Load and Angle Dependent Patellar Kinematics in the Patellar Femoral Pain Syndrome Population

By

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A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University

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Introduction

Patellar femoral pain syndrome (PFPS) is a common musculoskeletal condition, which affects the knee and involves the patellar femoral joint and surrounding soft tissues. Incidence, depending on the source and population ranges from 15 to 30 % (Arroll et al, 1997; Beckman et al, 1989; McConnell, 1986). Although a consensus is present that this condition affects the knee, controversy exists regarding: 1) an appropriate definition, 2) the cause of this condition and 3) the effectiveness of treatment interventions such as patellar taping and vastus medialis re-training in restoring strength and function.

Originally PFPS was referred to as "Chondromalacia Patellae". This diagnosis was given in the presence of anterior knee pain as it was suspected that the pain was due to degeneration of the patellar hyaline cartilage (Arroll et al, 1997; Puniello, 1993; Beckman et al, 1989). The literal definition of chondromalacia is "abnormal softening of the cartilage" (Melloni et al, 1985). Bentley in his 1978 article was more specific in his definition stating that it is a "pathological state" of softening of the "articular cartilage" of the patella often involving "fibrillation", "fissuring" or "erosion" of the cartilage. The term "patellar femoral pain syndrome" evolved over time with the condition being differentiated from "Chondromalacia Patellae" as a result of improved surgical techniques and testing (Arroll et al, 1997; Puniello, 1993; McConnell, 1986; Fulkerson, 1983; Insal, 1976; Bentley, 1978). With these improvements in technology it was observed that not all individuals with diffuse anterior knee pain had evidence of changes i.e. fissuring or softening of the articulating cartilage of the patella. (Arroll et al, 1997; Puniello, 1993; McConnell, 1986; Fulkerson, 1983; Insal, 1979). Conversely, not all individuals with softening or fissuring of the patellar cartilage have anterior knee pain (Puniello, 1993; Beckman et al, 1989; Fulkerson, 1983; Insall, 1979). Consequently, the diagnosis of "chondramalacia patellae" is currently reserved for those individuals demonstrating degenerative changes to the patellar cartilage through investigative procedures such as arthroscopic surgery and /or magnetic resonance imaging.

Patellar femoral pain syndrome (Arroll et al, 1997; McConnell, 1986) and patellar femoral dysfunction (Puniello, 1993; Shelton and Thigpen, 1991; Beckman et al, 1989) are terms that are utilized in the literature in reference to pain associated with the patellar femoral joint. In comparing the described symptoms and definitions given by various authors these two terms are often but not always interchangeable in their usage. Patellar femoral dysfunction generally includes all congenital, traumatic and/or mechanical conditions of the patellar femoral joint and surrounding area involving pain, whereas patellar femoral pain syndrome generally encompasses a symptom set associated with patellar femoral dysfunction and a general consensus on the theory that that the condition is related to abnormal mechanics i.e. "tracking" of the patellar femoral joint (Arroll et al, 1997; Karst and Willett, 1995; Puniello, 1993; Shelton, 1992; Shelton and Thigpen, 1991). Other terms utilized in the literature are anterior knee pain, patellar pain, patellar femoral syndrome, extensor mechanism dysplasia and patellar malalignment (Grelsamer and McConnell, 1998; Puniello, 1993; Westfall and Worrell, 1992; Insall, 1982; Insall, 1979).

Although a variety of definitions are identified in the literature for PFPS there appears to be consensus regarding a number of consistently reported symptoms associated with this condition. These include: 1) insidious anterior knee pain that is exacerbated with stair ascent and/or descent, or provoked by prolonged sustained sitting; 2) difficulty arising from a chair; 3) giving away of the knee, a locking or catching sensation during knee extension under load and 4) complaints of "swelling" and /or a "crunching noise" i.e. crepitous (Grelsamer and McConnell, 1998; Arroll et al, 1997; Beckman et al, 1989; McConnell, 1986;Insall, 1979; Ficat and Hungerford, 1977).

The mechanisms of patellar femoral pain syndrome are not fully elucidated but the majority of authors concur that it is related to the tracking or more precisely the pattern of movement of the patella relative to the condyles as it articulates with the femur (trochlear groove) during knee movement (flexion and extension) (Grelsamer and McConnell, 1998; Arroll et al, 1997; Karst and Willett, 1995; Puniello, 1993; Grabiner et al, 1993; Shelton and Thigpen, 1991; Shellock et al, 1989; McConnell, 1986; Fulkerson, 1983;

Insall, 1979). Although the authors in general support this view further research is needed to determine if a specific patellar femoral tracking pattern exists that can be definitively associated with the condition of patellar femoral pain syndrome. To date, a limited number of studies have focused on determining if a specific tracking pattern of the patella with knee range of motion exists in the normal population in non-weight-bearing. Those in existence are cadaver studies with small sample sizes, a single in vivo study with one subject, a study utilizing motion triggered cine magnetic resonance involving 13 subjects confirmed with patellar "maltracking", a few studies utilizing magnetic resonance imagining to assess patellar tracking and patellar femoral geometry, a study utilizing in vivo fluoroscopy as well as a study utilizing digital imagining in researching the patellar tracking pattern in a normal population (Moro-oka et al, 2002; Harman et al, 2001;Suchak et al, 2000;Brossmann et al, 1993; Koh et al, 1992; Hefzy et al, 1991; van Kampen and Huiskes, 1990). A few recent studies have also focused on the patellar femoral tracking pattern in weight bearing utilizing a variety of methodologies including ultrasound, magnetic resonance imaging and computed tomography. Even fewer studies have addressed the development of a recognized "abnormal" tracking pattern which has generally been associated with dislocation or subluxation of the patella or have involved cadaveric research on the effects of patellar tendon adhesions on patellar femoral tracking (Tyler et al, 2002; Ahmad et al, 1998; Brossmann et al, 1993). To date there has been only three studies performed on subjects with anterior knee pain with symptoms consistent with patellar femoral pain syndrome. Across study comparisons identify inconsistencies in the results as well as in the methodologies and demographics of the subjects (O'Donnell et al, 2004, Harman et al, 2001; Witonski et al, 1999).

Given that the tracking pattern in the normal population has not been fully defined with few studies providing insight into the pattern associated with the PFPS population, further research is needed to aid in defining the specific patterns associated with each group as well as identifying the amount of inherent variability within each group. Therefore, it is important to include both limbs of the Normal control group as well as the PFPS group including the affected and non-affected limbs when making within and between group comparisons. This will not only provide insight into the tracking patterns

and inherent variability associated with each group, but will also further the base of knowledge pertaining to potential causative factors and/or mechanisms that may be responsible for the development of this condition.

Literature Review

The review of the literature will lead the reader to the purpose of examining the tracking patterns of the subjects with PFPS in comparison to the control subjects. Initially the topic of patellar tracking will be discussed followed by the sections of patellar femoral contact characteristics, as well as factors affecting patellar alignment. These following sections have been included to outline the complexity of this condition as well as identify the importance of contributing to the research in this area.

A significant amount of research has been performed on patellar femoral contact surfaces in the normal population. Although there has been no research to date in this area utilizing the PFPS population, "maltracking" has being associated with the mechanism of altering the forces about the knee, affecting the patellar femoral contact pressures causing pain and if not addressed, possible degeneration of the cartilage. To date PFPS research has also been focused on identifying the cause of the "maltracking" pattern i.e. VM/VL ratio imbalance, large Q-angle, and altered foot biomechanics. Prescribed treatment for this condition has also been based on the premise that an "abnormal" or "maltracking" pattern exists. Although it has been presumed in all areas of research that an "abnormal" or "maltracking" pattern is in existence, a specific pattern has not been identified for the PFPS population, nor has it been established that the pattern differs significantly from that of the normal population. Thus the research to date focusing on the cause and treatment of the "maltracking" pattern in the PFPS population has to be considered in the context that the underlying premise is faulty, as the existence of a "maltracking" pattern associated with this population has not been verified

Patellar Tracking

A Biomechanical Approach

Grabiner et al (1993) state that the tracking of the patella within the femoral trochlear groove influences the magnitude of the forces acting on the patellar femoral joint which

in turn influences the patellar femoral contact pressures. According to the authors, these factors play a role in the development of patellar femoral pain but the exact contribution of each factor is unclear, as "normal" and "abnormal" tracking patterns are not fully understood. The research to date focuses on the motions of the patella in relation to the knee joint as it moves through flexion. Studies in this area were initially cadaveric with small sample sizes with one single subject in vivo study also conducted (Koh et al, 1992; Hefzy et al, 1991; van Kampen and Huiskes, 1990). More recent studies include magnetic resonance imaging as well as digital imaging (Moro-oka et al, 2002; Suchak et al, 2000; Brossmann et al, 1993; Brossmann et al, 1994). Results from cadaver studies while informative are not as powerful as those from *in vivo* studies as they do not fully represent the normal *in vivo* population and as such need to be considered in this context. (Brossmann et al, 1994; Brossmann et al, 1993; Koh et al, 1992) The patellar movements defined and discussed in the literature are patellar lag (flexion), patellar tilt, patellar rotation and medial/lateral patellar position. Also discussed is the effect of tibial rotation on patellar movement.

Patellar Lag/Flexion: Patellar lag is defined as the movement of the patella through a parasagittal plane. Authors from reviewed literature on patellar tracking consistently conclude that the patella lags behind the knee during knee flexion (Koh et al, 1992; Hefzy et al, 1991; van Kampen and Huiskes, 1990). Although the authors agree on the presence of the patellar lag, the amount of lag is not consistent across all three studies. van Kampen and Huiskes (1990) from their cadaver study on patellar tracking report that the patella lags behind the knee in flexion by 20 % and that this lag is more pronounced after 105 degrees of flexion. Hefzy et al (1991) also utilizing cadaver specimens reported a similar patellar lag of approximately 20%. Koh et al (1992) in their 1 person *in vivo* case study agree with the two cadaver studies in regards to the existence of the patellar lag, but their findings indicate a lag of 40 to 50%.

Patellar Tilt: Tilting of the patella is defined as the movement of the patella about a parasagittal axis. The presence of tilting of the patella is not conclusively demonstrated in van Kampen and Huiskes (1990) study. The authors state that the patella during flexion

"wavers" from a medial to a lateral tilt and a lateral to a medial tilt depending upon the subject. Hefzy at al's (1991) findings are more consistent across the specimens studied. They indicate a medial tilt in the first 20 to 30 degrees of knee flexion with a change to a lateral tilt during 30 to 80 degrees of range. Koh et al's (1992) findings also demonstrate a lateral tilt but at 15 degrees verses the 30 degrees outlined by Hefzy et al (1991). Their findings also indicate a greater magnitude of lateral patellar tilt than that which was identified by van Kampen and Huiskes (1990). Moro-oka et al's (2002) findings are inconsistent with Koh et al's (1992) and Hefzy at al's (1991), indicating that the patella tilts medially as knee flexion increases. Brossmann et al (1993) report an absence of a significant patellar tilt with passive knee extension from a starting position of 30 degrees of knee flexion, with a lateral tilt of 12 degrees identified with dynamic knee extension through the same range of motion with the tilt being observed to commence at 25 degrees. This change in tilt from an absence of a significant tilt in the passive condition to a lateral tilt under dynamic conditions is the finding that led us to believe that the position of the patella may be load dependent.

Patellar Rotation: Patellar rotation is defined as the movement of the patella about an anterior/posterior axis. Consensus amongst the researchers is apparent with patellar rotation being reported as being insignificant in the first 40 degrees of knee flexion with the tibia in a neutral position (Koh et al, 1992; Hefzy et al, 1991; van Kampen and Huiskes, 1990). Van Kampen and Huiskes (1990) state that patellar rotation becomes significant as knee flexion increases with the patella rotating medially. This data cannot be compared with Koh et al (1992), as range in the *in vivo* study was limited to 60 degrees of flexion. This parameter was not assessed in the imaging study conducted by Moro-oka et al (2002, nor in the study performed by Brossmann et al (1993).

Medial/Lateral Patellar Position: Medial/lateral patellar position or shift refers to translation of the patella in a medial or lateral direction. Literature indicates that the patellar progressively shifts laterally with respect to the medial femoral condyle as the knee extends through 60 degrees of flexion to full extension (Shih et al, 2004; Moro-oka et al, 2002; Brossmann et al, 1994; Brossmann et al; Koh et al, 1992; Hefzy et al, 1991;

van Kampen and Huiskes, 1990). Authors from these studies agree that lateral patellar translation occurs but differ in the amount of resultant displacement. Koh et al (1992) report a displacement of 9 mm (n=1) in their in vivo study whereas the two cadaver studies of van Kampen and Huiskes (1990) and Hefzy et al (1991) indicate displacement values of 4–6 mm and 2–5 mm respectively. Brossmann et als' (1993) and Suchak et als' (2000) findings are not fully consistent with the other authors. Their findings indicate the presence of significant lateralization of the patella but only under dynamic or loaded conditions. They report a lack of significant patellar displacement under static or unloaded conditions. Under dynamic conditions Brossmann et al (1993) reports a trend of lateral patellar displacement as the knee extends from 30 degrees of flexion to full extension. They note a 4 mm lateral displacement in the healthy group with a more significant value of 8 mm identified for the group with recurrent patellar dislocations. Suchak et al (2000) also report under low loads (5% of maximal at each joint angle) a significant displacement of the patella laterally as the knee range approached 0 degrees with a mean patellar displacement of 3.37 mm.

