PFPS. Powers' study does not specify whether this observation represents a characteristic of individuals predisposed to PFPS, or whether the

abnormal mechanics assumed by the PFPS group were developed as a compensatory strategy in an attempt to reduce pain.⁴¹

It is possible that other factors proximal to the foot are influencing the movement of the femur and must be considered in future investigations. Powers hypothesized that the rotation of the pelvis and its influence on femoral rotation could be a mechanism by which people with PFPS limit their femoral internal rotation, and that this may be a compensatory mechanism following the development of patellofemoral pain.⁴¹

A recent study by McPoil et al.⁴² assessed arch height, midfoot width, and FMM in weight-bearing and non-weight-bearing positions in subjects with and without PFPS. A foot measurement platform was used, similar to the one used in the current study, as well as a digital caliper. It was found that those with PFPS were four times more likely to have a larger than normal difference between weight-bearing and non-weight-bearing arch height, and a higher FMM score, as compared to controls. No significant differences were found in static arch height between those with PFPS and controls, suggesting there was no difference in static foot posture although there were statistically significant differences in foot mobility between the two groups.⁴²

FOOT MEASUREMENT

The lack of consensus on which factors predispose one to developing PFPS is partially due to limited research, but also due to the lack of use of consistent measurement methods. Historically, many different measurement techniques have been used to describe static foot posture.⁴³ More recently, research has turned to examining dynamic foot mobility measurement methods which provide a more accurate representation of the foot during weight-bearing

activities. It is for this reason that McPoil⁵¹ sought to develop the foot mobility magnitude that was used in the current study.

Two of the most common foot mobility assessment methods are the navicular drop and navicular drift tests. The navicular drop test (NDT) has been used to assess the amount of subtalar joint pronation. It is performed by marking the navicular tuberosity bony landmark then measuring the distance it drops from closed kinetic chain subtalar joint neutral (CKC STJN) position to a relaxed bilateral standing position.⁴⁴ Previous studies of the NDT have reported high levels of intra-rater reliability but poor to moderate levels of inter-rater reliability. It is thought that the lower levels of inter-rater reliability are due to inconsistencies in identifying the navicular tuberosity bony landmark as well as placing the subtalar joint in neutral position via palpation.⁴³

Picciano et al.⁴⁴ looked at the intra-rater and inter-rater reliability of the open kinetic chain subtalar joint neutral (OKC STJN) position, CKC STJN position, and the NDT. The testers were two inexperienced physical therapy students who underwent a two-hour training session and then measured both feet on fifteen different subjects (N= 30 feet). The intra-rater reliability for OKC STJN, as described by the intraclass correlation coefficient (ICC), ranged from .06-.27 (considered poor) and the inter-rater reliability was 0.00. The intra-rater reliability for CKC STJN ranged from .14-.18 and inter-rater reliability was .15. The NDT revealed intra-rater reliability levels of .61 and .79, with an inter-rater reliability of .57. The authors concluded that the OKC STJN, CKC STJN, and NDT cannot be completed reliably by inexperienced testers.⁴⁴

Evans et al.⁴⁵ assessed the intra-rater and inter-rater reliability of resting calcaneal stance position (RCSP), neutral calcaneal stance position (NCSP), and the NDT. Three examiners

assessed 29 children and four examiners assessed 30 adolescents and 30 adults. Examiners had between 11 and 15 years of clinical experience. The intra-rater reliability ICC values for RCSP ranged from .17-.85, .07-.91 for NCSP, and .51-.89 for NDT among the four examiners. The inter-rater reliability for the RCSP was .54, .55, and .25 in the children, adolescents, and adults groups respectively. For NCSP, inter-rater reliability was .02, .12, and .33, and NDT inter-rater reliability was .55, .47, and .46. The authors warned that these particular measures should be used with great caution when repeated measures are to be used because of the poor inter-rater reliability found.⁴⁵

A third study by Shultz et al.⁴⁶ examined the intra-rater and inter-rater reliability among multiple testers in measuring several different lower extremity anatomic characteristics including subtalar pronation using the NDT. Four testers were trained in 12 two-hour sessions over four weeks by an instructor who had two years of extensive experience with the clinical measures. Two other testers, who had previously been trained 18 months earlier, also participated and their results were compared to the newly-trained testers. All four newly-trained testers had excellent intra-rater reliability with ICC values of .95, .95, .91, and .97. However, their inter-rater reliability ICC values were .67 on day one, which is considered moderately reliable, and .56 on the second day of testing, which is considered poor reliability. The two previously-trained testers had slightly better inter-rater reliability with an ICC of .76. When all six testers were compared, their inter-rater reliability was .72. The authors concluded that multiple investigators can be trained at different times to measure anatomic characteristics with good to excellent intratester reliability and moderate intertester reliability.⁴⁶

The navicular drift test measures the displacement of the navicular along the transverse plane in neutral stance as compared to relaxed stance. It was first proposed by Menz in 1998,

who noted that the navicular drop test only assesses motion in the sagittal plane and that the motion of the navicular bone in the transverse plane should not be ignored.⁴⁷ He suggested that looking at both planes of movement in the foot would provide further insight into talonavicular joint mechanics.⁴⁷ Cornwall et al.⁴⁸ reinforced Menz's proposal by demonstrating that the navicular bone does indeed undergo significant vertical and medial displacement during the stance phase of walking. Cornwall et al. assessed the rearfoot and navicular bone movement of 106 subjects using the 6D-RESEARCH electromagnetic motion analysis system. They found that the mean maximal vertical depression of the navicular bone was 5.9mm(\pm 2.8) and the maximum medial displacement was 4.7mm(\pm 2.0). They also found that these two events occurred at very different times during the stance phase, further emphasizing the fact that both vertical and mediolateral displacement of the navicular should be measured when assessing foot function.⁴⁸

A study by Vinicombe et al.⁴⁹ looked at the reliability of the navicular drift test as a clinical predictor of foot posture. Five podiatric physicians, who underwent three 1-hour training sessions, examined 20 subjects and ended up with poor to moderate reliability coefficients. The ICC values ranged from .44 to .77 for intra-rater reliability and .32 to .53 for inter-rater reliability. Paired *t*-tests of the inter-rater data found a significant difference in approximately half of the examiners' scores indicating that their measures were consistently different in these cases. Standard error of measurement values (95% confidence interval) revealed a high level of variability ranging from \pm 2.8mm to \pm 4.4mm. The range of navicular drift values obtained was 9mm, meaning that 33% to 55% of the range of values represent potential error. The authors concluded that it is “. . . questionable as to whether measurement of navicular drift provides useful clinical information regarding foot posture.”⁴⁹ They hypothesized that the large amount

of error in their study could have risen from variations in locating the navicular tuberosity. The examiners reported difficulty in consistently palpating this landmark in some of the subjects due to anatomical differences. They also thought the error could be attributed to the poor reliability of establishing a neutral stance position.⁴⁹

As a result of these common clinician errors, McPoil et al.⁵⁰ sought to establish a new foot mobility measurement method that did not require the examiner to identify anatomical bony landmarks nor place the foot in a specific position. They measured the change in dorsal arch height from a non-weight bearing position to 50% weight-bearing using digital image analysis. The intra-rater reliability ICC values for measuring total foot length, dorsal arch height, and change in arch height ranged from .73 to .99. The inter-rater ICC values for the previously listed measurements were .73-.98, which is considered good to excellent reliability. To determine the validity of this measure, lateral-view radiographs of the right foot of the same 12 random subjects were taken and the total foot length and dorsal arch height measurements were computed from the radiograph images. The radiographic measurements were all positively correlated with the measurements taken from the digital images. The authors concluded that the intra-rater and inter-rater consistency was acceptable based on the statistical analyses performed. They stated that their study demonstrated the difference in dorsal arch height in non-weight bearing versus 50% weight-bearing is a valid and reliable measurement alternative to the navicular drop test.⁵⁰

Recognizing the importance of both mediolateral (navicular drift) and vertical (navicular drop) displacement in foot function, McPoil et al.⁵¹ sought to establish the reliability of a new composite measurement, the foot mobility magnitude, which combines arch height and midfoot width. They suggested using the difference in midfoot width from weight-bearing to non-

weight-bearing as an alternative way to measure mediolateral mobility of the midfoot instead of navicular drift. A study by Vicenzino et al.⁵² supported the use of midfoot width as they found the change in midfoot width to be one of the four predictors for identifying individuals with PFPS who would benefit from foot orthoses. McPoil et al.⁴³ were the first to look at the reliability of the midfoot width measurement. They recruited 345 participants who had their dorsal arch height and midfoot width measured both in weight-bearing and non-weight-bearing positions, as well as total foot length in weight-bearing. Reliability was established using the measurements of three examiners, who received one hour of training, and found excellent levels of both intra-rater and inter-rater reliability for all five measurements. The intra-rater ICC values ranged from .97-.99 for both within-session and between-session measurements taken by the three examiners. The inter-rater ICC values were also .97-.99. The authors concluded that the reliability of the measurements was acceptable, so they performed statistical analyses to establish normative data from the 345 subjects measured. According to the authors, their methods are easily reproducible and reliable, and a set of normative data on a large group of healthy individuals has been established. McPoil's composite measure (the Foot Mobility Magnitude [FMM]), which combines the differences in weight-bearing and non-weight-bearing arch height and midfoot width, appears to be the best way to measure both vertical and mediolateral mobility of the foot to date.⁴³

Chapter III: METHODS

Study Design

A case control pilot study design was used to assess differences in hip strength, core muscle endurance, foot mobility, and ankle dorsiflexion in females with PFPS compared with an age- (± 3 years) and gender-matched control group.