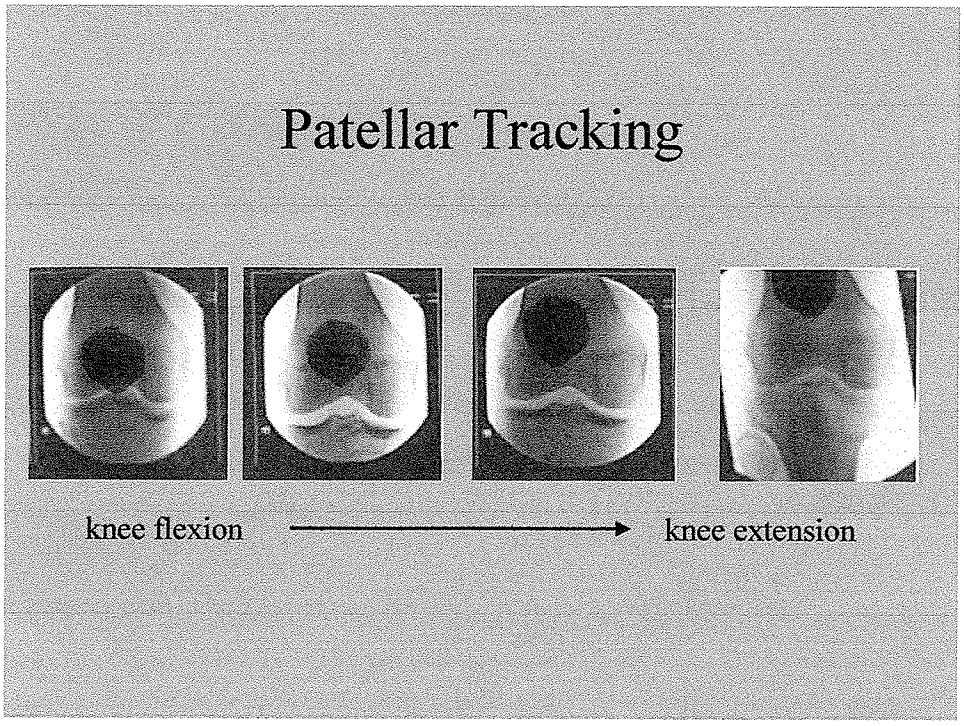


Figure 1: Patellar Tracking - Digitally Manipulated X-Ray Exhibiting Patellar Motion During Knee Extension (unpublished data)

Tibial Rotation: Tibial rotation is about a vertical axis with movement through a horizontal plane. Van Kampen and Huiskes(1990) and Hefzy et al (1991) both agree that tibial positioning does not have a significant effect on patellar flexion lag, but does have an effect on patellar tilt. Although the authors from both studies are in agreement regarding tibial rotation effecting patellar tilt, their findings are not identical. Hefzy et al (1991) report a medial tilt with internal tibial rotation and a lateral tilt with external tibial rotation. This relationship was not demonstrated consistently in the 4 specimens studied by van Kampen and Huiskes (1990) with regards to external tibial rotation being coupled with lateral patellar tilt. Hefzy et al (1991) also state that tibial rotation only effects patellar tilt in the first 30 degrees of knee flexion. These findings are not consistent with those of van Kampen and Huiskes (1990). Hefzy et al's (1991) study also indicates a significant relationship between tibial rotations and their effect on patellar rotation through 60 to 90 degrees of knee flexion. Reported is medial patellar rotation with internal tibial rotation and lateral patellar rotation with external tibial rotation. Van kampen and Huiskes (1990) and Hefzy et al (1991) agree that tibial rotation also effects patella shift or translation through knee flexion, primarily in the first 30 degrees. Hefzy et al (1991) report an increase in lateral shift by 3 mm with external tibial rotation. O'Donnell et al (2004) identify a relationship between tibial rotation and patellar tilt, but they do not define the specific parameters.

To date there have been few studies that have examined the tracking pattern in subjects with anterior knee pain. Witonski et al (1999) studied the patellar motion in women with anterior knee pain utilizing kinematic and dynamic axial magnetic resonance imaging, assessing the parameters of patellar tilt angle, sulcus angle and congruence angle across 0,10,20, and 30 degrees of knee flexion. The affected group was comprised of 12 knees with the control group consisting of 20 knees. The results identified 5 patterns of "malalignment" with the most common being that of lateral tilt combined with lateralization (n=5) followed by lateral tilt (n=1), medialization (n=1) and lateral/medial translation (n=1). Lateralization on its own was identified only with the quadriceps activated. A significant number (n=4-5) of the anterior knee pain subjects at 33 to 42%

exhibited "normal" tracking patterns. Harman et al (2001) studied the tracking pattern in 17 men (20 knees) with suspected patellar femoral incongruency with persistent anterior knee pain. The study utilized kinematic fluoroscopy with the patellar tilt angle, the sulcus angle and congruency angles measured. The identified range of motion was listed as 0 to 45 degrees with no other specifics provided. The authors' also identified 5 tracking patterns including normal (n=2), lateralization of the patella (n=10), patellar tilt (n=2), lateralization combined with patellar tilt (n=2) and medialization (n=4).

The most recent study by O'Donnell et al (2004) studied men and women with a control group consisting of 97 knees and a symptomatic group of 98 knees. The control group consisted of 60% females with 66% of the symptomatic group also comprised of females. The study utilized Magnetic Resonance Imagining (MRI), but the patellar tilt angle, the sulcus angle and congruency angles were not utilized to define the tracking pattern. The researchers utilized visual inspection of the MRI to categorize each individual into either "central" which was defined as normal, Type 1 defined as "minimal lateral subluxation", Type 2 defined as "minor lateral subluxation" and Type 3 defined as "major subluxation" with the category of "tilt" also listed. It is interesting to note that 57% of the anterior knee pain subjects were classified as "central" which is similar to the findings for the control group at 62%. A greater number of the subjects from the control group were classified as Type 1(n=32) relative the symptomatic group (n=13). A greater number of the subjects from the symptomatic group were classified as Type 2(n=17) relative the control group (n=9) as well as Type 3(n=7). The Type 3 classification was comprised almost solely of females. No subjects in the control group were classified as Type 3.

Based upon the reviewed literature it would appear that there is agreement regarding components of the patellar femoral tracking pattern that would be associated with the "normal" population. Consensus is apparent regarding the patella lagging behind the knee in flexion, a lack of patellar rotation during the first 40 degrees of knee flexion and an effect on patellar tilt and shift with changes in tibial positioning. Some consensus is also present regarding a lateral patellar tilt at various knee angles, with a trend identified for this tilt to occur at 25 or 15 degrees of knee flexion, depending upon the source.

Consensus is also apparent with translation of the patella laterally as the knee extends through flexion (60 to 0 degrees), although the magnitude of the translation varies amongst the studies. The magnitude of the patella translation also appears to be load dependent with increased lateralization reported in loaded or dynamic conditions. This trend of lateralization was also identified in the subluxing population with a greater magnitude of displacement recorded in comparison to the normal group under loaded conditions as well as in all 3 the patellar femoral pain syndrome studies.

Some discrepancies may have arisen as a few of the studies involve cadaver specimens while others involve assessment under static and dynamic conditions with live subjects. As such the neuromuscular activation present with the *in vivo* studies utilizing live subjects especially under dynamic conditions cannot be fully and accurately replicated with cadaver studies. Another consideration is the small sample sizes of many of the studies as well as the variety of methodologies utilized and poorly defined terminology with regards to patellar kinematics and the range of motion about the knee (flexion vs. extension). Hence, these studies provide a basis for future research, supplying information on the "normal" tracking pattern of the patella, but do not as yet provide a clear indication of the amount of variability inherent in normality. Without a clear understanding of what "normal" tracking is, the exact nature of "maltracking" also remains unresolved at this time.

The patellar femoral pain syndrome studies have provided a preliminary framework of information in identifying 4-5 patterns of "malalignment" associated with this but further research is needed to establish consistency of the identified trends as well as define the amount of inherent variability especially given that 32-57% of the symptomatic knees assessed presented with findings consistent with that of the norm. Also of concern is that the authors across the studies do not clearly and consistently identify whether the subject is extending the knee through flexion or if the subject is flexing the knee from full extension. This makes comparisons difficult, as the tracking pattern will vary depending upon the direction of knee movement. Other limitations such as poorly defined loads and dynamic movement also make comparisons difficult. Witonski et al (1999) do not define

the load or the dynamic movement utilized, with no description provided regarding the type of contraction or the musculature involved i.e. quadriceps verses hamstring. They use the generic term of "thigh" muscles with no further information on cueing to activate the muscles supplied or parameters surrounding the contraction such as repetitions, time of contraction, method by which the contraction was performed listed.

Patellar Femoral Contact Characteristics

Many authors have postulated that an abnormality in patellar tracking will change the congruence between articulating surfaces of the patellar femoral system (Heegaard et al, 1995; Grabiner et al, 1993; Hefzy et al, 1991; Huberti et al, 1984). It has also been reported that these changes in contact characteristics may be the mechanical stimulus responsible for generating pain and leading to damage to the articular cartilage (Grabiner et al, 1993; Hefzy et al, 1991; Hungerford and Barry, 1979).

Patellar Femoral Contact Areas

There is consensus in the literature regarding the pattern and area of patellar contact as the knee moves through flexion. Huberti et al (1984) in their cadaver study (n=12) on patellar femoral contact pressures utilizing pressure sensitive film, report that as the knee moves through flexion from 20 to 90 degrees, the patellar contact area changes from the distal third to the proximal half with the most proximal margin of the cartilage being reached only at 120 degrees of flexion. Hefzy et al (1991) findings (n = 4) utilizing cadaver limbs, with geometric measurements, support Huberti et al (1984) in regards to the patellar contact area, concluding that the contact area becomes more distal as the knee angle decreases. Hungerford & Lennox (1983) and Hungerford & Barry (1979) also report that patellar femoral contact first occurs at 10 to 20 degrees of flexion in a "continuous band" at the inferior margin of the patella, which corresponds to the distal portion of the patella. Like, Huberti et al (1984), they discuss the pattern of contact area of the patella in regards to increased flexion or knee angle stating that the contact area proceeds proximally as knee flexion increases. Heegaard et al (1995) using a 3 -

dimensional computer model of human patellar biomechanics during passive knee flexion also support what they refer to as the "contact patterns" of the patella originating from the distal articular surface of the patella to the proximal pole of the patella as flexion progresses. Consensus across the studies is apparent regarding the trend of an increase in contact surface area occurring as the knee angle increase, from 0 to 90 degrees (Heegaard et al, 1995; Hefzy et al, 1991; Huberti et al, 1984; Hungerford and Lennox, 1983; Hungerford and Barry, 1979; Matthew et al, 1977; Ficat and Hungerford, 1977; Seedham and Tsubuku, 1976).

A consistent trend has not been identified for the contact surface areas after 90 degrees with increased knee flexion. Two studies identify different findings with Huberti et al's (1984) indicating a lack of significant change in contact area after 90 degrees and Matthews at al (1977) indicating a decrease in contact area after 90 degrees.
Although a general trend has been identified between 0 and 90 degrees of flexion, some discrepancies are present in the literature regarding the magnitude of the patellar femoral contact area at various knee angles. These findings have been outlined in Table 1.

Table 1: Patellar Femoral Contact Area at Different Knee Angles

KNEE ANGLE	CONTACT SURFACE AREA (cm^2)				
Degrees	**Ficat and Hungerford (1997) n=4**	**Huberti et al (1984) n=12**	**Hefzy et al (1992) n=4**	**Seedham and Tsubuku (1976) n=2**	**Matthews et al (1997) n=15**
0			1.20		
20		2.6 (0.4)			
30	2.0	3.0 (0.3)	2.07		2.6
45			2.21	1.8	
60	3.1	3.9 (0.6)	2.37	2.28/2.56	3.8
75			2.36		
90	4.7	4.1(1.2)	2.39	2.28/1.48	3.6
120		3.8			1.8

Patellar Femoral Contact Force and Stresses

The patellar femoral contact force is reported by Hungerford and Lennox (1983) to be dependent upon the angle of knee flexion and is a measurement of the compression of the patella against the femur. These authors state that this phenomenon pertains only to loading the knee from above or in a weight-bearing position. Hungerford & Lennox (1983) and Hungerford and Barry (1979) report that the increase in contact area found with increased knee flexion is necessary to distribute an increasing patellar femoral force that is to create to a "contact stress load". Literature from various authors also supports a direct relationship between patellar femoral contact area and contact pressure and/or stress (Heegaard et al, 1995; Grabiner et al, 1993; Hefzy et al, 1991; Huberti et al, 1984; Hungerford & Lennox, 1983; Hungerford and Barry, 1979; Matthew et al, 1977). Patellar femoral contact stresses acting on the joint surfaces are reported by Hefzy at al (1992) to be inversely proportional to the contact areas. They state that these stresses must be within certain limits to avoid deterioration of the tissue with "broad –based" contact areas to resist shearing forces and provide stability to the joint. Grabiner et al (1993) also discuss the relationship between contact force and contact area. They report that an increase in patellar femoral contact force and /or a decrease in patellar femoral contact area may be associated with "malalignment" of what they term the "patellar femoral force system". Hungerford and Lennox (1983) state that with knee extension against resistance in a non-weight bearing situation, the patellar femoral contact area decreases while the force increases. Hungerford and Barry (1979) state that the decreased contact area and increased force, concentrates the patellar compression which may exceed "physiologic loading" at some point and clinically cause pain. It is also theorized that an increase in patellar femoral contact pressure may be a cause of damage to the cartilage (Ficat and Hungerford, 1977; Outerbridge and Dunlop, 1975).

Various studies have addressed the topic of the measurement of patellar femoral contact forces, but the method of measuring these forces as well as the unit of measure is not consistent across the studies. Huberti and Hayes (1984) in their cadaver study utilized pressure sensitive film, which produced with applied pressure, a color pattern at various

knee angles while clamping the quadriceps to mimic an isometric knee extensor moment. Their results indicate that the contact pressure as well as the patellar femoral contact force increased as the knee angle increased to 90 degrees with a rapid drop in pressure and force reported from 90 to 120 degrees. Perry et al (1975) also measured patellar femoral compressive forces, but they utilized two pressure transducers beneath the patellar surface on cadavers to measure these forces. The authors, conclusions were consistent with Huberti and Hayes (1984) identifying an increase in the patellar compressive force with an increase in the knee angle from 0 to 60 degrees. They attributed the compressive forces to the quadriceps tension with both being dependent upon the knee angle. Matthews et al (1977) utilized a methylene blue contact print to measure the contact surface area of the patellae of 15 cadaver specimens under applied load at 15-degree intervals with a starting angle of 5 degrees with measurements taken to 90 degrees. Their findings also indicate that the patellar femoral contact area increases with an increase in the knee flexion angle up to and including 60 degrees. Seedhom and Tsubuku (1976) utilized a technique called "Controlled Cartilage Compression Casting" to determine contact surface area, as they wanted to take into account the time dependent nature of cartilage deformation. The 3 knee angles of 45,60 and 90 degrees were utilized in this study. Once again the trend of increased contact pressure was identified with an increase in the angle of the knee. Hungerford and Barry (1979) utilized freestanding body diagrams with mathematics utilized to calculate patellar femoral compression of joint reaction forces with Ferguson et al (1979) studying patellar femoral contact stresses. For both studies, there is a consistent trend of increased patellar femoral contact force as the knee angle increased from 0 to 90 degrees.

The literature reviewed indicates a strong relationship between knee joint angle, contact surface area and quadriceps force and the influence that they have on patellar femoral contact force, pressure and contact stress (Heegaard et al, 1995; Grabiner et al, 1993; Hefzy et al, 1991; Huberti and Hayes, 1984; Hungerford and Lennox, 1983; Hungerford and Barry, 1979; Matthews et al, 1977; Seedhom and Tsubuku, 1976; Perry et al, 1975).