Participants

Institutional Review Board (IRB) approval was obtained through St. Catherine University in order to recruit subjects from Physical Therapy Orthopaedics Specialists Inc. clinics and the St. Catherine University campuses. IRB approval was also obtained through Park Nicollet in order to recruit patients from TRIA Orthopaedic Center. Twenty-seven females from the St. Paul and Minneapolis campuses of St. Catherine University in Minnesota agreed to participate. All testing was performed on the campus of St. Catherine University. Criteria for inclusion in the PFPS group were (1) females ages 15-40; (2) insidious onset of symptoms unrelated to trauma and persistence of symptoms for at least one month; (3) presence of anterior knee pain during at least two of the following activities: walking, running, stairs, kneeling, squatting, prolonged sitting. Exclusion criteria for both groups included current low back pain, hip pain, or other lower extremity pain below the knee; pregnancy; fibromyalgia, cancer or other systemic disease such as rheumatoid arthritis; history of knee surgery, or history of lower extremity fracture in the past three years.

For each participant, one limb was used for comparison between groups. For participants with unilateral knee pain, measurements of the injured limb were recorded. For participants with

bilateral knee symptoms, the participant's self-reported most-affected side was considered the involved side. The corresponding limb of the age- and gender-matched controls was tested. Written informed consent was obtained from all subjects. Subjects were not compensated for participating in the study, but were entered into a random drawing for one \$100 cash prize.

Procedures and Instrumentation

The testers were five physical therapy students and one physical therapist. Each of the testers was trained specifically in one of three areas of testing, with two trained in each area, so that each measurement was performed by one of two testers. The areas of testing were: peak isometric hip strength testing, foot measurements (dorsal arch height, midfoot width, FMM) and a combination of core strength/longitudinal arch angle/dorsiflexion measurements. A reliability check was done between the two testers in each area after 10 participants. All testers achieved an acceptable level of reliability.

A physical therapist not involved in the testing of subjects screened the participants based on inclusion and exclusion criteria and assigned them to the case or control condition so that the investigating testers were blinded to subject group. Before testing, demographic information was collected, including: age, height, weight, and duration of symptoms.

Participants rated their knee pain using several 10-cm visual analog scales for usual pain in the past week, worst pain, and pain with activities including: walking, stairs, sitting, and squatting. Next, participants completed the Kujala Anterior Knee Pain Scale, a 13-point self-administered pain and disability questionnaire with a maximum score of 100, which indicates no disability. This tool is recommended as a validated and responsive measure of anterior knee pain by Wang et al.⁵³ Finally, each subject completed the SF-12, a self-administered survey, which is

a valid and reliable shortened version of the SF-36. It is a 12-question survey that provides insight into physical functioning and overall health-related quality of life.⁵⁴

Three different tools were utilized for measuring foot length, arch height in weight-bearing and non-weight-bearing, and midfoot width in weight-bearing and non-weight-bearing. A foot measurement platform was constructed at St. Catherine University. This platform was similar in design to one utilized and described by McPoil et al.⁴² The platform had two heel cups mounted six inches apart from the center of heels at one end in order to equally align the posterior aspect of both feet in standing. A central ruler was imbedded into the center of the board. On either side of the central ruler there were two sliding knobs with extension arms used to read measurements taken while subjects were in standing (Figure 1).

The following measurements used in this study have been previously described by McPoil et al.⁴³ Weight-bearing and non-weight-bearing arch height measurements were obtained with use of a digital caliper (Mitutoyo Corporation, Kawasaki, Japan). For the non-weight-bearing arch height measurements, the caliper was attached to a wooden clipboard with 80-grit sandpaper. A second electronic digital caliper (Cen-Tech Inc., Model 47261, Kansas City, MO) was used for midfoot measurements taken in weight bearing and non-weight bearing. This caliper was modified using plastic plates over the ends of both moving arms in order for increased comfort of midfoot measurements.

Dorsal Arch Height

The dorsal arch height measurements in weight-bearing and non-weight-bearing were obtained following the procedures described by McPoil et al., in which reliability and validity has been established.⁴³ In order to measure dorsal arch height in weight-bearing, subjects were

asked to place the posterior aspect of each calcaneus in the heel cups on the previously described foot measurement platform, stand with their feet pointed straight ahead, and distribute their weight equally between both lower extremities while bilateral foot length and arch height measurements were taken. As they stood with their gaze directed forward, the testers moved the sliding knobs one at a time up towards their feet until the subject reported feeling each one touching their longest toe, in order to measure total foot length. Next, dorsal arch height at 50% of total foot length was measured bilaterally using a digital caliper. In weight-bearing, the arch height was obtained by aligning the metal bar of the caliper at half the foot length on the foot measurement platform, positioning the sliding metal bar of the caliper over the 50% length mark, and then recording the vertical distance from the dorsum of the foot to the superior aspect of the foot platform (Figure 2). The vertical arch height was recorded at the point that the subject reported feeling the metal bar of the caliper touching the dorsal aspect of their foot. This arch height measurement was repeated twice on each foot and the average of the two sets of measurements was recorded for data analysis. The inter-rater reliability was found to be .91 in the pilot reliability study.

Dorsal arch height in non-weight-bearing was measured by asking the subject to sit on the end of a table so that both lower legs were hanging in a perpendicular position to the floor with the ankles in slight plantar flexion. A portable platform, covered by a standard piece of 80-grit sandpaper was positioned under the plantar aspect of the subject's foot and the subject was instructed to state when the platform was equally sensed under the surface of the heel and lateral and medial aspects of the forefoot simultaneously. When this ideal position was reached, the vertical digital caliper attached to the platform was positioned so that the metal bar could be aligned with the 50% foot length mark on the dorsal aspect of the foot (Figure 3). Once the

subject reported feeling the metal rod over the dorsal aspect of their foot, the vertical measurement was recorded and obtained twice for each foot. The averages of each set of measurements were used in the data analysis. The inter-rater reliability was found to be .84 in the pilot reliability study.

Midfoot Width

Midfoot width measurements were obtained following the procedures described by McPoil et al., in which reliability and validity has been established.⁴³ Midfoot width was measured in standing with weight equally distributed to obtain the weight-bearing value. The digital caliper was first zeroed, then positioned so that the edges of the arms were aligned medially and laterally to the 50% mark on the dorsal aspect of the foot. Contact was first made with the lateral aspect of the foot, then the medial arm was slowly moved until light contact was made with the medial aspect of the foot (Figure 4). The measurement was recorded and repeated. Two measures were made on the opposite foot in the same manner.

Midfoot width was measured in seated on a treatment table with legs dangling in a perpendicular position to the floor, with the ankles in slight plantar flexion in order to obtain the non-weight-bearing value. The digital caliper was first zeroed, then positioned so that the edges of the arms were aligned medially and laterally to the 50% mark on the dorsal aspect of the foot. Contact was first made with the lateral aspect of the foot, then the medial arm was slowly moved until light contact was made with the medial aspect of the foot (Figure 5). The measurement was recorded and repeated. Two measures were made on the opposite foot in the same manner, and the average of these two measurements was used in statistical analysis.

Foot Mobility Magnitude

As previously discussed, the foot mobility magnitude (FMM) is a measurement described by McPoil et al., designed to measure dynamic foot mobility.⁴³ The FMM takes into account the difference in arch height and difference in midfoot width from a weight-bearing position to a non-weight-bearing position. The difference in arch height corresponded to the vertical side, and the difference in midfoot width corresponded to the horizontal side of a right triangle. The FMM is then defined as the hypotenuse of the resulting triangle, using the following formula:

. It has been shown to have both inter- and intra-rater ICC values ranging from .97-.99 using raters with varying levels of experience (Figure 6).⁴³

Longitudinal Arch Angle

Longitudinal arch angle was measured in standing using adhesive markers placed on the most prominent aspects of the navicular, head of the first metatarsalphalangeal joint, and medial malleolus of both feet. Subjects stood in staggered stance with equal weight-bearing on a platform with a camera attached. The front foot was placed farther away from the camera than the back foot. The front foot was placed so the navicular marker was perpendicular to the line of the camera lens, which was marked on the platform. The heel of the front foot and the great toe of the back foot were aligned and a 5-inch plexi-glass spacer was placed between the feet. A subject number was placed next to the platform. Subjects were instructed to keep both legs

straight and their weight equally distributed, as the digital photo was taken by the researcher. The process was repeated on the other foot.

Photos were uploaded to a computer and software was used to calculate the longitudinal arch angle (ImageJ software, National Institutes of Health version 1.44p). A photo was opened and the angle tool was used by connecting the three markers on the photo (Figure 7) to give the longitudinal arch angle, which was then used in the data analysis.

Dorsiflexion Measurements

Ankle dorsiflexion active range of motion was measured after the subject completed a three-minute warm-up walk. A colored marker was placed on the subjects' fibular heads. Subjects were positioned in prone and dorsiflexion was measured with the knee in full extension (Figure 8) and flexed to 90 degrees (Figure 9). The goniometer was aligned such that the axis was distal to the lateral malleolus, stationary arm aligned with the fibular head marker, and moving arm aligned with the 5th metatarsal/base of the calcaneus. Subjects were instructed "Pull your toes up toward your shin as far as you can". Three trials were performed in each position (knee extension and 90-degrees knee flexion) on each leg. The three trials were averaged to determine the mean to be used for statistical analysis. Reliability of goniometry has been demonstrated to range from moderate to excellent in the literature (.64-.92),⁵⁵ and was found to be excellent for dorsiflexion in our pilot reliability study (ICC .92-.94).

Hip Strength

Peak isometric hip strength was measured with a Microfet2 hand-held dynamometer (Hoggan Health Industries, West Jordan, Utah, 2008). Hip strength measurements were done on

a treatment table in various positions, depending on the muscle group being tested. The order of testing was randomized, as well as which extremity would be tested first. In every assessment, the subject was instructed to do a sub-maximal contraction for five seconds in order to practice the movement. The tester would count to three, and say the word “push” five times for a total of five seconds. After this, the patient was instructed to do a maximal contraction, “push as hard as you can on the count of three,” and the tester would say “push” five times again. After the first maximal contraction, the subject was given a 30-second rest break, and then instructed to do another maximal contraction of the same muscle group in the same aforementioned manner.

The force of the hip flexors, internal rotators, and external rotators was tested in a seated position on the treatment table. For the hip flexors, the dynamometer was placed on the anterior aspect of the distal thigh, approximately 2 cm proximal to the knee. The subject was instructed to cross her arms, and the tester stabilized on the opposite shoulder during contraction. For internal rotation, the dynamometer was placed 2 cm proximal to the lateral malleolus, with stabilization by the therapist on the subject’s ipsilateral medial knee. For external rotation, the dynamometer was placed 2 cm proximal to the medial malleolus, with stabilization by the therapist on the subject’s ipsilateral lateral knee.

Hip abduction and adduction were tested in sidelying, with the subject’s upper extremity closest to the treatment table behind their head, with the contralateral upper extremity grasping it. Additionally, the tester made sure that the head, shoulders, and hips were in the same plane throughout the testing. For abduction, the tester demonstrated the movement to the subject, and was instructed to hold their leg in the air parallel to the treatment table. The dynamometer was placed 2 cm proximal to the lateral epicondyle of the knee, and stabilizing at the ipsilateral pelvic crest. For adduction, the lower extremity closest to the treatment table was to be tested. The

subject was instructed to relax the contralateral lower extremity while the tester supported it. The dynamometer was placed 2 cm above the ipsilateral medial epicondyle of the knee, and the subject was instructed to push up against the resistance.

Hip extension with the knee straight and bent was tested with the subject in the prone position. The dynamometer was placed 2 cm proximal to the popliteal crease. For knee-bent extension measurement, the subject's lower extremity was brought into 90 degrees of knee flexion, and instructed to push up against the dynamometer into extension. Knee-straight extension was measured in full knee extension, with the dynamometer still 2 cm proximal to the popliteal crease.

Reliability of handheld dynamometry has been well established in the literature^{56,57}, and ranged from .71-.94 in the pilot reliability study. The recorded strength measurements, in pounds, were normalized to body weight and the peak force from the two maximal contractions was used for statistical analysis.

Core Endurance

Methods used for core endurance were based off of a study by McGill et al.,⁵⁸ which were shown to be reliable and valid. Core endurance was measured using a front plank and bilateral slide planks. The front plank was performed first with the subject lying prone on a padded mat with knees extended, ankles dorsiflexed, and hips and feet placed shoulder width apart (Figure 10). The subject was instructed to lift their torso and hips off the mat to maintain their body in a straight line, and to support themselves on both elbows and feet for as long as they could. One practice attempt was given to familiarize the subject with the required position for less than 5 seconds. The subject then lifted off of the mat and timing began using a

stopwatch when both the hips and torso were off of the mat. A squeaking device was placed under the center of the subject's hips. When the subject touched the device, causing it to squeak, testing was finished and the time was recorded. A 1-2 minute rest break was given before moving on to the side plank.

The side planks were performed with the subject lying on their side with knees extended. The top foot was placed in front of the bottom foot on the mat for support, while the top arm was held across the chest with the hand placed on the opposite shoulder (Figure 11). The subject was instructed to lift their hips off of the mat and maintain their body in a straight line. One practice attempt was given to familiarize the subject with the required position for less than 5 seconds. The subject then lifted their hip off of the mat and timing began using a stopwatch. Testing was ended when the subject touched their hip to the mat, and the time was recorded. A 1-2 minute rest break was given, and the test was repeated on the opposite side. Reliability of planks for measuring core endurance has been shown to have ICCs ranging from .96-.99.⁵⁸

Statistical Analysis

Descriptive statistics were calculated for the demographic variables of each group. Data was analyzed by comparing cases' involved lower extremity and controls' corresponding lower extremity using a two-sample t-test, which measures significance between group means. Correlations were investigated between hip strength, core endurance, foot mobility, and dorsiflexion using the Pearson correlation coefficient for continuous data. Both lower extremities of all subjects were used in the correlation data for n=54. Statistical analysis was performed with Number Cruncher Statistical Software (Kaysville, Utah, 2004). For all analyses, the alpha level was set at 0.05.

Chapter IV: RESULTS

Twenty-seven females, aged 18-33 years, participated in the study, and their data was included in the correlation analysis. Data from 24 subjects was utilized when comparing group means for the t-tests. Twelve subjects were assigned to the experimental group and another 12 age-matched controls were assigned for the purpose of comparison. Subject demographics are presented in Tables 1 and 2. Figure 12 displays the median visual analog scale (VAS) pain scores along a 10-cm scale for the “usual” and “worst” amount of pain reported by the case group within the week prior to being tested.

A two-sample t-test revealed no significant differences between the case and control groups with regards to body mass index, dorsiflexion range of motion, arch height and width, foot mobility magnitude, hip strength, core muscle endurance, and longitudinal arch angle.

Figure 13 represents the comparison of the mean peak dorsiflexion range of motion between the case and control groups. No significant differences between the two groups were noted.

Figure 14 displays the comparison of arch height and midfoot width differences in weight bearing and non-weight bearing between the case and control groups, as well as the calculated foot mobility magnitude. No significant differences were observed in any of these three variables between the case and control groups.

The strength of the correlation between variables of interest and the foot mobility magnitude are represented in Figure 15. The only significant correlation with the foot mobility magnitude was dorsiflexion tested with the leg straight with a p-value = 0.04.

Figure 16 displays the comparison of hip strength between the case and control groups. Overall, hip strength comparisons were not significantly different between the case and control groups.

Comparisons of core muscle endurance, as assessed by time to exhaustion in the front and side plank positions, between the case and control groups are represented in Figure 17. The control subjects displayed a trend towards greater overall core endurance, holding the front plank for an average of 100 seconds vs. 65 seconds, and the side plank for an average of 94 seconds vs. 54 seconds compared to the case group respectively. These differences in times however, were not significant.

As shown in Figure 18, there was a fairly low severity of knee pain among all cases, with a clear cut-off between a subgroup of cases with minimal involvement and a more involved subgroup with higher pain scores. As a result, a VAS worst pain score of 30mm, a cut-off commonly used in the literature, was used as an inclusion criterion for an additional analysis of the six subjects with the highest pain scores.^{12,16,30} This sub-group analysis compared hip strength, core endurance, and the FMM between the six worst cases and 12 age-matched controls using a 2:1 model. No significant differences were noted, however the trend toward decreased core muscle endurance among the case subjects persisted, averaging 50 seconds for the front plank and 86 seconds for the side plank compared to the control group which averaged 62 and 101 seconds respectively. This difference may have reached significance with a larger subgroup.

Chapter V: DISCUSSION

Patellofemoral pain syndrome is one of the most common sources of pain in the young, active population.¹⁻³ It remains unclear what predisposes an individual to developing this condition. Three main theories have been proposed to explain the biomechanics of patellofemoral pain: the top-down mechanism, the bottom-up mechanism, and factors local to the knee.⁵ Hip weakness has been well established in the literature to be a common characteristic in those with PFPS,^{1,3,11-15,29-31} however uncertainty remains as to whether it is a cause or consequence of knee pain. Recent research has also suggested that overpronation of the foot, which may be related to ankle flexibility, might be implicated in the development of PFPS.^{8-10,18,19,40} Core muscle endurance, meanwhile, has not previously been examined for an association with PFPS. Because of these questions, this research study sought to explore the relationship between isometric hip strength, foot mobility, core endurance, and ankle flexibility.

This study found that subjects with patellofemoral pain did not demonstrate hip weakness, excessive foot mobility, decreased core endurance, nor decreased ankle flexibility as compared to individuals without knee pain. Despite using measurement methods that have been well established by previous researchers, and very good inter-rater reliability found in the pilot sample, the findings in this particular study do not support the bottom-up nor the top-down mechanisms. Our results seem to support the findings of Boling et al.¹⁶ who prospectively followed nearly 1600 U.S. Naval Academy freshmen from 2005 to 2008. A total of 24 women and 16 men developed PFPS. Decreased knee flexion and extension strength and increased hip external rotation strength were risk factors for developing patellofemoral pain, yet hip muscle weakness was not a predisposing factor for the development of PFPS.¹⁶

Furthermore, a study published by Thijs et al.²⁷ in June 2011 measured the isometric hip strength of 77 healthy female novice runners prior to the start of a 10-week “start-to-run” program. Their statistical analysis found no significant difference in strength of the assessed hip muscle groups between the runners who developed PFPS over the 10-week training period and those who did not. Their findings also suggested that isometric hip muscle strength may not be a predisposing factor for the development of PFPS.²⁷

As detailed in the introduction, this is in contrast to several other studies that have found an association between hip weakness and PFPS^{2,6,16,38} and those that have found hip strengthening to be an effective treatment for PFPS.^{30,31} One potential reason why this particular study did not find an association could be the lower severity of knee pain in the cases. It is possible that hip weakness may not be an issue with less severe cases of knee pain.

Another possibility for the lack of association between hip strength measurements and PFPS cases in this study could be the fact that isometric peak hip muscle strength was measured and perhaps hip/core muscle endurance is more implicated in PFPS. Thijs et al.²⁷ have suggested that muscle function parameters such as eccentric hip strength or endurance of the hip musculature could play a more prominent role than isometric hip muscle strength in controlling the excessive femoral adduction and internal rotation leading to knee pain. There may be a relationship that exists between hip muscle function and PFPS and it may not be adequately measured by peak isometric strength. Additionally, an important trend that emerged from the sub-group analysis was the difference in core endurance between controls and the most-involved cases. Cases demonstrated 15% less front plank core endurance and 20% less affected side plank core endurance when compared to controls. These findings may suggest that core endurance is implicated in PFPS. Our findings also support the results of an interventional case series study

by Earl et al⁵⁹ which targeted core endurance in women with PFPS. Women who completed an eight-week core-strengthening program had significant improvements in VAS pain levels and function as measured by the Kujala.⁵⁹

Hip weakness, as theorized by the top-down mechanism, has potential contributions to lower-extremity abnormal alignment.⁹ We hypothesized that poor proximal stability within our subjects would be linked to overpronation. If this was evident within our sample, the effect was very small. Our results showed small, non-significant negative correlations for hip abduction strength, ER strength, side plank endurance, and foot mobility magnitude. One potential reason for this low correlation may be the younger population examined (average age of cases was 25 years). Hypothetically, if the case subjects had been older, there would have been time for hip weakness to lead to greater pronation. Therefore, stronger correlations between strength and foot mobility may have been identified.