Although the studies reviewed utilized different methodology and units of measure,

consistent trends were recognizable throughout. The first trend is that patellar femoral contact surface area increased with an increase in the angle of knee flexion from 0 to 90 degrees (Huberti and Hayes, 1984; Hungerford and Lennox, 1983; Hungerford and Barry, 1979; Matthews et al, 1977). The second trend identified is that patellar femoral contact force, pressure and stress also increased as the angle of knee flexion increased from 0 to 60 or 0 to 90 degrees depending upon the source (Huberti and Hayes, 1984; Hungerford and Barry, 1979; Ferguson et al, 1979; Matthews et al, 1977; Seedhom and Tsubuku, 1976; Perry et al, 1975).

Balance of the patellar femoral system is once again associated with the tracking pattern of the patella. It is assumed that any alteration in the contact surface area between the patella and femur is a result of a change in the "normal" tracking pattern of the patella, causing an increase in the contact forces resulting in pain and dysfunction (Heegaard et al, 1995; Grabiner et al, 1993; Hefzy et al, 1991; Huberti et al, 1984; Hungerford and Barry, 1979; Ficat and Hungerford, 1977; Outerbridge and Dunlop, 1975). Again the premise is that an "abnormal" or "maltracking" pattern is in existence without conclusive research having been performed to verify this with the "normal" tracking pattern also not as yet having been fully defined. Studies to date have not focused on identifying patellar femoral contact characteristics that may be associated with the PFPS population.

Factors Affecting Patellar Tracking

The PFPS literature to date has been based upon the unverified assumption that the pain and dysfunction related to this condition is a result of an abnormal or "maltracking" pattern of the patellar femoral joint. Many factors have been cited in the literature as affecting or determining patellar tracking or alignment. These include the shape of the lateral femoral condyles, the articular facets of the patella, patellar femoral contact areas, the Q - angle, the relationship between the contractile structures including the vastus medialis and vastus lateralis (vastus medialis insufficiency), forces within the passive non-contractile structures of the iliotibial tract and lateral retinaculum, the presence of tightness of the lower extremity musculature, patella alta, and excessive subtalar

pronation which may have an effect on the Q angle (Asano et al, 2003; Schulthies et al, 1995; Karst &Willet, 1995; Puniello, 1993; Shelton, 1992; Hefzy et al, 1992; Beckman et al, 1989; McConnell, 1986; Schutzer et al, 1985; Hubarti and Hays, 1984; Fulkerson, 1983; LeVeau and Rogers, 1980; Insall, 1979 & 1982; Ficat and Hungerford, 1977). All of these factors have been associated with the development of PFPS either individually or in combination but imbalances in the medial (VMO) and lateral force vectors (VL, iliotibial band) have been of primary focus both in identifying this imbalance as the cause of the "maltracking" pattern as well as addressing this imbalance through treatment to correct or "normalize " the tracking pattern.

LeVeau and Rogers (1980) state that the alignment of the patella is a product of the force vectors acting about the patella. The force vectors are created by a number of contractile (vastus lateralis, vastus medialis, vastus intermedius, rectus femoris, tensor fasciae latae and non-contractile structures (retinaculum, iliotibial band). Each structure creates a force vector as with its attachment it has a point of application to the patella, a line of action (or angle) and a magnitude. The magnitude of the individual force vectors for the contractile (muscle) structures is dependent upon the activation or recruitment of the muscle, which is under the control of the nervous system. The resultant force vector applied to the patella represents all the individual contractile and non-contractile force vectors and is often referred to as the patellar femoral joint reaction force (Figure 2). Imbalances in any of these forces (decrease in activation of the vastus medialis, increase in activation of the vastus lateralis, tight iliotibial band) may lead to changes in the tracking pattern or motion of the patella. This has been the primary premise defining the presence of a maltracking pattern in the PFPS population.

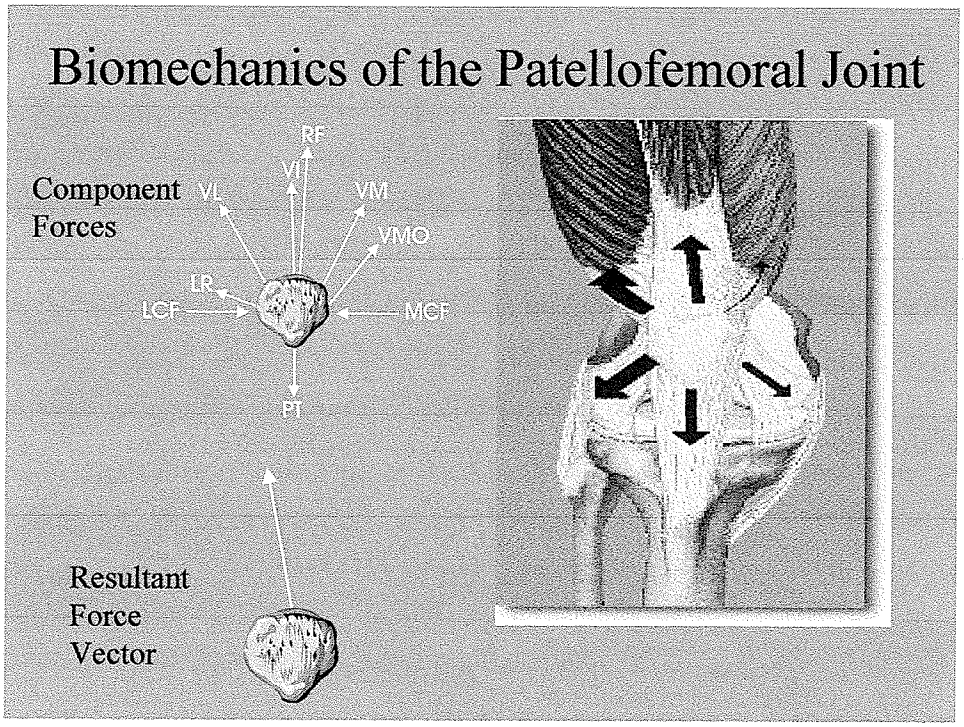


Figure 2: Biomechanics Of The Patellar Femoral Joint

Commonly discussed in the literature is the laterally directed force vector created by the Q-angle, the vastus lateralis muscle and the lateral non-contractile tissues (iliotibial band, lateral retinaculum), which makes it imperative to have a counteracting medially directed force (Lin et al, 2004; Huberti and Hayes, 1984;LeVeau and Rogers, 1980). This function is attributed to the vastus medialis (VM) or more specifically the vastus medialis oblique (VMO) muscle (LeVeau and Rogers, 1980; Lieb and Perry, 1968). The PFPS literature to date has placed the emphasis on the relationship between these two force vectors outlining specifically the role of the vastus medialis oblique on patellar alignment and positioning through knee range of motion.

Patellar Alignment – Role of the Vastus Medialis

Mariani and Caruso (1979) discussed the role of the VM and VL in patellar alignment and how these muscles may affect subluxation of the patella. They examined 5 "normal" subjects and 8 subjects suffering from subluxation of the patella utilizing electromyographic investigation through knee extension at 3 different ranges including

90 to 60 degrees, 60 to 30 degrees and 30 degrees to neutral. Their results for the normal subjects indicate that the EMG activity for the VM and the VL was not significantly different through the last extension 30 degrees of extension, but identified the activity of both as being the highest through this range. The reported results for 7 out of the 8 patients affected with subluxation of the patella, indicate that the EMG activity of the VM prior to the operation was significantly less in comparison with that of the VL across the whole range of extension, but noted that the deficit was most severe during the last 30 degrees of extension. In one subject with subluxation there was no reported difference in EMG of the two muscles. The authors conclude from EMG testing after surgery to correct malalignment of the extensor mechanism, that the VM activity level was clearly higher than that observed prior to surgery. The performance of the VM was reported as having returned to the same levels as the VL. The authors also suggest that decreased VMO activity was a secondary event as surgically operating on the patellar tendon and the extensor mechanism appeared to correct the muscle imbalance. The interpretation of findings is questionable, as pertinent information is not provided regarding the method by which the examiners normalized the EMG between test dates.

Cowan et al's (2002) findings with regards to the recruitment pattern of the vastii musculature were fairly consistent with Mariani and Caruso (1979) although the tasks performed differed i.e. weight-bearing verses non-weight bearing. Cowan et al (2002) utilized EMG to study the recruitment pattern of the vastii in completing a postural task, comparing subjects with patellar femoral pain syndrome to an asymptomatic control group. A secondary aim was to determine if there was a change in the coordination of the postural response by the central nervous system in subjects with PFPS. The authors' findings indicate that in the asymptomatic subjects the vastii contracted simultaneously as part of the feed-forward postural response associated with ankle movements in standing. A different pattern was identified in the PFPS group, with the onset of the vastis lateralis occurring prior to the vastus medialis oblique. The authors', based upon their findings, report a difference in the motor control in subjects with PFPS, stating that their results substantiates the hypothesis that there is a change in the recruitment pattern or timing of

the vastii in this population which supports the focus of physiotherapy intervention for this condition.

Goh et al (1995) studied 6 left lower cadaver limbs with the goal of evaluating the role of the VMO and the effect of a lateral release on patellar tracking. The authors conclude from their data and observations that a deficient VMO results in more laterally directed tension in the quadriceps with a greater load on the lateral facet occurring. They also conclude that the VMO is important in controlling the patellar femoral contact area and pressure distribution throughout the full range of movement. The authors state that a 40 % reduction in lateral tension to simulate a lateral release was necessary to compensate for the simulated deficient VMO. They applied this to the clinical setting stating that a lateral release may not achieve the reduction needed to reduce the "lateral vector" without potentially compromising the strength of the quadriceps as a unit thus they advocated improving the "medial force vector" via strengthening the vastus medialis oblique.

Robertson and Ward (2002) also discuss the importance of the VMO in the function of the knee and lower extremity. Utilizing a single case study design they examined the effect of electrical stimulation of the VMO on pain, stiffness and function for a patient that had delayed functional recovery after a lateral release. They report that the subject 5 months post surgery, although highly motivated had made little progress with taping and participation in an exercise program. They report a significant increase in the subject's function, pain and stiffness with the ability to ascend stairs unassisted after 8 days and to hop after 21 days of daily use of the muscle stimulator. A full recovery as indicated by the authors' occurred after 36 days of treatment utilizing electrical stimulation.

The literature supports the importance of the VMO in patellar alignment creating a medially directed force vector to balance the laterally directed forces about the knee, but its role in PFPS etiology is still unknown. Consensus is apparent regarding simultaneous recruitment of the vastus medialis and the vastus lateralis in a range of 0-30 degrees in the asymptomatic population with a late onset of the VMO in the PFPS population.

Improved functional outcomes were apparent with focus on the VMO utilizing electrical stimulation.

Treatment Interventions

1) Strengthening the Vastus Medialis Oblique

Based upon force vector imbalances leading to abnormal tracking of the patella and pain provocation, McConnell (1986) developed a series of non-weight bearing and weight bearing exercises. The outlined purpose of the exercises is to correct the force vector imbalance through facilitating the contraction of the VMO and relaxation of the VL. She utilizes the hip adductor musculature to aid in facilitating the recruitment of the vastus medialis with cueing provided to relax the vastus lateralis. No EMG data is supplied by McConnell to support the concept that these exercises would facilitate the contraction of the VMO and or relaxation of the VL, nor does she theorize on the mechanism by which this occurs. McConnell's (1986) approach has stimulated research in this area to assess the effectiveness of the exercises prescribed in preferentially activating the VMO.

Bose et al (1980) theorizes that hip adduction facilitates VMO contraction and aids in the treatment of patellar femoral instability through it attachment to the adductor magnus, at its point of origin as the activated hip adductor muscle provides a stable base of support for the VMO. Hanten and Schulthies (1990) examined the activity of the VMO and the VL to observe differences while performing exercises involving hip adduction and internal rotation of the tibia utilizing indwelling fine wire electrodes inserted into the vastus lateralis and the vastus medialis. The authors report a proportional increase in VMO activity over VL activity with hip adduction with no significant increase in VMO activity over VL activity with volitional medial tibial rotation. Based upon their findings they conclude that the VMO may be selectively strengthened through participation in hip adduction exercises and that exercises utilizing internal rotation of the tibia are not warranted, as they have no effect on the recruitment of the VMO.

Zakaria et al (1997) also studied the role of hip adduction in facilitating VMO activation utilizing isometric contractions and EMG. The authors utilized different exercises and positioning as well as surface electrodes verses indwelling on the VL and VMO to determine the activity of the muscles. Their findings were not consistent with Hanten and Schulthies (1990), stating that there was no preferential activation of the VMO over the VL with hip adduction.

Rice et al (1995) also published a study (n=10) combining hip adduction with knee extension to determine if preferential activation of the VMO occurred. Surface electrodes were utilized to record EMG readings of the VMO and VL musculature. The authors report that their results demonstrate a significant reduction in EMG activity of the VL with knee extension both concentrically and eccentrically when combined with hip adduction with no significant change in EMG activity noted for the VMO. This finding, although not focussed on the VMO will still result in an increase in the medially directed force vector, which in turn will impact on the resultant force vector applied to the patella.

Karst and Jewett (1993) published a study with the purpose of investigating whether exercises combining hip adduction with knee extension activate the medial quadriceps and rectus femoris musculature. The authors utilized the exercises of quadriceps setting (QS), straight leg raise (SLR), straight leg raise with the hip externally rotated (SLR/LR) and straight leg raise with isometric hip adduction (SLR/ADD). Their reported findings are not supportive of preferential activation of the VM utilizing hip adduction.

Can the VM be Selectively Trained?

LeVeau and Rogers (1980) examined the possibility of recruiting and selectively training the VM to contract independently from the VL as according to the authors an optimal functioning VM is crucial in maintaining the "alignment of the extensor mechanism" of the knee, which is necessary for optimal tracking of the patella. They state that the VM must be trained to contract independently with enough force to balance the force of the VL. The authors report that the subjects were successful in significantly decreasing the

VL activity, but were not successful in maintaining a set value for the VM activity. The subjects were more successful in increasing the VM activity while maintaining the reduced VL activity with a significant difference noted. The authors concluded that the activity levels of the VM and VL can be altered which has important implications for rehabilitation of the knee, specifically relating to conditions involving the patellar femoral joint including PFPS by increasing the strength of the VM to improve patellar alignment. The authors concluded that further study would have to be performed as they were uncertain whether the biofeedback techniques could be successfully utilized with patients with knee problems.

2) Taping

Pain Control and Patellar Taping

It has been well documented in the literature that pain in subjects with patellar femoral syndrome is reduced by 25 to 92.6 % with the application of tape to the patella with the force of application directed medially. (Salsich et al, 2002; Ng Gy, Cheng, 2002; Gilleard et al, 1998; Powers et al, 1997; Kowall et al, 1996; Cerny, 1995;Cushnaghan et al, 1994; Worrell et al, 1994 Bockrath et al, 1993;McConnell, 1986) The mechanism by which the tape reduces the pain is not fully understood. It is theorized that the tape applied with a medially directed force, corrects the position of the patella as it tracks through the trochlear groove with knee flexion (Powers et al, 1997; Kowall et al, 1996; Cushnaghan et al, 1994; Bockrath et al, 1993; McConnell, 1986). With this correction in position the "normal" tracking pattern and force distribution is restored, thus pain is alleviated. It has also been reported in the literature that patellar taping with the associated reduction in pain may facilitate improved Vastus Medialis Oblique recruitment which will "normalize" patellar tracking (Gilleard et al, 1998;Bockrath et al, 1993;). In most studies pain was assessed utilizing a form of a Visual Analogue Scale (VAS).

The theory based upon the concept that the application of tape directed medially alters the tracking pattern of the patella is not substantiated by the current research especially under loaded conditions. Bockrath et al (1993) utilizing a merchant view x-ray assessed the position of the patella pre and post taping. The authors' results indicate a significant decrease in pain with taping of the patella, but that the application of tape did not significantly alter patellar femoral congruency, angle and/or patella rotation. Gigante et al (2001) in a more recent study utilized Computed Tomography to determine the effectiveness of patellar taping for medialization of the patella and concluded also that patellar incongruence was not affected by the application of the tape and as such the method of pain reduction was not associated with changes in the position of the patella. They reported noting a non-significant alteration in the position of the patella in the no load condition in a few of the cases, but never with contraction of the quadriceps. Consequently the authors concluded that the significant reduction in pain found with tape is not due to a significant change in patellar position. Another recent study performed by Pfeiffer et al (2004) utilizing Kinematic MRI to assess the McConnell taping technique before and after exercise at the knee joint angles of 0,12, 24 and 36 degrees concluded that the application of the tape resulted in significant medialization of the patella at all angles prior to exercise (sprint, back pedalling, right and left side shuffling, squats) having been performed. This medialization effect did not continue with repeat testing post exercise. The authors' conclude that the application of tape may be effective under controlled rehabilitation conditions where exercise tends to have a lower intensity.

It is apparent from the literature that pain is reduced with taping of the patella, but the mechanism that allows for this remains undetermined. Treatment with tape has been implemented based upon the theory that the condition of PFPS is associated with "abnormal" tracking of the patella generally in a lateral direction. The application of the tape primarily applied in a medial direction is to alter the position of the patella, "normalizing" the tracking pattern and thus relieve pain. A clear consensus in this area is not apparent in the literature with inconsistent findings pertaining to the affect of tape on the tracking pattern in an unloaded status. A consistent lack of effect or change in patellar position is identified with the application of tape under loaded or dynamic conditions.

Facilitation of selective activation of the vastus medialis, "normalizing" the patella position has also been proposed as the mechanism of pain reduction associated with the application of tape. At present research has not provided conclusive findings to identify the mechanism responsible for pain reduction.

Summary

The tracking pattern of the patellar femoral joint has been defined as being determined by the patellar femoral joint reaction force representing all of the individual contractile and non-contractile force vectors about the knee. Imbalances in any of these forces (decrease in activation of the vastus medialis, increase in activation of the vastus lateralis, tight iliotibial band) are theorized to lead to changes in patella motion causing "maltracking" of the patella. This in turn is theorized to affect the patellar femoral contact characteristics provoking pain.

Research on patellar femoral pain syndrome has focused to date on identifying the factors that cause the "maltracking" associated with PFPS as well as treatment to normalize this tracking pattern. This is problematic, as "normal" tracking of the patella is not clearly understood with limited research and studies that consist of small sample sizes with varying methodologies and inconsistent terminology utilized to define patellar kinematics as well as movement about the knee. Many of the studies have also utilized cadavers which although representative of in vivo subjects are limited in their application. Further research is necessary to clarify the "normal" tracking pattern of the patella and the amount of inherent variability. This will allow for a standard of comparison to aid in identifying a tracking pattern or patterns associated with the PFPS population. Only 3 studies have been performed to date on the patellar femoral pain syndrome population with approximately 32 to 57 % of the subjects presenting with tracking patterns consistent with those of the control population and the remainder exhibiting one of 5 identified tracking patterns. As a single pattern has not been definitively identified for the patellar femoral pain syndrome population, the underlying clinical assumption of increased lateralization of the patella cannot be clearly supported.

Purpose

This study is designed to evaluate differences in patellar position between PFPS affected limbs and a) limbs of control subjects and b) non-affected limbs of PFPS subjects at 8 static joint angles under three load conditions.

Hypothesis

As generally accepted in the literature and in clinical practice, it is hypothesized that there will be greater lateralization of the patella through the last 30 degrees of knee extension in both the passive and loaded conditions in the PFPS relative the Normal control group.

Assumption(s)

1. It is assumed that the motion of the dynamometer actuator arm is representative of the motion of the knee (Herzog et al 1988 J Biomechanics).

2. It is assumed that the axis of the dynamometer is representative of the instantaneous axis of rotation of the knee.

3. It is assumed that the moment of the weight corrections computed by the dynamometer will be representative of the actual moment of the weight of the lower limb.

4. It is assumed that with proper stabilization of the subject, there will be a lack of significant movement between the lower limb and the actuator arm.

5. It is assumed that the PFPS populations studied are representative of the general population between the ages of 18 – 60 years.

Delimitations

1. The study will examine male and /or female subjects 18 to 60 years of age.

2. Isometric measurements will be delimited to those taken with backrest set at 15 degrees from the vertical, decreasing the amount of hip flexion.

Limitations

1. Measurements taken during the isometric testing are dependent on the voluntary effort of the subjects. Testing will be terminated upon the request of the subject.

2. Testing is not representative of the full range of velocities that are obtained in everyday functional activities.

3. Testing is not representative of multi-segmental motion, as testing is isolated to rotation of the leg about the knee joint.

Methodology

Experimental Design

This is a cross-sectional study comparing a group representative of the patellar femoral pain syndrome population with that of a Normal control group. Digital images of the knees were utilized to compare the 2 groups under experimentally controlled conditions to assess the patellar kinematics across the 3 load conditions of no load, submaximal load and maximal load at 8 angles ranging from 0 to 40 degrees

Recruitment

Healthy subjects of either gender with no known knee pathology were recruited (Appendix A). Ethical approval was granted by the Faculty Committee on the Use of Human Subjects in Research at the Faculty of Medicine, University of Manitoba. Written informed consent was obtained from all subjects prior to commencement of the study. (Appendix B & C). A screening assessment was completed prior to commencement of the testing protocol to ensure each subjects suitability (Appendix D).

Inclusion Criteria

Normal Control Group

1. Male or female
2. 18-60 years of age

PFPS Group

1. Male or female 18 – 60 years of age
2. The presence of atraumatic anterior knee pain characteristic of PFPS

Exclusion Criteria

Normal Control Group

1. History of neuromuscular conditions of the lower extremities
2. History of trauma to the knee including ligamentous injury, dislocations, cartilaginous injuries, fractures and/or surgery
3. History of osteoarthritis of the lower extremity including the hip, knee and/or foot
4. Systemic arthritis such as rheumatoid arthritis

5. History of cardiovascular or medical conditions that may preclude involvement in testing procedures
6. Current use of narcotics or corticosteriod medication
7. Pregnant or lactating females

PFPS Group

1. History of neuromuscular conditions of the lower extremities
2. History of trauma to the knee including ligamentous injury, dislocations, cartilaginous injuries, fractures and/or surgery
3. History of osteoarthritis of the lower extremity including the hip, knee and/or foot
4. Systemic arthritis such as rheumatoid arthritis
5. History of cardiovascular or medical conditions that may preclude involvement in testing procedures
6. Current use of narcotics or corticosteriod medication
7. Limitation in non - weight bearing active knee range through an arc of 90 degrees
8. Pregnant or lactating females

Recruitment

Subjects were recruited by word of mouth and by poster advertisement at the Bannatyne and Fort Garry Campus' of the University of Manitoba. Subjects were also recruited by formal written request to physiotherapy and medical clinics.

Protocol

The age (yrs) and body mass (kg), of the subjects was recorded with the Q-angle (degrees), patellar width (mm) and bicondylar width (mm) measured. Knee pain at rest and upon completion of testing was also evaluated using the Visual Analogue Pain Scale.

Assessment of patellar position utilizing digital images with the angle of the knee controlled by the dynamometer was then undertaken as described below.

Procedures

Dynamometer Testing

A dynamometer (Kin-Com 500H, Chattecx, Hixson,TN) was utilized in this study to evaluate isometric strength of the knee extensors. The mechanical reliability of this device has been established by Farrell and Richards (1986) to range from 0.948 to 0.999 depending upon the variable tested. All subjects were given uniform instructions regarding the procedure on the isometric test prior to the initiation of testing. Testing was performed across both groups (PFPS, Normal) on both legs for all subjects. Leg dominance was identified by the subjects' and was based upon identification of the leg utilized to kick a ball.

The backrest and seat of the dynamometer was positioned so that the subjects' lateral femoral condyle was aligned with the axis of rotation of the actuator arm of the dynamometer and so that a 90 degree range of motion was available. The non-test leg was allowed to hang pendant being supported under the thigh by the seat. The trunk was stabilized at the chest and waist with Velcro straps, as was the thigh of the test leg to minimize accessory muscle use and movement. The resistance pad attached to the force transducer was placed 3 – 5 cm proximal to the malleoli in a position of comfort. The distance (m) from the force transducer to the actuator arm axis of rotation was recorded.

Correction for the moment of the weight of the lower limb of the test leg was obtained by using 'gravity correction' software supplied by the manufacturer. This procedure computes the moment of the weight (Nm) of the lower limb plus the footwear as it changes throughout the range of motion.

Isometric Testing

The subjects were instructed in the full protocol of the study prior to the onset of testing. This included the order of the load conditions and angles to be assessed with specifics as follows:

1. No load condition: 40, 35, 30, 25, 20,15,10, 5 degrees
2. Maximal load condition: 35, 20, 5 degrees
3. Submaximal load condition: 40, 35, 30, 25, 20,15,10, 5 degrees

The verbal discourse was then followed by a warm-up repetition for the no load condition, prior to testing at this load through all 8 angles. Digital images were taken at each angle (40 - 5 degrees). The no load condition was followed by the maximal load condition with the protocol for this load once again reviewed prior to a warm-up repetition being conducted. Digital images were taken at the angles of 35, 20 and 5 degrees with the resultant knee joint moment (RJM) generated at each angle also recorded. The resultant knee joint moment (Nm) was calculated by correcting the moment measured by the dynamometer for the moment produced by the weight of the leg and footwear. The maximal isometric transducer force (N) was then utilized to determine a 10% load specific target force value (matching the RJM values) for the joint angles being tested (5- 40 degrees) by means of linear interpolation. The force transducer values were used for feedback instead of RJM since the dynamometer does not display RJM instantaneously. The identified values across all angles were then utilized in collecting digital images across all angles (40-5degrees).

The subjects were cued regarding the protocol for the submaximal load condition prior to commencement of testing. They were instructed in the utilization of visual feedback (graphical and numerical) to maintain the identified 10% target force value (N) during the isometric contraction at each angle while a digital image was taken. The discourse was then followed by 1 to 3 practice repetitions.

Patellar Position Test

The position of the patella relative the condyles of the knee was assessed utilizing digital images with the knee positioned by the dynamometer at 8 angles ranging from 0 to 40 degrees at 5 degree increments across all 3 load conditions of no load, sub maximal (10% of maximal) load and maximal load. Images across all loads were taken with the knee joint angle at 40 degrees of flexion for the no load and submaximal load conditions and at 35 degrees of flexion for the maximal load condition with testing completed at the 5-degree angle. In the no load condition, the weight of the lower limb was supported by the dynamometer, with instruction provided to the subjects to relax. The dynamometer positioned the lower limb to achieve the appropriate knee angles with an image taken by the investigator at each angle. The no load condition was performed first, followed by the maximal load and finishing with the submaximal load condition. The subjects were asked to maintain a 3 to5 second isometric contraction at each angle at the specified 10% target load utilizing visual feedback (graphical and numerical) while the image was taken.

Digital Imaging

Digital images of the patella were acquired at each of the joint angles tested (Canon Power Shot G2, 4.0 megapixel resolution). The images were stored utilizing lossy JPEG compression. For image scaling a calibrated scale bar was attached to the skin overlying the patella. The camera was attached to a tripod and placed parallel to the frontal plane of the knee at an approximate distance of 12 cm. Very good accuracy of the digital imagining technique (r=0.96) was established by Suchak et al (2000) in comparing patellar position data with data acquired from frontal plane x-ray images. Test – retest reliability was also excellent (ICC=0.95).

Visual Analogue Scale (VAS)

The visual analogue scale is a tool utilized to measure pain. It is presented as an unmarked 10 cm line with one end representing no pain and the other end, the worst

imaginable pain. It was utilized during the course of the study to determine if there was an exacerbation in the subjects' pain with participation in the study to ascertain if pain affects performance. The subjects were asked to complete a VAS prior to the commencement of the study and upon completion of the maximal isometric testing condition.

Data Collection and Analysis

The digital images were imported into an image processing software (Corel Photopaint) to obtain the x, y pixel coordinates of required points. Coordinates were obtained for the following:

1. Scale bar
2. Medial condyle of femur
3. Lateral condyle of femur
4. Medial border of patella
5. Lateral border of patella

The pixels were scaled to millimeters (mm) using the pixel to mm conversion factor computed for each image. Using the scaled coordinate data, the following derived measures were computed:

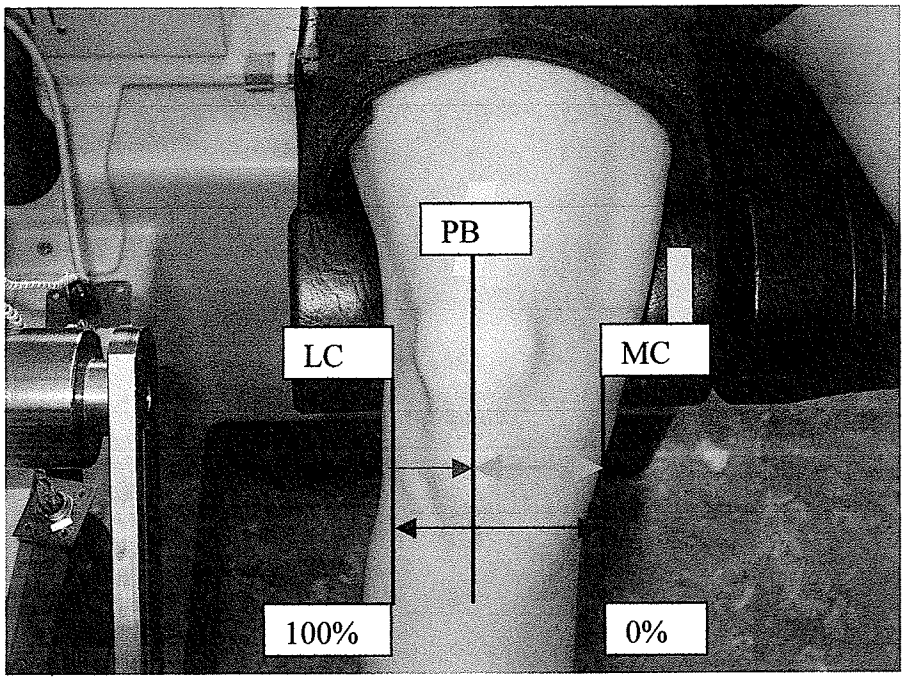
1. The width of the patella,
2. The bicondylar width
3. The midpoint of the patella derived as the bisection of the medial to lateral position.