Our primary statistical analysis also found no significant differences in foot mobility between patellofemoral pain cases and controls. The number of studies supporting this bottom-up mechanism is limited, and findings have been mixed. Therefore, one must be cautious in associating overpronation with PFPS. Although different foot measurement techniques were used, our results may support the findings of a prospective study by Witrouw et al.,⁷ which also did not find an association between foot structure and PFPS. This study prospectively followed 282 physical education students (151 boys and 131 girls) over two years. They examined several static and dynamic patellofemoral characteristics including weight-bearing foot alignment and arch structure. A total of 24 students (9%) developed PFPS at the end of the study (7% boys and 10% girls). They concluded that there were no significant differences in foot structure associated with the occurrence of patellofemoral pain syndrome.⁷

Conversely, a recent study by McPoil et al. did find significant differences in the feet of those with PFPS.⁴² The researchers examined 43 male and female subjects with PFPS (average age of 29 years) and compared them to age- and sex-matched controls using the same foot mobility measurements used in this study. They found that individuals with PFPS are four times more likely to have a greater-than-normal sagittal midfoot mobility (as measured by the difference in arch height from non-weight-bearing to weight-bearing). They also found statistically significant differences in foot mobility magnitude and arch height difference between the PFPS and control groups. These results indicate that those with patellofemoral pain have increased mobility in their feet, thus providing further evidence for the bottom-up mechanism. As McPoil et al. suggested, these measurements should be a component of the examination when assessing those at risk for PFPS.⁴²

Additionally, there were no significant differences between cases and controls in ankle dorsiflexion measurements. Evidence for decreased ankle dorsiflexion in people with PFPS has been mixed. Barton et al.²⁰ did not find significant differences in weight-bearing ankle DF among those with PFPS. Whereas, Witvrouw et al. did find significantly different DF in weight-bearing in the cases versus the controls.⁷ It is difficult to compare our results to these studies due to differences in measurement techniques.

One potential explanation for the lack of significant differences between cases and controls in our study is the low severity of knee pain amongst the cases. There was a clear cut-off between the subgroup of cases with minimal involvement, and the more involved subgroup with worse pain scores (Figure 18). A VAS worst pain score of 30mm is a commonly used inclusion criteria in the literature.^{12,16,30} Thus, in order to determine if the low severity of our cases had an impact on our results, we performed a sub-group analysis detailed in the results

section. It was concluded that even with strict inclusion criteria, and elimination of the less severe cases, no clear pattern of hip weakness nor excessive foot mobility in the PFPS subjects emerged.

The correlation analysis indicated one significant, but low negative correlation between subjects' dorsiflexion with their leg straight and their foot mobility magnitude. In theory, if one's dorsiflexion is limited during the gait cycle, the subject will compensate during the mid-stance of gait by overpronating. Based on this theory, their continued compensation would potentially lead to a higher foot mobility magnitude. Over time, this increased foot mobility can be a potential risk factor linked to knee pain as the research has hypothesized.^{9,10,42}

A few limitations to this study are evident. The low number of cases was a significant drawback to the study. There were only 12 cases with knee pain and six of them had relatively low levels of knee pain. The sample size may have been too small to detect differences between cases and controls. Ideally, 20 cases paired with age-matched controls would have provided 80% power, which would have improved the likelihood of finding statistically significant results. This was the main issue with the sub-group analysis, which had even less statistical power. The authors had difficulty recruiting from the clinical setting, all cases came from the university setting. None of the participating subjects were actively seeking treatment for their pain; therefore, the low severity of pain in the sample is not surprising. Future research should address these limitations by recruiting case subjects who are actively seeking treatment for their knee pain.

Additionally, only peak-isometric hip strength was measured in the current study. Examination of other hip muscle function parameters such as endurance and eccentric muscle control should be used in order to more accurately represent functional muscle performance.

Finally, future research should also prospectively measure hip function and foot mobility to determine if these do in fact predispose one to patellofemoral pain.

Chapter VI: CONCLUSION

In conclusion, the primary analysis of this study found no significant differences in hip strength, core endurance, ankle flexibility, and foot mobility between PFPS cases and controls. Additionally, with the exception of DF with leg straight and foot mobility magnitude, there were no significant correlations found. A sub-group analysis of the six most severe cases also failed to find a significant difference in foot mobility or hip strength between cases and controls, although there was a trend toward lower core endurance among cases.

REFERENCES

1. Magalhaes E, Fukuda TY, Sacramento SN, Forgas A, Cohen M, Abdalla RJ. A comparison of hip strength between sedentary females with and without patellofemoral pain syndrome. *J Orthop Sports Phys Ther.* 2010;40(10):641-647. Accessed 10-27-10.
2. Oakes JL, McCandless P, Selfe J. Exploration of the current evidence base for the incidence and prevalence of patellofemoral pain syndrome. *Physical Therapy Reviews.* 2009;14(6):382-387. Accessed 1-21-11.
3. Cichanowski HR, Schmitt JS, Johnson RJ, Niemuth PE. Hip strength in collegiate female athletes with patellofemoral pain. *Med Sci Sports Exerc.* 2007;39(8):1227-1232. Accessed 12-8-10.
4. Taunton J, Ryan MB, Clement D, McKenzie D, Lloyd-Smith D, Zumbro B. A retrospective case-control analysis of 2002 running injuries. *Br J Sport Med.* 2002;36:95-101.
5. Davis IE, Powers C. Patellofemoral pain syndrome: Proximal, distal, and local factors. *J Orthop Sports Phys Ther.* 2010;40(3):A1-A7. Accessed 9-22-10.
6. Boling MC, Padua DA, Marshall SW, Guskiewicz K, Pyne S, Beutler A. Gender differences in the incidence and prevalence of patellofemoral pain syndrome. *Scand J Med Sci Sports.* 2010;20:725-730. Accessed 1-24-10.
7. Witvrouw E, Lysens R, Bellemans J, Cambier D, Vanderstraeten G. Intrinsic risk factors for the development of anterior knee pain in an athletic population: A two year prospective study. *Am J Sports Med.* 2000;28(4):480-488. Accessed 10-27-10.

8. Thijs Y, Van Tiggelen D, Roosen P, De Clerq D, Witvrouw E. A prospective study on gait-related intrinsic risk factors for patellofemoral pain. *Clin J Sports Med.* 2007;17(6):437-445. Accessed 10-27-10.
9. Powers CM. The influence of altered lower-extremity kinematics on patellofemoral joint dysfunction: A theoretical perspective. *J Orthop Sports Phys Ther.* 2003;33(11):639-646. Accessed 9-22-10.
10. Hollman JH, Kolbeck KE, Hitchcock JL, Koverman JW, Krause DA. Correlations between hip strength and static foot and knee posture. *J Sport Rehabil.* 2006;15:12-23. Accessed 9-22-10.
11. Baldon RM, Nakagawa TH, Muniz TB, Amorim CF, Maciel CD, Serrão FV. Eccentric hip muscle function in females with and without patellofemoral pain syndrome. *J Athletic Train.* 2009;44(5):490-496.
12. Bolga LA, Malone TR, Umberger BR, Uhl TL. Hip strength and hip and knee kinematics during stair descent in females with and without patellofemoral pain syndrome. *J Orthop Sports Phys Ther.* 2008;38(1):12-18. Accessed 10-12-10.
13. Dierks TA, Manal KT, Hamill J, Davis IS. Proximal and distal influences on hip and knee kinematics in runners with patellofemoral pain during a prolonged run. *J Orthop Sports Phys Ther.* 2008;38(8):448-456. Accessed 10-12-10.
14. Ireland M, Willson J, Ballantyne B, Davis IE. Hip strength in females with and without patellofemoral pain. *J Orthop Sports Phys Ther.* 2003;33(11):671-676. Accessed 10-14-10.

15. Prins MR, Van Der Wurff P. Females with patellofemoral pain syndrome have weak hip muscles: A systematic review. *Aust J Physiother.* 2009;55:9-15. Accessed 12-8-10.
16. Boling MC, Padua DA, Marshall SW, Guskiewicz K, Pyne S, Beutler A. A prospective investigation of biomechanical risk factors for patellofemoral pain syndrome: The joint undertaking to monitor and prevent ACL injury (JUMP-ACL) cohort. *Am J Sports Med.* 2009;37:2108-2116. Accessed 10-12-10.
17. McPoil T, Cornwall M, Medoff L, Vicenaio B, Fosberg K, Hilz D. Arch height change during sit-to-stand: An alternative for the navicular drop test. *J Foot Ankle Res.* 2008;2(17). Accessed 12-7-10.
18. Waryasz G, McDermott A. Patellofemoral pain syndrome(PFPS): A systematic review of anatomy and potential risk factors. *Dynamic Medicine.* 2008;7(9). Accessed 10-5-2010.
19. Kosashvili Y, Fridman T, Backstein D, Safir O, Bar Ziv Y. The correlation between pes planus and anterior knee or intermittent low back pain. *Foot Ankle Int.* 2008;29(9):910-913.
20. Barton C, Bonanno D, Levinger P, Hylton B. Foot and ankle characteristics in patellofemoral pain syndrome: A case control and reliability study. *J Orthop and Sports Phys Ther.* 2010;40(5):286-296.
21. Thomeé R, Grimby G, Svantesson U, Osterberg U. Quadriceps muscle performance in sitting and standing in young women with patellofemoral pain syndrome and young healthy women. *Scand J Med Sci Sports.* 1996;6(4):233-241.