The midpoint or bisect of the patella was then utilized to determine the position of the patella in relation to the femoral condyles. The bisect or midpoint of the patella was utilized as the reference point in measuring the position of the patella relative to the

condyles to minimize size and gender differences. The patellar position was calculated for each angle in all load conditions across all groups. The images of the knee at all 8 angles for each subject were analyzed in random order.

Patellar Position

The absolute patellar position relative the medial condyle was calculated utilizing the bisect of the patella as a percentage of the intercondylar space for both legs of each subject in each group (PFPS, Normal) for the knee joint angles of 5 and 35 degrees. These values have been expressed as a percentage relative the medial condyle. Figure 3 illustrates the components involved in the calculation of the absolute position of the patella relative the medial condyle.



Symbol	Definition
⟷	Bicondylar distance
→	Distance from lateral condyle to bisect of patella
⟷	Distance from medial condyle to bisect of patella
LC	Lateral condyle
MC	Medial condyle
PB	Patellar bisect

Figure 3: Visual Definition of the Absolute Patellar Position Relative the Medial Condyle

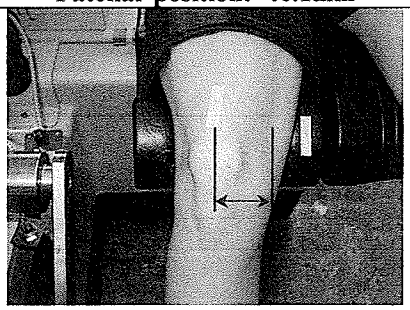
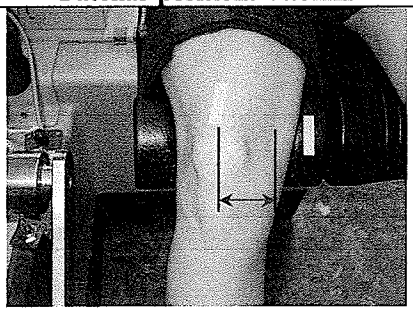
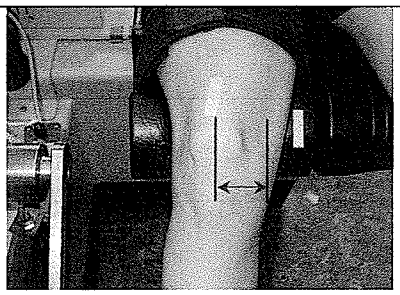
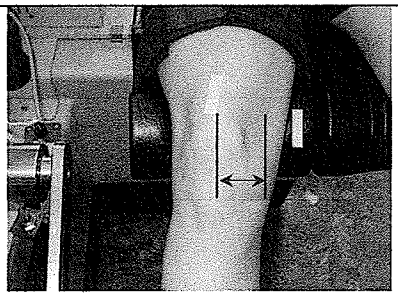
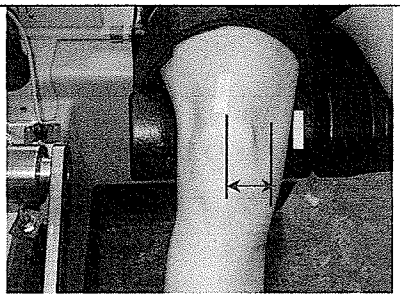
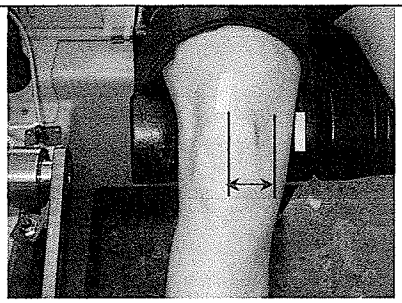
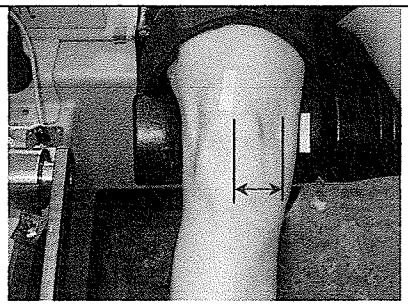
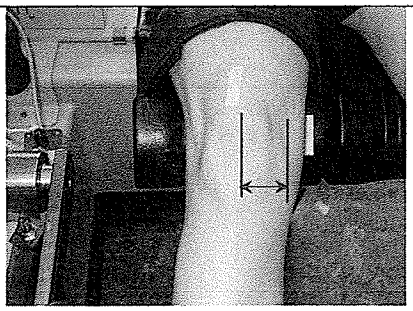
40°	35°
Patellar position: 46.1mm	Patellar position: 44.8mm
	
30°	**25°**
Patellar position: 42.8mm	**Patellar position: 42.5mm**
	
20°	**15°**
Patellar position: 39.0mm	**Patellar position: 38.0mm**
	
10°	**5°**
Patellar position: 38.6mm	**Patellar position: 37.8mm**
	

Figure 4: Patellar Position Relative the Medial Condyle during Knee Extension Across all Knee Joint Angles (40-5 degrees) under the Submaximal Load Condition for One Subject.

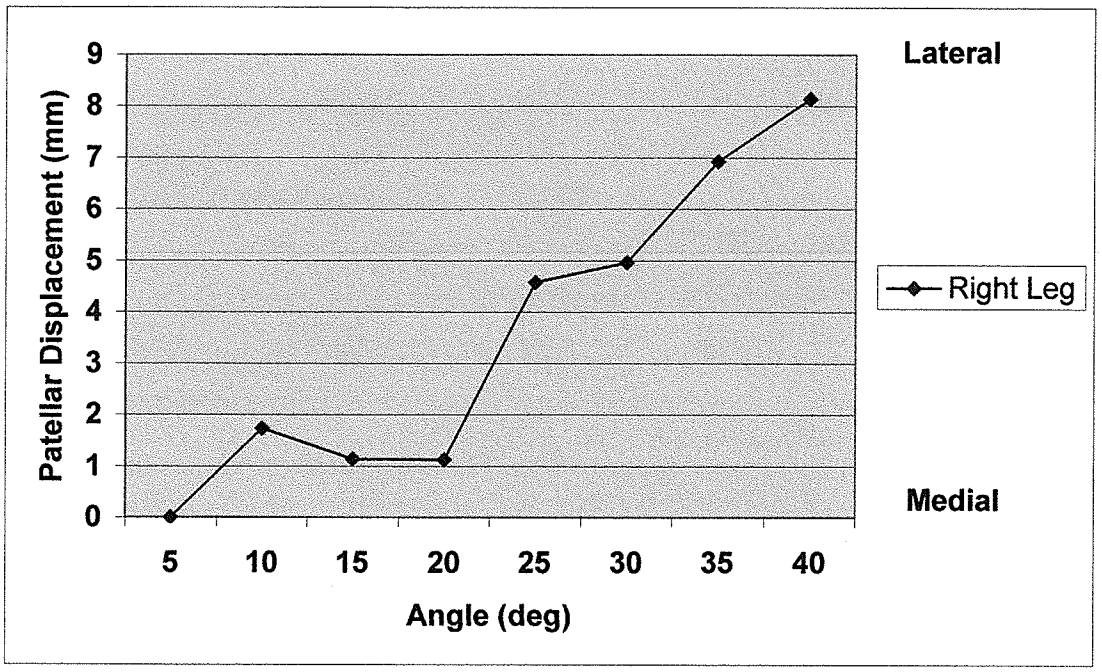


Figure 5: Patellar Displacement for One Subject Under the Submaximal Load Condition Across all Knee Joint Angles as the Knee Extends from 40 to 5 Degrees. The Pattern Corresponds to Images in Figure 2

The images in Figure 4 depict the displacement of the patella with knee extension from 40 to 5 degrees relative the medial condyle under the submaximal load condition. Please note that the series is for illustrative purposes only. Figure 5 demonstrates the patellar displacement associated with these digital images. It can be observed in the figures that the patella is moving medially as the knee extends from 40 to 5 degrees. This is represented by a shift in the graph towards zero patellar displacement as patellar displacement is defined relative to the medial condyle

Statistical Analysis

To address the hypothesis that a different tracking pattern exists between the Normal control group and the PFPS group a univariate multifactorial ANOVA was performed followed by post-hoc testing where indicated (Tukeys and T –test) with a stepwise linear regression with associated ANOVA also being performed. Within and across group comparisons were preformed as follows with the level of significance assessed at an

alpha level of 0.05.

1. Within group comparisons:

   PFPS

   1 Change in patellar position of the affected verses the non affected limb in the PFPS group

   2 Change in patellar position with load in the PFPS group

   3 Change in patellar position with angle in the PFPS group

   Normal

   2 Change in patellar position in the right verses the left limb in the Normal control group

   3 Change in patellar position with load in the Normal control group

   4 Change in patellar position with angle in the Normal control group

2. Between groups comparisons:

   1 Change in patellar position with load in the PFPS group compared to the Normal control group

   2 Change in patellar position with angle in the PFPS group compared to the Normal control group

Results

Subject Demographics

Twelve subjects participated in the study with 7 in the patellar femoral pain syndrome group and 5 in the Normal control group. Both groups contained males and females, although the PFPS group was predominantly female with the Normal control group comprised of a more heterogeneous mixture. Participants' ages ranged from 28-51 years with a mean of 37.8 (9.28) for the PFPS group and 36 (5.24) for the Normal control group. The body mass (kg) of the participants ranged from 54.5 to 102.3 for the PFPS group with a mean of 70.2 (17.9) with the range for the Normal control group identified as 54.5 to 79.5 with a mean of 71.3 (10.9). The duration of symptoms ranges from 0.30 to14 years with a mean of 5.76 (4.58). The Q- angle for the PFPS group ranges from 4 to 22 degrees with a mean of 12.1 (5.50). The range for the Normal control group is identified as 5 to 20 with a mean of 12.1 (4.84). As 2 of the subjects in the PFPS group reported bilateral knee symptoms, both legs were classified as affected; as such 9 legs comprise the affected PFPS group with 5 legs comprising the non-affected PFPS group (Table 2). The Normal control group, comprised of 5 subjects consists of 10 legs with both the right and left legs being utilized (Table 3).

Table 2: Subject Demographics-PFPS Group

Subject		**1**	**2**	**3**	**4**	**5**	**6**	**7**
Gender		Female	Female	Female	Male	Female	Female	Female
Age		51	24	37	43	43	39	28
Duration of Symptoms (years)		12	2	4	5	5	12	0.30
Body mass (kg)		75	79.5	56.8	95	54.5	58.1	55.4
Q-Angle (°)	**Right**	22	15	12	6	15	5	7
	Left	20	10	13	7	20	4	13
Leg	**Right**	A	A	NA	NA	A	NA	NA
	Left	A	NA	A	A	A	A	A
Dominant Leg		Right	Right	Right	Right	Right	Right	Right

PFPS=patellar femoral pain syndrome, A=affected, NA=non-affected

Table 3: Subject Demographics -Normal Control Group

Subject		8	9	10	11	12
Gender		Male	Male	Female	Female	Male
Age		30	34	41	33	42
Body mass (kg)		77.3	65.9	81	54.5	79.1
Q-Angle (°)	Right	17	11	9	20	5
	Left	15	13	12	14	5
Dominant Leg		Left	Right	Right	Left	Right

T-tests were performed comparing the Q-angles of the PFPS and Normal control group to determine if a significant difference would be identified. For both groups the left and right legs were combined, as there was no significant difference between the legs identified in performing within group comparisons. No significant difference was identified between the PFPS group and the Normal control group with Q-angle comparisons between the two groups. The mean and standard deviation for the PFPS group is 12.1° (5.89) with the respective values for the Normal control group identified as 12.1° (4.84). A Pearson correlation was also performed between the Q- angles for all subjects in both groups and the data for the patellar position at 5 degrees in the no load condition. Results for the Normal control group indicates the presence of a correlation between the two variables with an r value of –0.7214 and a level of significance of $p<0.05$. A correlation between the two variables was not identified for the PFPS group with an r value of 0.16113.

T- tests were also performed utilizing the parameters of age and body mass with no significant differences identified between the groups with a mean age and standard deviation for the PFPS group identified as 37.9(9.28) and for the Normal control group as 36 (5.24). The mean body mass and associated standard deviation for the PFPS group is 68.8(17.9) with the values for the Normal control group identified as 71.6(10.0).

Visual Analogue Scale

The Visual Analogue Scale (VAS) for pain was utilized to assess the response of the

PFPS group to the testing protocol to determine if any trends could be identified. Generally the PFPS group prior to testing reported minimal to no pain with 5 of the 7 subjects rating their symptoms utilizing the VAS as 0 to 1/10. At the time of testing, only two subjects were identified as sub acute on chronic with both rating their pain utilizing VAS prior to testing as 2.8/10. The function of one of the subject (subject 1) from this subset group was more affected than the other (subject 2) with a patellar femoral brace reportedly utilized throughout the day with all weight bearing activities. VAS testing, upon completion of the maximal load condition was also performed. Subject 1 whose function was significantly affected provided a pain rating of 6.2/10 with the second subject (subject 2) providing a VAS rating of 4/10. Subject 2 post testing reported the sensation of the knee "giving out" with "instability" noted towards the end of the stance phase with knee extension. All subjects in the PFPS group did report knee symptoms while exerting during testing under the maximal load condition especially at the 5-degree angle but denied, with the exception of subject 1 and 2, the persistence of symptoms with completion of testing.

Patellar and Condylar Width Comparisons

For the purpose of examining the accuracy and consistency of the digital imagining technique the actual patellar and condylar widths as well as the widths depicted in the digital images were measured. The patellar and condylar widths, measured utilizing digitally imagining were recorded for both knees across all subjects with a mean patellar width and associated standard deviation for the right legs being 44.3 mm (1.08) with respective values for the left being 44.5 mm (1.03). The mean condylar width and associated standard deviations for the right knees is 79.7 mm (2.02) with the mean measure for the left knees identified as 78.6 mm (1.08).

The actual patellar and condylar widths, measured utilizing digital callipers were also recorded for both knees across all subjects with a mean patellar width and associated standard of deviation for the right legs of 53.1 mm (4.94) and the left of 48.1 mm (3.57). The mean condylar width with associated standard deviation for the right knees is

identified as 93.3 mm (16.55) with the values for the left being 94.4 mm (16.82). Specifics are outlined in Table 4.

Table 4: Patellar and Condylar Widths Comparison of Images with Actual.

Subject	Leg	Digital Patellar Width Mean (mm)	Standard Deviation	Actual Patellar Width (mm)	Digital Patellar Width Compared to Actual (%)	Digital Condylar Width Mean (mm)	Standard Deviation	Actual Condylar Width (mm)	Digital Condylar Width Compared to Actual (%)
1	Right	42.4	0.35	60	71	88.9	0.71	110	81
	Left	41.8	1.81	58	72	88.5	0.80	105	84
2	Right	45.4	0.45	50	91	97.9	2.01	140	70
	Left	46.0	0.83	50	92	101.5	1.03	140	72
3	Right	39.9	0.91	47	85	68.9	1.86	78	88
	Left	43.8	1.55	49	89	69.2	1.16	77	90
4	Right	52.6	1.60	60	88	88.8	3.07	101	88
	Left	51.7	1.91	56	92	86.1	1.57	101	85
5	Right	41.9	1.31	53	79	79.4	1.46	84	95
	Left	42.1	0.81	53	79	77.5	2.77	85	91
6	Right	41.1	0.71	49.7	83	77.2	2.33	87	89
	Left	40	0.59	49.7	80	73.6	2.09	85.3	86
7	Right	41.6	0.92	48	87	74.6	2.48	90	83
	Left	42.0	0.57	51	82	75.1	1.73	86	87
8	Right	46.5	3.14	60	77	76.5	3.72	88	87
	Left	47.9	0.93	56	85	74.4	2.61	88	85
9	Right	50.7	1.02	57	89	82	2.40	94	87
	Left	48.6	1.11	54	90	83.1	4.21	93.8	88
10	Right	40.3	0.96	49	82	73.6	1.77	86	86
	Left	39.6	0.71	49	81	70.1	0.88	84	83
11	Right	48.9	0.44	53	92	78.	1..34	90	87
	Left	49.2	0.57	56	88	75.5	0.93	92	82
12	Right	40.1	0.75	50	80	70.3	1.13	85	83
	Left	40.8	0.99	47	87	69.	1.97	83	83
Subject 1-12 Mean Widths and SD	**Right**	**44.3**	**1.08**	**53.1 (4.94)**	**84**	**79.7**	**2.02**	**93.3 (16.55)**	**85**
	Left	**44.5**	**1.03**	**48.1 (3.57).**	**85**	**78.6**	**1.88**	**94.4 (16.82)**	**85**

Coefficient Of Variation

The coefficient of variation was also calculated for the patellar and condylar measurements for each subject. The coefficient of variation for each of the subjects' patella measurements ranges from 0.9 to 6.75 % with a mean coefficient variation of 2.4%. The range for the condylar values is 0.89 to 5.1% with a mean coefficient variation of 2.4 % also identified (Figure 6).

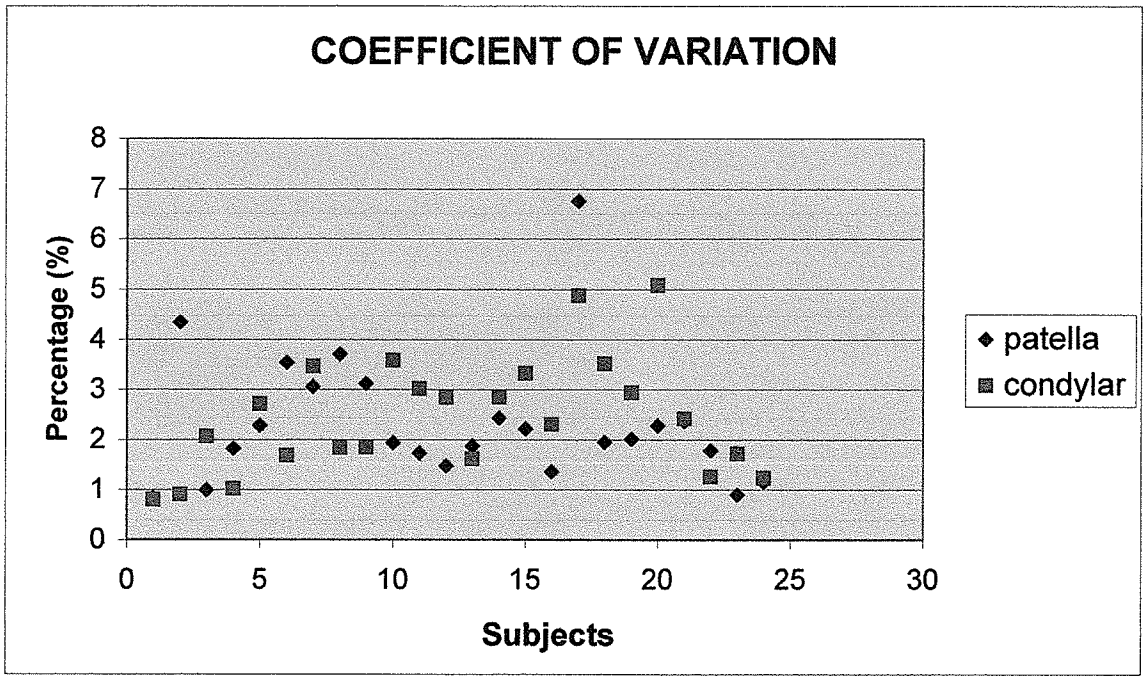


Figure 6: Coefficient of Variation of the Patellar and Condylar Widths Measured by Digital Images.

Digital Verses Actual Comparisons

Although the coefficient of variation values represent consistency with imaging, the measurements obtained from the digital images for condylar and patellar widths were less than the actual values across all subjects with an average underestimation for the condylar widths of 15% and for the patella of 15.5%. This underestimation may be attributed to properties of digital imaging in which objects appear smaller than they are in reality with the amount dependent upon the distance that the object is from the camera lens. In future studies increasing the camera to knee distance would reduce this

systematic error. In addition having two scale bars, one at the plane of the patella and one at the plane of the condyles would further minimize this error. As the scale was not located directly on the surface of the patella, placed proximal to the superior border, a consistent underestimation has been identified. Identifying and utilizing the difference between the scale bar to the patella measurement point and then "scaling" the scale bar data for this effect could compensate for the data. However due to the consistency of the underestimation this was not done as the data could be individually scaled for each subject after the fact because the actual patellar and condylar widths were recorded. As such comparisons both within group and between groups would not be affected. Comparisons can also be made with other researchers data as we have identified the percentage of underestimation for the widths of the patella and condyles. It is expected that the patellar position would also be underestimated by the same percentage, which allows for across study comparisons.

The discrepancy in actual verses measured values may also be influenced by body fat composition. Generally in the area of the knee, the overlying tissue and fat provides an increase in girth of 4 mm (2 mm on each side). This increased girth would be detected in the actual measurements utilizing callipers but not with the digital values as the landmarks for the medial and lateral edges of the patellae and the condyles were generally quite defined in the images with the exception of 2 of the subjects. There was a greater discrepancy between the digital image values and the actual values in these 2 subjects as they had higher body fat compositions. As such these images were more difficult to evaluate as the patellae and condyles were less clearly defined.

Statistical Results

The software SPSS was utilized to perform the statistical analysis. The patellar position relative the condyles was computed and represented as a shift relative to the 5 degree joint angle allowing for within and across group comparisons. An initial univariate ANOVA was performed on the dependent variable of patellar position utilizing the following factors/conditions of:

1) Group (PFPS, Normal),
2) Leg condition (affected, non-affected, Normal)
3) Load (no load, sub maximal load, maximal load)
4) Angle (0, 5, 10,15, 20, 25, 30, 35, 40)
5) Leg (right, left)

Significance was observed for the interactions of load and group (p=0. 002), load and leg condition (p=0. 023) and load, group and leg (p=0. 013). Based upon these statistically significant interactions, post-hoc comparisons (Tukeys) were performed for the conditions of load and leg with the dependent variable for both comparisons being patellar displacement. Findings indicate significant differences across all load comparisons with p values of <0 .0001 identified for the relationship between the no load and submaximal load variables as well as the no load and maximal load variables. A p value of 0.016 is identified for the relationship between the submaximal and maximal load conditions. Significance was also identified for leg condition in comparing the non-affected with the normal legs as well as the affected with the normal legs with p values of < 0.001. No significant difference was identified in comparing the affected and non-affected legs with a p value of 0.076.

A multiple linear regression was also performed to predict the displacement of the patella based upon the known and controlled conditions of joint angle (40-5), load (no load, submaximal, maximal), group (PFPS, Normal) leg (right, left) and leg condition (control, affected, non-affected). All conditions and associated variables were entered into the regression to predict the dependent measure of displacement. A stepwise regression was performed where the variables were excluded from the predictive model based on low predictive ability. All variables must pass the tolerance criterion to be entered in the equation. The default tolerance level is 0.0001. Also, a variable is not entered if it would cause the tolerance of another variable already in the model to drop below the tolerance criterion. The results of the stepwise regression outlined below in Table 4 provides R-values for group, load and condition as predictors of displacement with R= 0.378 for group, R= 0.449 for group combined with load and R=0.458 for group combined with

load and condition.

Table 5: Stepwise Regression Model Summary.

Model	R	R Square	Adjusted R Square	Standard Error of the Estimate
1	0.378[a]	0.143	0.141	2.15519
2	0.449[b]	0.202	0.198	2.08181
3	0.458[c]	0.210	0.204	2.07390

MODEL 1 [a]-Predictors: (constant), Group
MODEL 2 [b]- Predictors: (constant), Group, Load
MODEL 3[c]-Predictors: (constant), Group, Load, Condition

As a result of the regression, an ANOVA was performed to examine the significance of the overall model(s) for prediction utilizing the conditions of group, load and leg condition with patellar displacement as the dependent variable. The results are outlined below in Table 6 with all 3 conditions of group, load and leg condition being deemed highly significant with a p value of < 0.0001.

Table 6: ANOVA

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	350.690	1	350.690	75.501	<0.001[a]
	Residual	2108.750	454	4.645		
	Total	2459.440	455			
2	Regression	496.159	2	248.080	57.241	<0.001[b]
	Residual	1963.281	453	4.334		
	Total	2459.440	455			
3	Regression	515.363	3	171.788	39.941	<0.001[c]
	Residual	1944.077	452	4.301		
	Total	2459.440	455			

MODEL 1[a]-Predictors: (constant), Group
MODEL 2[b]- Predictors: (constant), Group, Load
MODEL 3[c]-Predictors: (constant), Group, Load, Condition

Post Hoc T-Test Comparisons

T-Tests were utilized to further quantify relationships of significance within and across groups utilizing the dependent variable of patellar displacement (mm) and independent conditions of group, load, leg, and leg condition across all angles. Findings are as

follows:

Patellar Femoral Comparisons

1. PFPS –Within Group Comparisons-Affected verses Non-Affected Legs

In comparing the PFPS population, affected verses non-affected legs, no significant differences were noted between the 2 groups under any load condition across all angles with comparisons including no load, sub-maximal loads and maximal loads. The respective mean patellar displacement for each load condition across all angles for the affected knees is 1.70 mm for no load, 0.59 mm for the submaximal load and 0.99 mm for the maximal load with respective mean standard deviations of 1.74, 1.43 and 2.16. The mean patellar displacement for the non-affected knee across all angles is 2.93 mm for the no load condition 2.62 mm for the submaximal load and 1.70 mm for the maximal load condition with average standard deviations of 2.09, 3.27, and 2.98 respectively. Figure 7 depicts the mean patellar displacement relative the medial condyle, across all angles for the no load condition for the affected and non-affected legs as well as the associated standard deviations. As there were no significant differences identified the non-affected and affected legs were combined to form a PFPS group comprised of 14 legs.

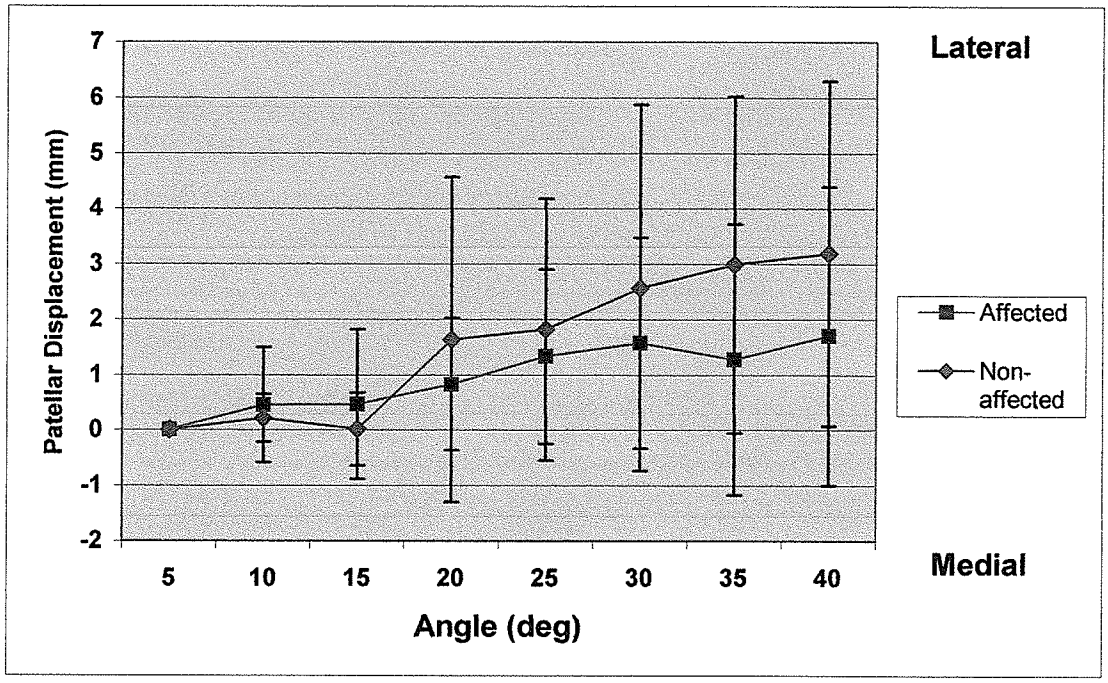


Figure 7: PFPS - Comparison of the Patellar Displacement Verses the Joint Angle of the Affected and Non-affected Leg in the No Load Condition with Extension of the Knee

2. PFPS –Within Group Comparisons-No load Verses Sub maximal Load

In comparing the no load and sub maximal load conditions within the PFPS group, no significant difference was identified across all angles with a mean patellar displacement of 2.23 mm for the no load condition and 1.32 mm for the sub maximal load condition with respective mean standard deviations of 1.95 and 2.46. Figure 8 depicts the mean patellar displacements relative the medial condyle and associated standard deviations across all angles under the 2 load conditions of no load and submaximal load with extension of the knee from 40 to 5 degrees.