22. Sanchis-Alfonso V, Rosello-Sastre E, Martinez-Sanjuan V. Pathogenesis of anterior knee pain syndrome and functional patellofemoral instability in the active young. *Am J Knee Surg.* 1999;12(1):29-40. Accessed 1-30-11.
23. Tang SFT, Chen C, Hsu R, Chou S, Hong W, Lew HL. Vastus medialis obliquus and vastus lateralis activity in open and closed kinetic chain exercises in patients with patellofemoral pain syndrome: An electromyographic study. *Arch Phys Med Rehabil.* 2001;82(10):1441-1445. Accessed 1-30-11.
24. Huberti HH, Hayes WC. Patellofemoral contact pressures. the influence of q-angle and tendofemoral contact. *J Bone Joint Surg Am.* 1984;66A(5):715-724. Accessed 1-30-11.
25. Wilson T. The measurement of patellar alignment in patellofemoral pain syndrome: Are we confusing assumptions with evidence? *J Orthop and Sports Phys Ther.* 2007;37(6):330-341.
26. Willson JD, Kernozek TW, Arndt RL, Reznichem DA, Straker JS. Gluteal muscle activation during running in females with and without patellofemoral pain syndrome. *Clinical Biomechanics.* 2011;26:735-740.
27. Thijs Y, Pattyn E, Van Tiggelen D, Rombaut L, Witvrouw E. Is hip muscle weakness a predisposing factor for patellofemoral pain in female novice runners? *Am J Sports Med.* 2011;39(9):1877-1882.
28. Willson JD, Davis IS. Lower extremity mechanics of females with and without patellofemoral pain across activities with progressively greater task demands. *Clinical Biomechanics (Bristol, Avon).* 2008;23(2):203-211.

29. Souza R, Powers CM. Differences in hip kinematics, muscle strength, and muscle activation between subjects with and without patellofemoral pain. *J Orthop Sports Phys Ther.* 2009;39(1):12-19.
30. Fukada T, Rosetto F, Magalhaes E, Bryk F, Lucarelli P, Carvalho N. Short-term effects of hip abductors and lateral rotators strengthening in females with patellofemoral pain syndrome: A randomized controlled clinical trial. *J Orthop Sports Phys Ther.* 2010;40(11):736-742.
31. Ferber R, Kendall KD, Farr L. Changes in knee biomechanics after a hip-abductor strengthening protocol for runners with patellofemoral pain syndrome. *J Athletic Train.* 2011;46(2):142-149.
32. Thomeé R, Augustsson J, Karlsson J. Patellofemoral pain syndrome: A review of current issues. *Sports Med.* 1999;28(4):245-262.
33. Messier SP, Davis SE, Curl WW, Lowery RB, Pack RJ. Etiologic factors associated with patellofemoral pain in runners. *Med Sci Sports Exerc.* 1991;23(9):1009-1015.
34. Haim A, Yaniv M, Dekel S, Amir H. Patellofemoral pain syndrome: Validity of clinical and radiological features. *Clin Orthop Relat Res.* 2006;451:223-228.
35. Callaghan MJ, Oldham JA. Quadriceps atrophy: To what extent does it exist in patellofemoral pain syndrome? *Br J Sports Med.* 2004;38(3):295-299.
36. Heino Brechter J, Powers CM. Patellofemoral stress during walking in persons with and without patellofemoral pain. *Med Sci Sports Exerc.* 2002;34(10):1582-1593.

37. Fairbank JC, Pynsent PB, Van Poortvliet JA, Phillips H. Mechanical factors in the incidence of knee pain in adolescents and young adults. *J Bone Joint Surg Br.* 1984;66(5):685-693.
38. Waryasz G. Patellofemoral pain syndrome (PFPS): A systematic review of anatomy and potential risk factors. *Dynamic medicine DM.* 2008;7:9.
39. Reischl SF, Powers CM, Rao S, Perry J. Relationship between foot pronation and rotation of the tibia and femur during walking. *Foot Ankle Int.* 1999;20:513-520.
40. Tiberio D. The effect of excessive subtalar joint pronation on patellofemoral mechanics: A theoretical model. *J Orthop and Sports Phys Ther.* 1987;9(4):160.
41. Powers CM, Chen PY, Reishl SF, Perry J. Comparison of foot pronation and lower extremity rotation in persons with and without patellofemoral pain. *Foot Ankle Int.* 2002;23(7):634-640.
42. McPoil TG, Warren M, Vicenzino B, Cornwall MW. Variations in foot posture and mobility between individuals with patellofemoral pain and those in a control group. *J Am Podiatr Med Assoc.* 2011;101(4):289-296.
43. McPoil T, Vicenzino B, Cornwall M, Collins N, Warren M. Reliability and normative values for the foot mobility magnitude: A composite measure of vertical and medial-lateral mobility of the midfoot. *J Foot Ankle Res.* 2009;2(1):6. <http://www.jfootankleres.com/content/2/1/6>.
44. Picciano AM, Rowlands MS, Worrell T. Reliability of open and closed kinetic chain subtalar joint neutral positions and navicular drop test. *J Orthop and Sports Phys Ther.* 1993;18(4):553-558.

45. Evans AM, Copper AW, Scharfbillig RW, Scutter SD, Williams MT. Reliability of the foot posture index and traditional measures of foot position. *J Am Podiatr Med Assoc.* 2003;93(3):203-213.
46. Shultz SJ, Nguyen A, Windley TC, Kulas AS, Botic TL, Beynnon BD. Intratester and intertester reliability of clinical measures of lower extremity anatomic characteristics: Implications for multicenter studies. *Clin J Sport Med.* 2006;16(2):155-161.
47. Menz HB. Alternative techniques for the clinical assessment of foot pronation. *J Am Podiatr Med Assoc.* 1998;88(3):119-129.
48. Cornwall MW, McPoil TG. Relative movement of the navicular bone during normal walking. *Foot Ankle Int.* 1999;20(8):507-512.
49. Vinicombe A, Raspovic A, Menz HB. Reliability of navicular displacement measurement as a clinical indicator of foot posture. *J Am Podiatr Med Assoc.* 2001;91(5):162-168.
50. McPoil TG, Cornwall MW, Medoff L, Vincenzino B, Forsberg K, Hilz D. Arch height change during sit-to-stand: An alternative for the navicular drop test. *J Foot Ankle Res.* 2008;1(1):3.
<http://www.jfootankleres.com/content/1/1/3>.
51. McPoil TG, Vincenzino B, Cornwall MW, Collins N. Variations in foot posture and mobility between individuals with anterior knee pain and controls. *J Orthop and Sports Phys Ther.* 2007;37:A15.

52. Vicenzino B, Collins N, Cleland J, McPoil T. A clinical prediction rule for identifying patients with patellofemoral pain who are likely to benefit from foot orthoses: A preliminary determination. *Br J Sport Med.* 2010;44:862-866.
53. Wang D, Jones MH, Khair MM, Miniaci A. Patient-reported outcome measures for the knee. *J Knee Surg.* 2010;23(3):137-151.
54. Ware JE, Kosinski M, Keller SD. A 12-item short-form health survey: Construction of scales and preliminary tests of reliability and validity. *Med Care.* 1996;34:220-233.
55. Youdas JW, Bogard CL, Suman VJ. Reliability of goniometric measurements and visual estimates of ankle joint active range of motion obtained in a clinical setting. *Arch Phys Med Rehabil.* 1993;74(10):1113-1118.
56. Kimura IF, Jefferson LM, Gulick DT, Coll RD. Intra- and intertester reliability of Chantillon and MicroFet hand-held dynamometers in measuring force production. *J Sport Rehabil.* 1996;5:197-205.
57. Bohannon RW, Andrews AW. Interrater reliability of handheld dynamometry. *Phys Ther.* 1987;67:931-933.
58. McGill SM, Childs A, Liebenson C. Endurance times for low back stabilization exercises: Clinical targets for testing and training from a normal database. *Arch Phys Med Rehabil.* 1999;80(8):941-944.

59. Earl JE, Hoch AZ. A proximal strengthening program improves pain, function, and biomechanics in women with patellofemoral pain syndrome. *Am J Sports Med.* 2011;39(1):154-163.

TABLES

Table 1. Demographic data of cases.

Variable	Mean ± SD (n=12)
Age	24.9 ± 3.8
Height (cm)	165.6 ± 3.8
Weight (kg)	68.5 ± 5.5
BMI (kg/m ²)	25.0 ± 2.1
Kujala	*86.7 ± 7.9
VAS Worst Pain (mm)	30.0 ± 28.8
VAS Usual Pain (mm)	16.0 ± 22.5

*100 represents the absence of pain

Table 2. Demographic data of controls.

Variable	Mean ± SD (n=15)
Age	23.9 ± 2.2
Height (cm)	163.7 ± 5.9
Weight (kg)	65.0 ± 8.0
BMI (kg/m ²)	26.1 ± 3.3

FIGURES

Figure 1. Foot measurement platform.