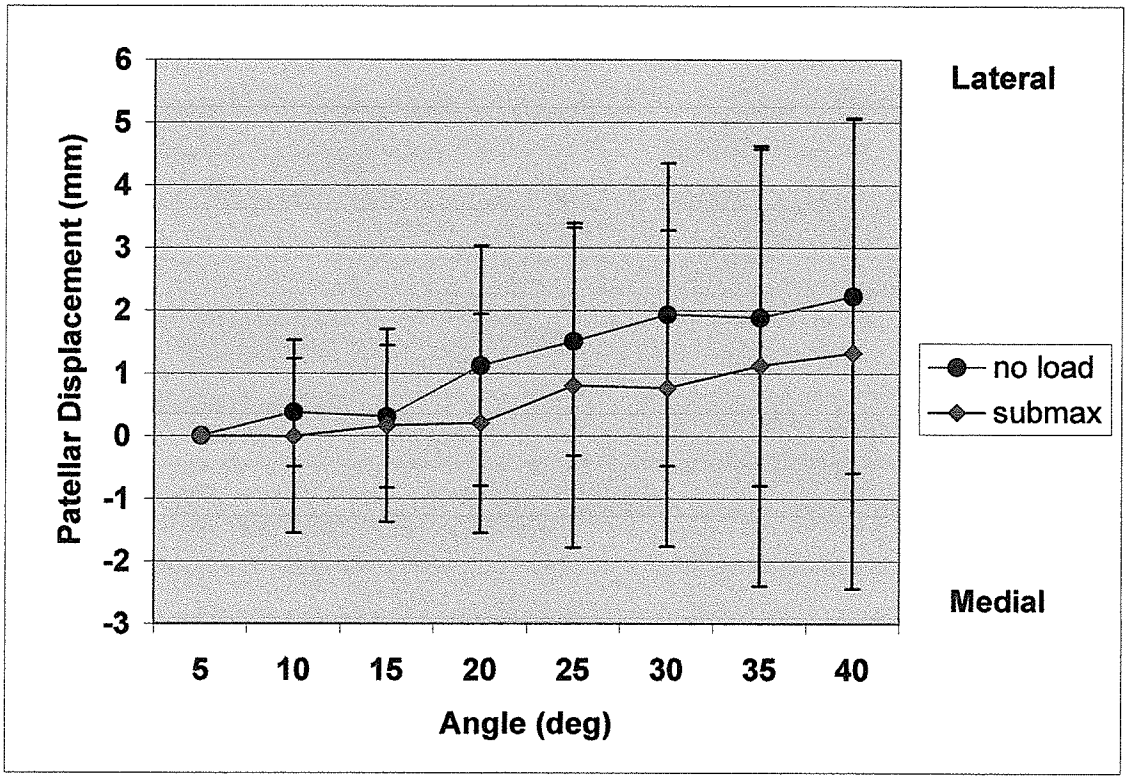


Figure 8: PFPS-Comparison of Patellar Displacement Verses Knee Joint Angle for the No Load and Submaximal Load Conditions as the Knee Extends from 40 to 5 Degrees

3. PFPS –Within Group Comparisons-No load Verses Maximal Load and Submaximal Load Verses Maximal Load

Values for the maximal load condition were obtained, during data collection at the angles of 0, 20 and 35 only. In comparing the no load condition with that of the maximal load, a significant difference ($p = 0.004$) was identified at the 20 degree angle with significance also noted at the 35 degree angle with a p value of 0.005. The average patellar displacement is 2.23 mm for the no load condition with a respective mean standard deviation of 1.95. Mean patellar displacement for the maximal condition is 1.24 mm with a mean standard deviation of 2.46. A significant difference was also identified between the submaximal and maximal conditions at 20 and 35 degrees with respective p values of 0.01 and 0.03. The mean patellar displacement for the submaximal condition is 1.32 mm with a respective mean standard deviation of 2.46. Figure 9 depicts the relationship of all load conditions with the mean patellar displacements relative the medial condyle for each angle across all load conditions utilized. Error bars are utilized to depict the associated

standard deviations.

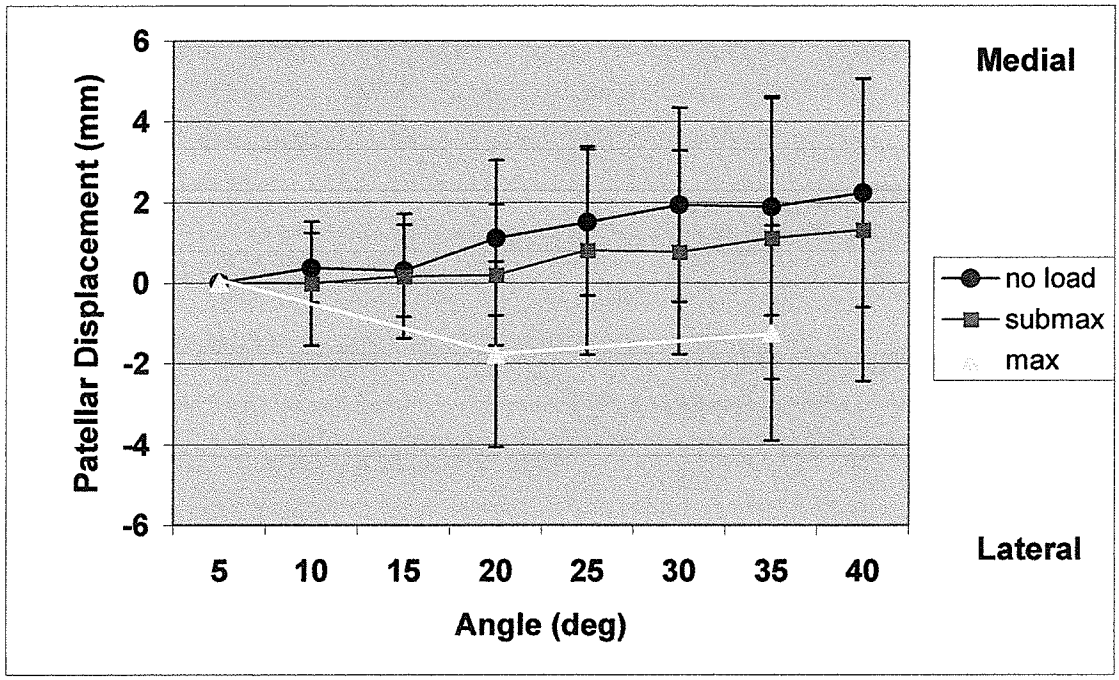


Figure 9: PFPS - Comparison of Patellar Displacement Verses Joint Angle Across the 3 Load Conditions as the Knee Extends from 40 to 5 Degrees

Normal Comparisons

1. Normal Control – Within Group Comparisons-Right Verses Left Legs

The right and left legs were compared across all joint angles and load conditions to determine if a significant difference would be identified. Results from the comparison indicate that there is no significant difference between the legs and as such the legs were combined to form a Normal control group of 10 legs. The mean patellar displacement across all angles for the right leg in the no load condition is 0.34 mm with an average standard deviation of 1.57. The mean patellar displacement for the left leg is 1.16 mm with an average standard deviation of 1.27. Results for the sub maximal condition include a mean patellar displacement of 3.14 mm for the right and 2.51 mm for the left with respective average standard deviations of 1.41 and 2.00. The mean displacement value for the maximal load condition for the right is 2.81mm with the displacement on the left being 0.41mm. Respective average standard deviations are 2.01 for the right and 2.87 for the left. Figure 10 depicts the individual mean patellar displacements relative the medial

condyle across all angles for the no load condition for the right and left legs with error bars included depicting the associated standard deviations.

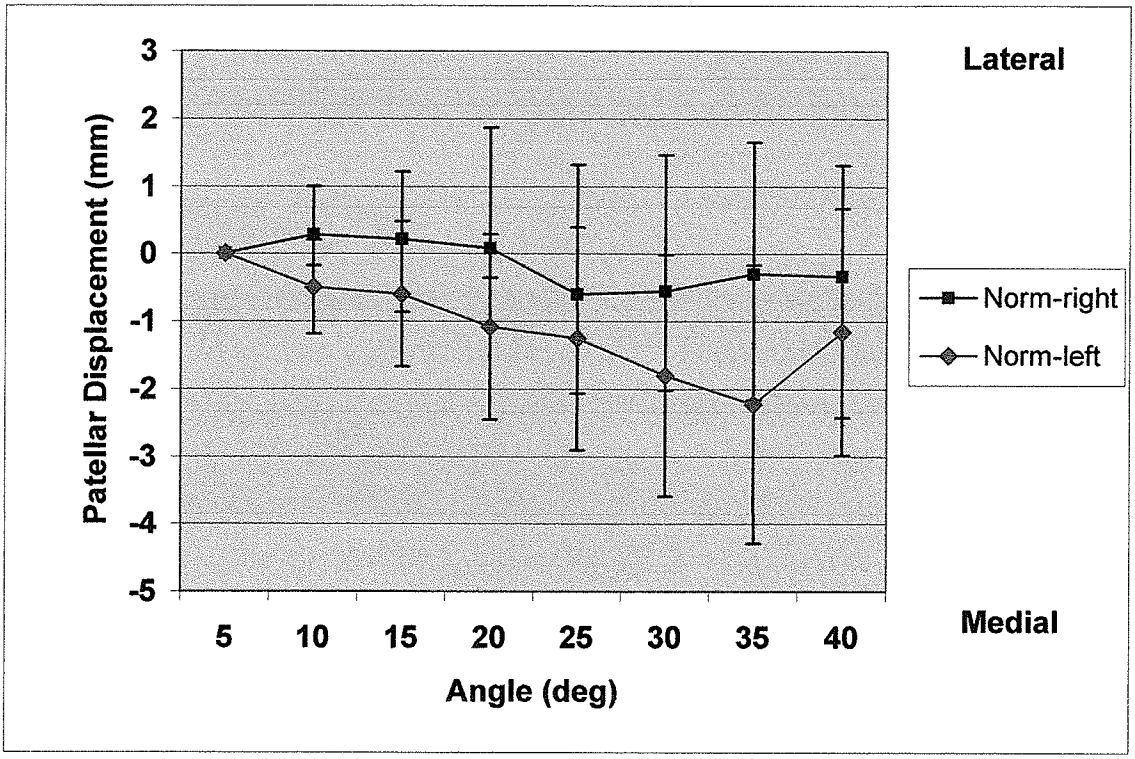


Figure 10: Comparison of Patellar Displacement Versus Joint Angle for the Right and Left Normal Control Legs with Extension of the Knee

2. Normal Control –Within Group Comparisons-No Load Verses Submaximal Load

In comparing the no load and submaximal load conditions within the Normal control group, a significant difference was identified across all angles with the exception of the angles of 30 and 35 degrees. Level of significance ranges from p =0 .006 to that of p= 0.03 with a p value of 0.068 identified for the 30 degree angle and 0.15 for the 35 degree angle. The average mean patellar displacement relative the medial condyles across all angles for the no load condition is 0.75 mm with an average standard deviation of 1.49. The mean displacement for the submaximal load condition is 2.82 mm with a respective average standard deviation of 1.70. Figure 11 depicts the mean patellar displacements relative the medial condyle and associated standard deviations for each angle across the 2 load conditions of no load and submaximal load.

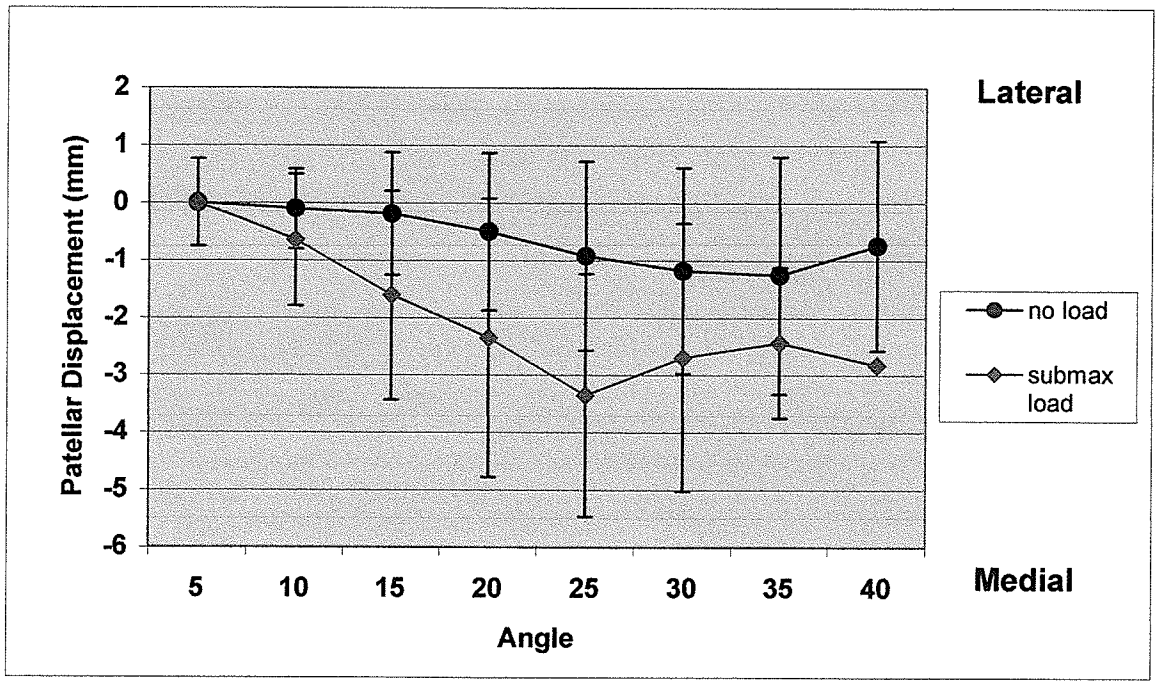


Figure 11: Normal Control Group – Comparison of the Patellar Displacement Verses Joint Angle for the No Load and Submaximal Load Conditions as the Knee Extends

3. Normal Control–Within Group Comparisons-No load Verses Maximal Load and Submaximal Load Verses Maximal Load

In comparing the no load condition with that of the maximal load, a significant difference with a p value of 0 .05 was identified at the 20 degree angle with no significance noted at the 35 degree angle with a p value of 0.48. The average patellar displacement is 0.75 mm for the no load condition with a respective mean standard deviation of 1.49. The mean patellar displacement for the maximal condition is 1.30 mm with a mean standard deviation of 2.57. As previously outlined the values for the maximal condition were only obtained during data collection at the angles of 0, 20 and 35 degrees. No significant difference was identified in comparing the submaximal and maximal conditions at 20 and 35 degrees with respective p values of 0.28 and 0.22. The direction of displacement is consistent for all 3-load conditions. Figure 12 depicts the relationship of all load conditions with the mean patellar displacements relative the medial condyle for each angle across all load conditions utilized. Error bars are also utilized to depict the associated standard deviations.