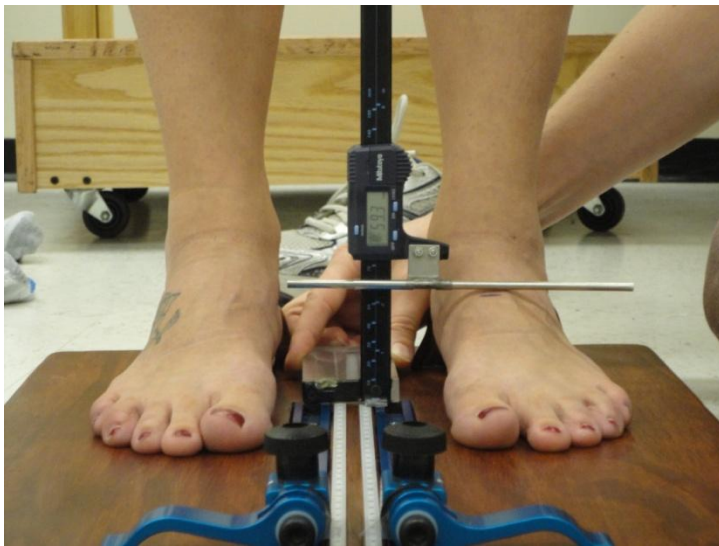


Figure 2. Arch height measurement in weight-bearing.

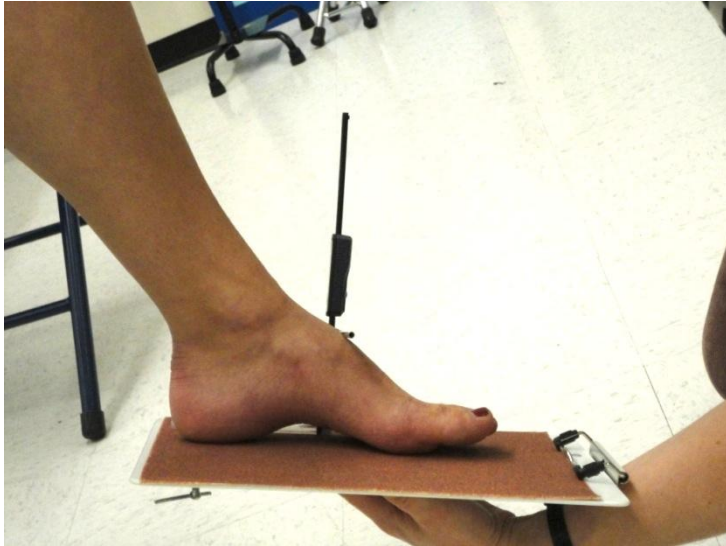


Figure 3. Arch height measurement in non-weight-bearing.



Figure 4. Midfoot width measurement in weight-bearing.



Figure 5. Midfoot width measurement in non-weight-bearing.

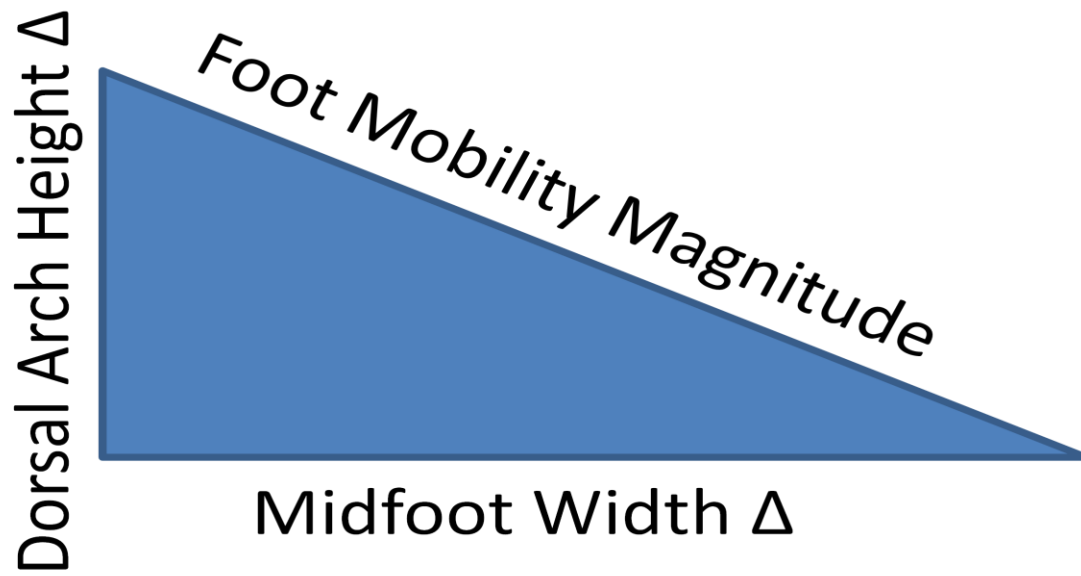


Figure 6. Calculation of foot mobility magnitude.



Figure 7. Measurement of longitudinal arch angle.



Figure 8. Ankle dorsiflexion measurement in knee extension.



Figure 9. Ankle dorsiflexion measurement in knee flexion.

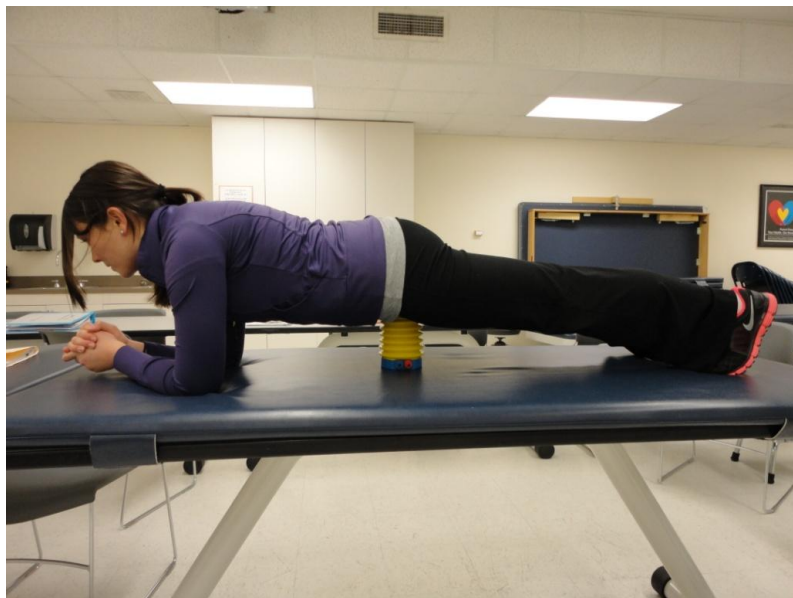


Figure 10. Front plank core endurance measurement.

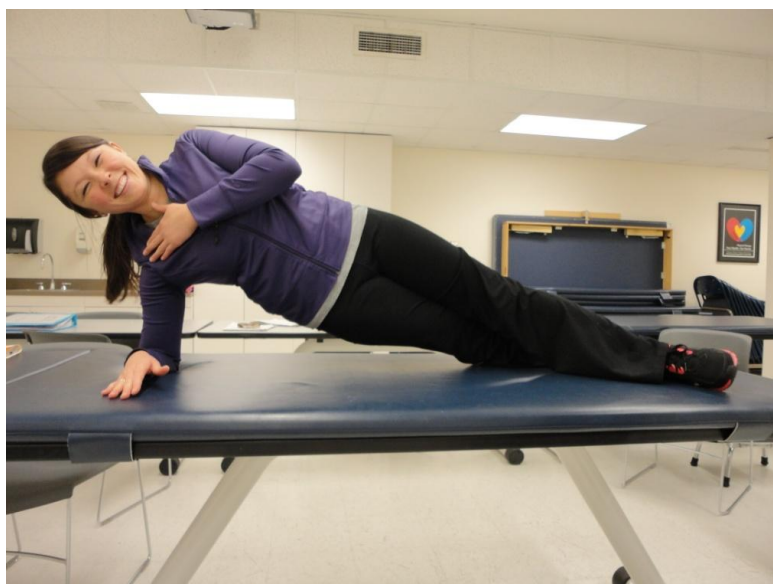


Figure 11. Side plank core endurance measurement

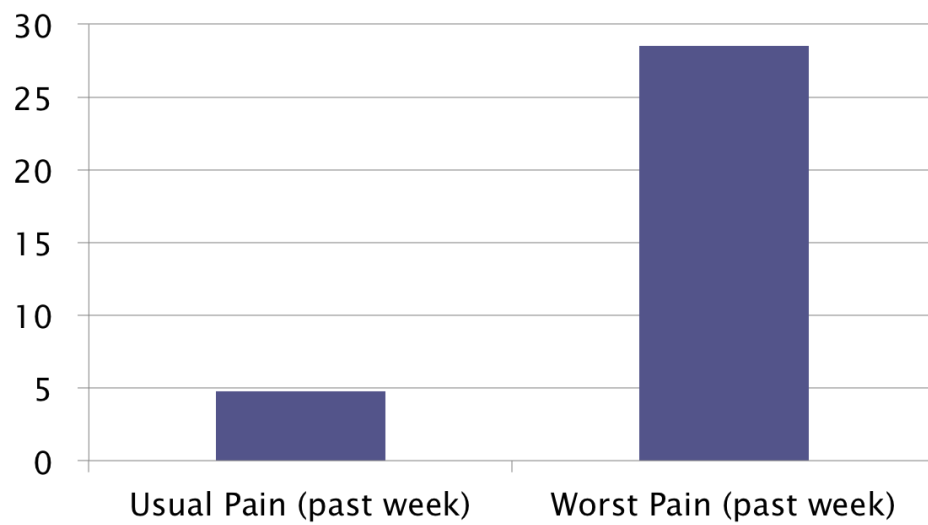


Figure 12. Median visual analog scale pain scores for PFPS cases.

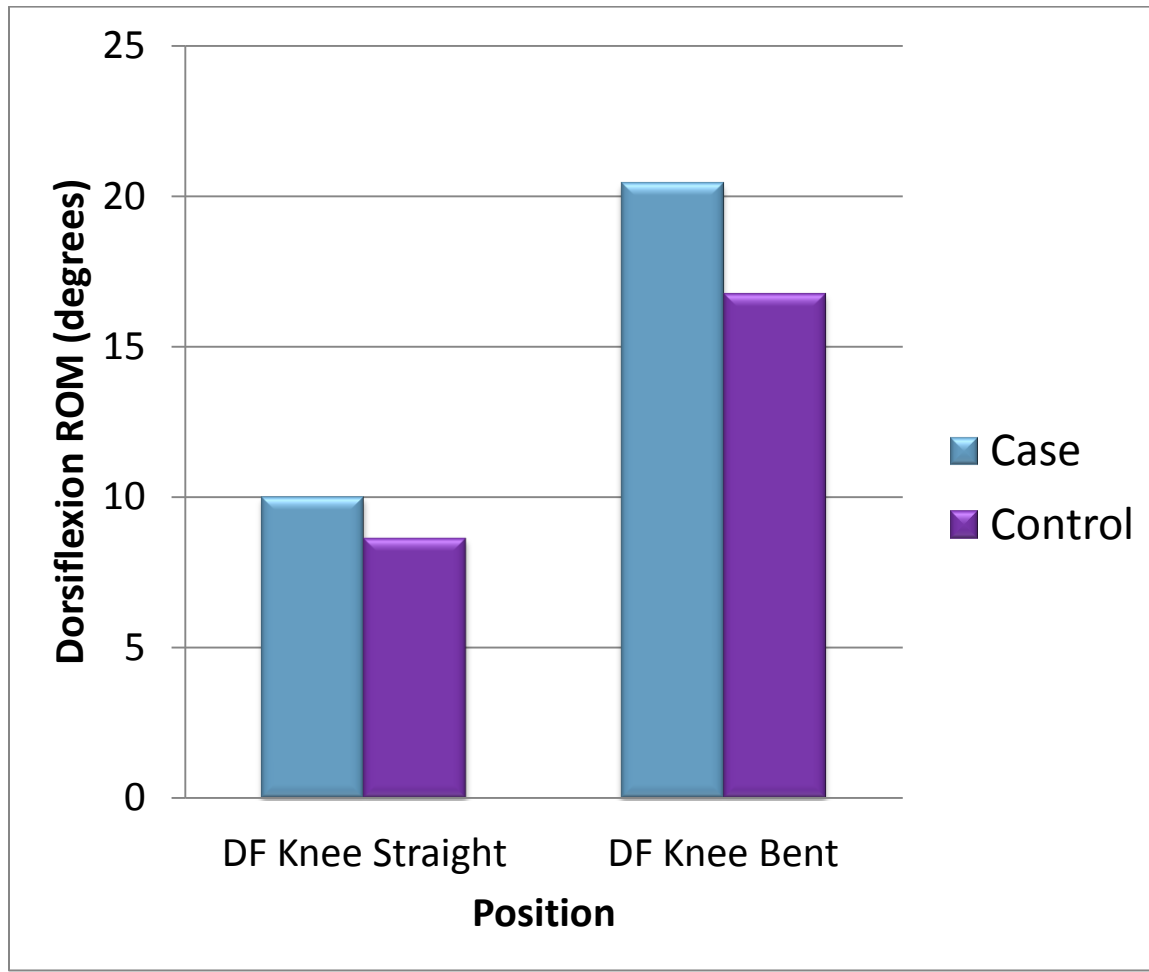


Figure 13. Mean peak dorsiflexion ROM.

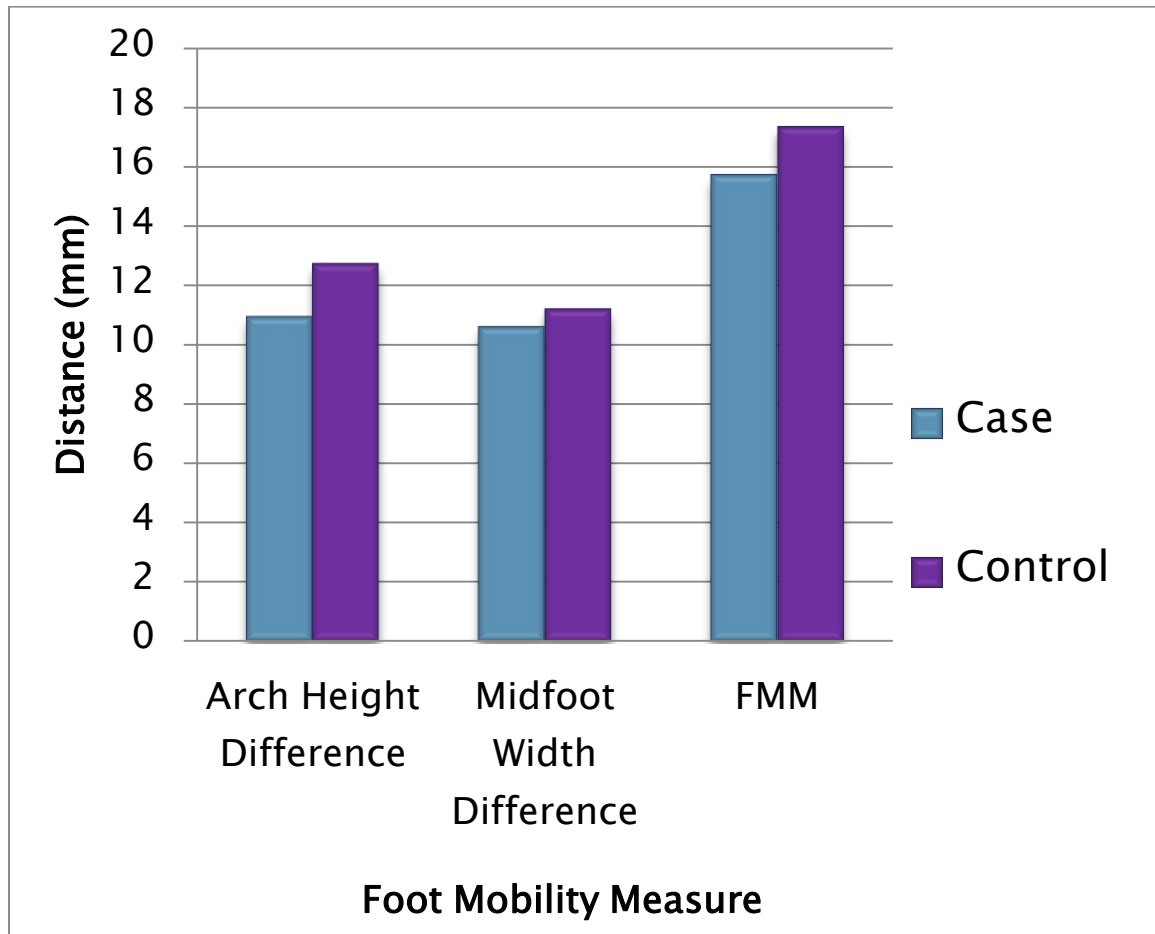


Figure 14. Comparison of foot mobility measurements between groups.

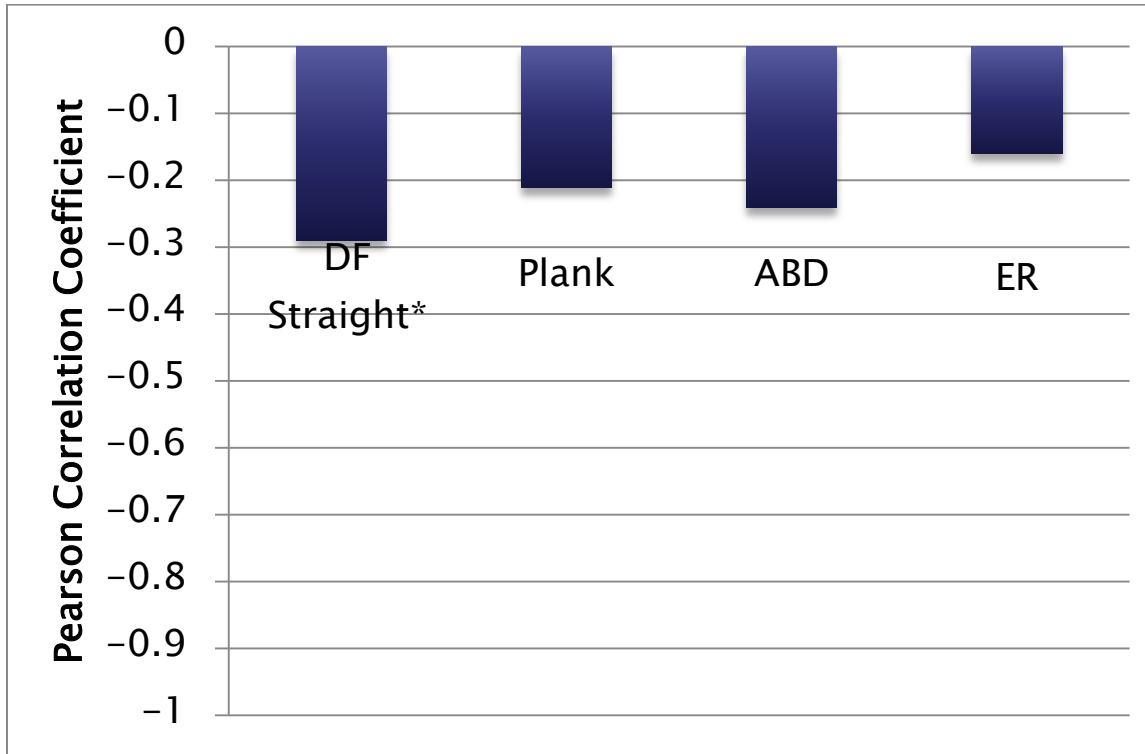


Figure 15. Correlations with foot mobility magnitude. Statistically significant correlations ($p < 0.05$) are marked with an asterisk.

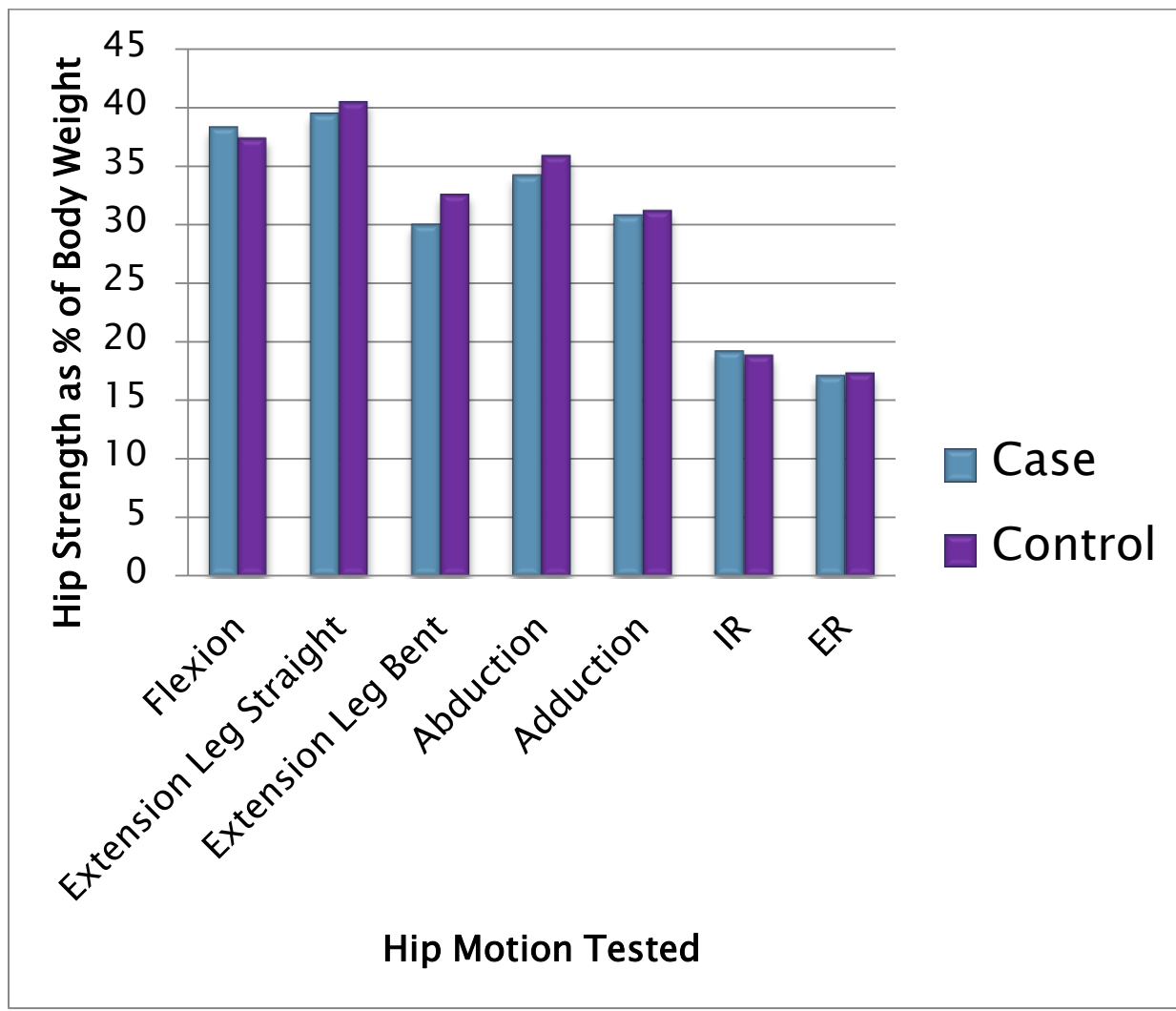


Figure 16. Comparison of hip strength between groups.

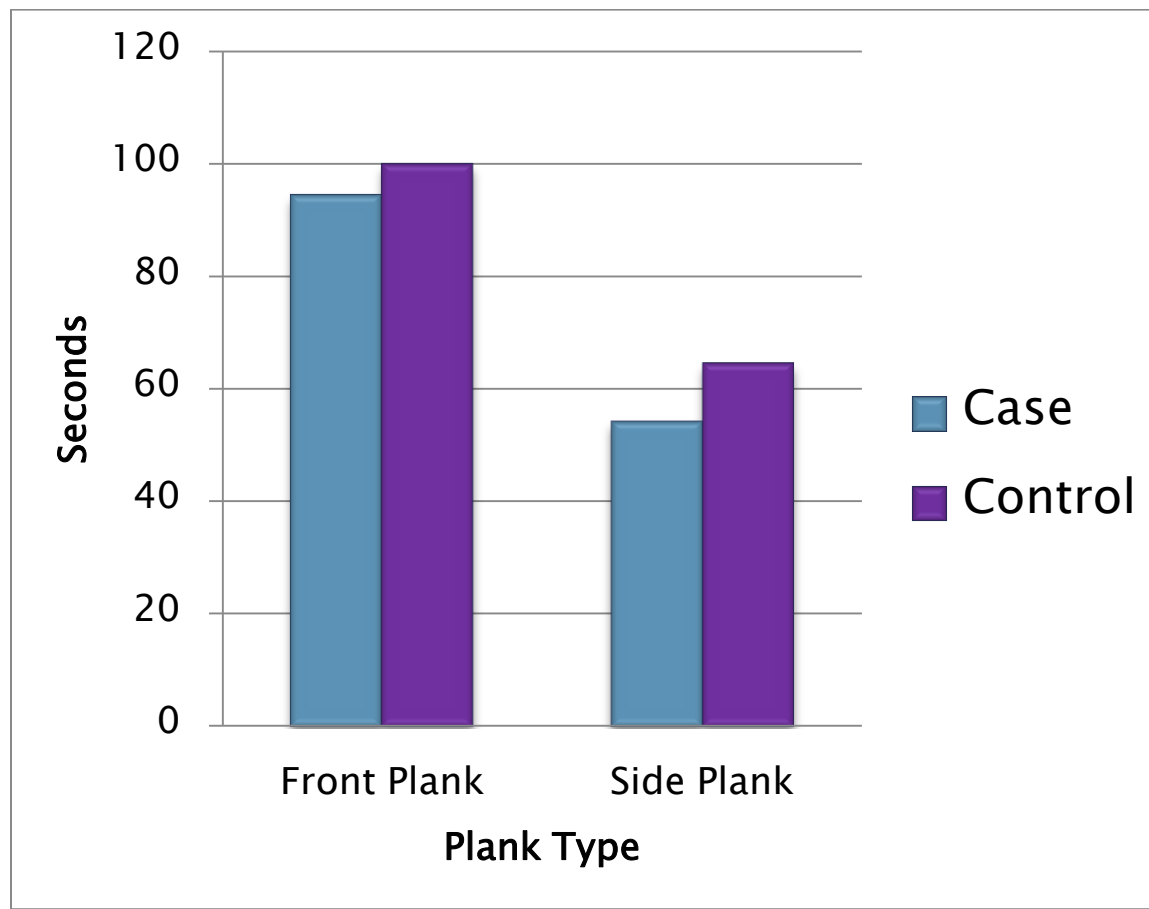


Figure 17. Comparison of core endurance between groups.

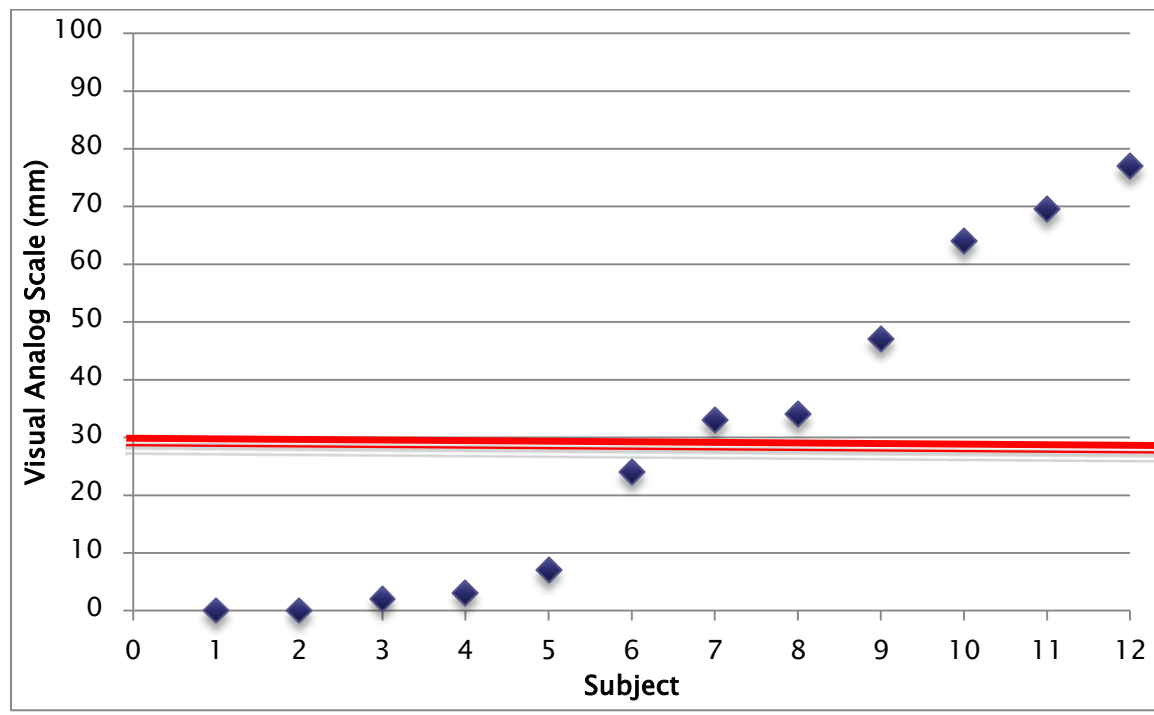


Figure 18. Distribution of cases' worse pain VAS scores.