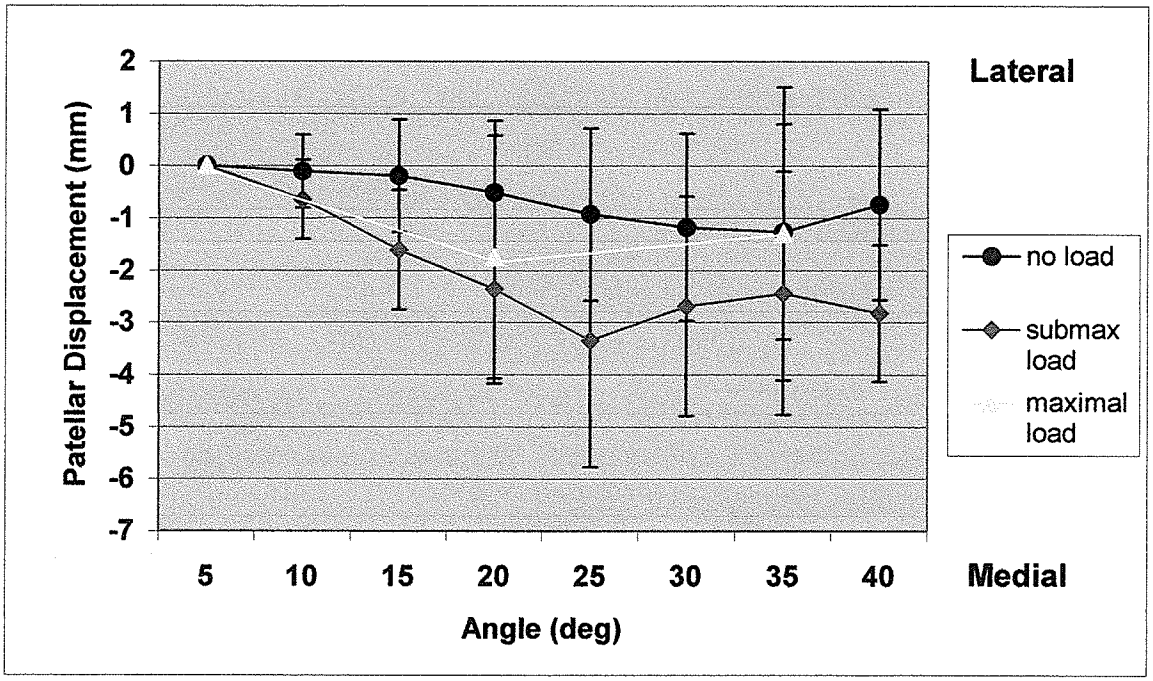


Figure 12: Normal Control Group – Comparison of the Patellar Displacement Verses Joint Angle Across the 3 Load Conditions with Knee Extension

Comparisons: Patellar Femoral Pain Syndrome Verses Normal

1. Between Group Comparisons: PFPS Verses Normal Control –No Load Condition

In comparing the no load condition across both group (PFPS vs. Normal) a significant difference is identified at the angles of 20, 25, 30, 35 and 40 degrees with p values ranging from .001 to .01. No significant difference is identified at the angles of 10 and 15 degrees with respective p values of 0.08 and 0.146. The mean patellar displacement across all angles for the PFPS group is 2.23 mm with the average mean displacement for the Normal control group identified, as 0.75 mm. Respective average standard deviations are 1.95 for the PFPS group and 1.49 for the Normal control group. The magnitude of the displacement differs between groups, as does the direction of the displacement with the PFPS group displacing medially and the Normal control group displacing laterally. Figure 13 depicts the mean patellar displacements relative the medial condyle and

associated standard deviations for each group and across all angles for the no load condition.

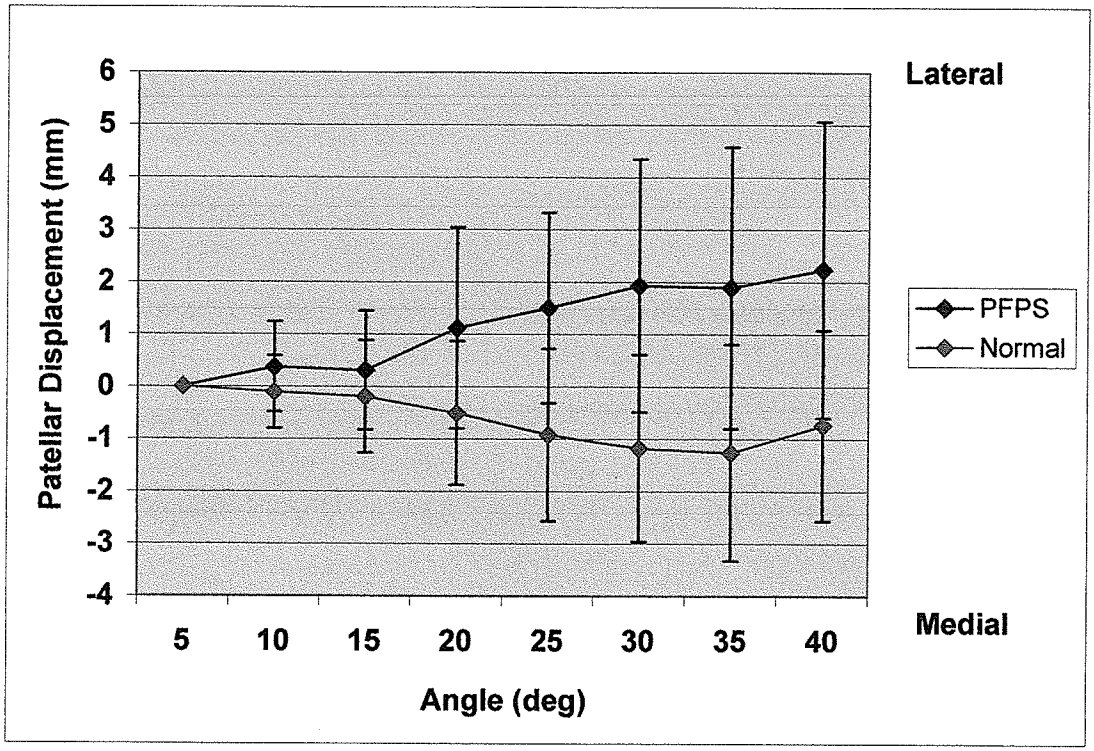


Figure 13: PFPS Vs Normal Control –Comparison of the Patellar Displacement Verses the Joint Angle in the No Load Condition with Knee Extension from 40 to 5 Degrees

2. Between Group Comparisons: PFPS Verses Normal –Sub Maximal Load Condition

In comparing the submaximal load condition across both groups (PFPS vs. Normal) a significant difference is identified at all angles with the exception of the 10 degree angle with p values ranging from 0 .0003 to 0.005. The p value associated with the 10 degree angle is 0.12. The mean patellar displacement across all angles for the PFPS group is 1.32 mm with a standard deviation of 2.46. The mean displacement for the Normal control group is 2.82 mm with an average standard deviation of 1.70. The direction of displacement associated with the PFPS group is medial with lateral displacement associated with the Normal control group. Figure 14 depicts the mean patellar displacement relative the medial condyle and associated standard deviations for each group and across all angles for the submaximal load condition.

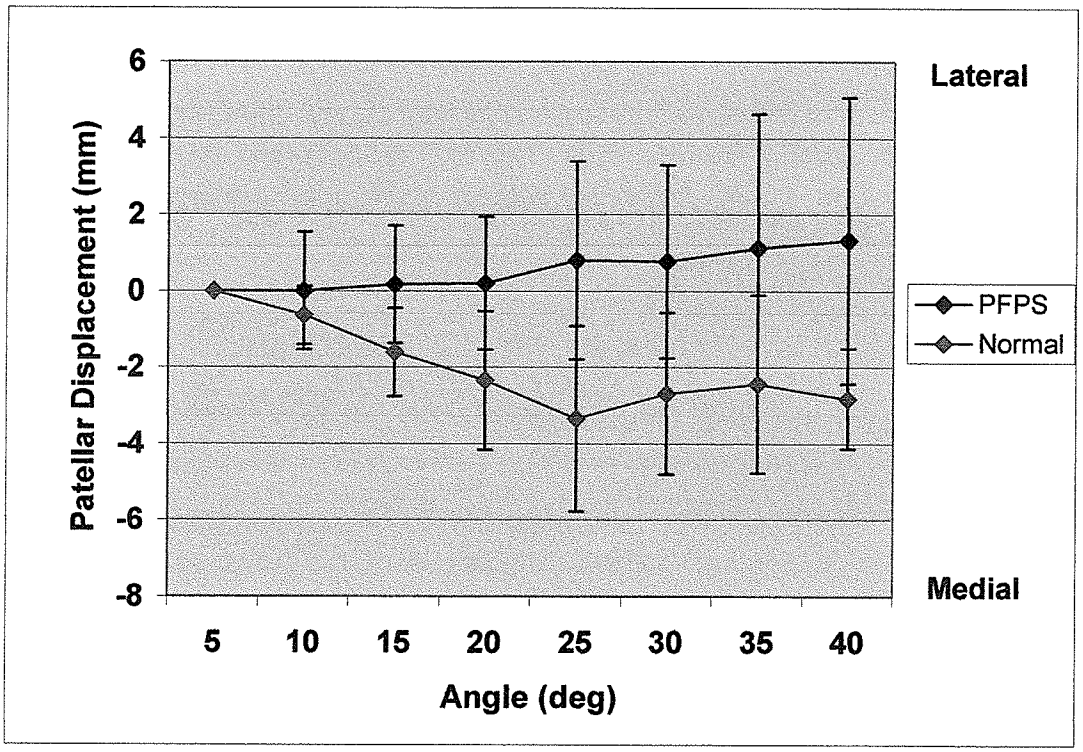


Figure 14: PFPS Vs Normal Control– Comparison of the Patellar Displacement Verses the Joint Angle in the Submaximal Load Condition with Knee Extension from 40 to 5 Degrees

3. Between Group Comparisons: PFPS Verses Normal Control –Maximal Load Condition

The maximal load condition for the PFPS group was compared with the Normal control group. Results of the comparison unlike the no load (Figure 13) and submaximal load (Figure 14) conditions, indicate that there is no significant difference between the 2 groups at the 20 and 35 degree angles with similar magnitudes and consistent directions of displacement identified. The mean magnitude of displacement for the PFPS group is 1.24 mm with an average standard deviation of 2.46. The mean patellar displacement for the Normal control group is 1.30 mm with an average standard deviation of 2.57. Figure 15 depicts the mean patellar displacements relative the medial condyles and associated standard deviations for each group and across all angles for the maximal load condition.

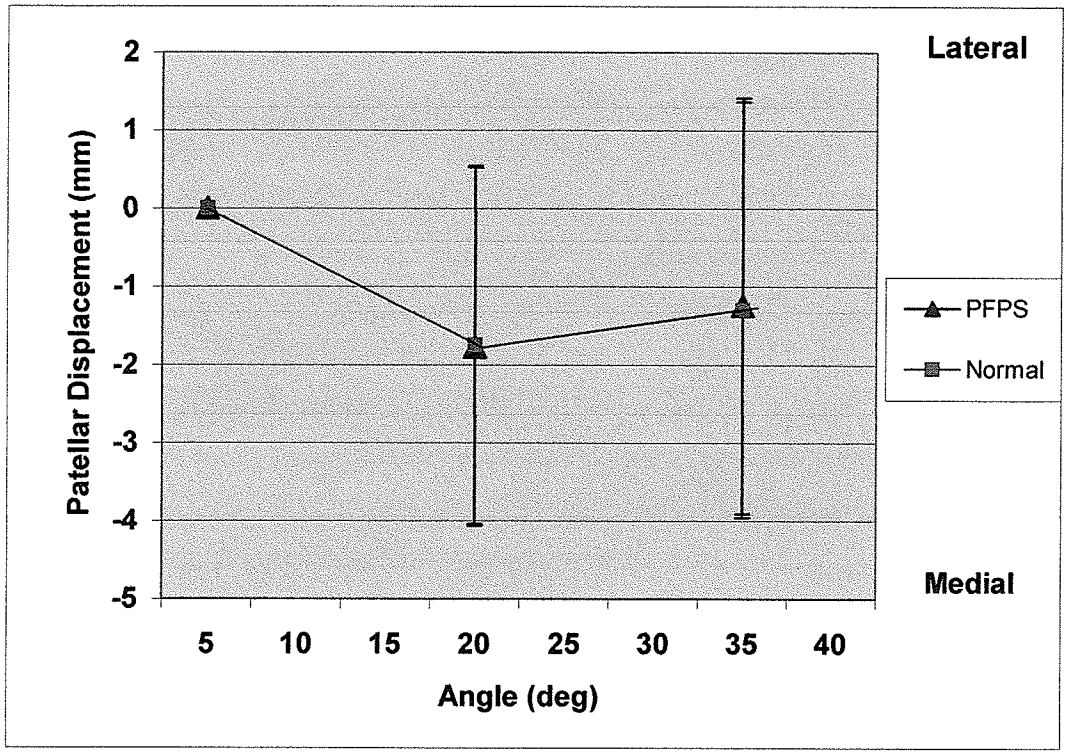


Figure 15: PFPS Vs Normal Control– Comparison of the Patellar Displacement Verses Joint Angle Across the 3 Load Conditions with Knee Extension from 40 to 5 Degrees

Patellar Displacement

The mean patellar displacements for each group and load condition including the magnitude as well as the direction has been summarized in Table 7. As noted previously although the magnitude of the displacement ranging from 0.41 mm to 3.14 mm may be consistent across groups under certain load conditions, the direction of the displacement differs in comparing the 2 groups under the no load and submaximal load conditions. Consistency of the direction of displacement is apparent between the 2 groups under the maximal load condition.

Table 7: Patellar Displacement: Magnitude and Direction

Group	Load	Leg Condition	Displacement		SD
			Magnitude (mm)	Direction	
Legs Separate					
PFPS	No Load	Affected	1.70	**Medial**	1.74
PFPS	No Load	Non-Affected	2.93	**Medial**	2.09
Normal	No Load	Right	0.34	**Lateral**	1.57
Normal	No Load	Left	1.16	**Lateral**	1.27
PFPS	Submax	Affected	0.59	**Medial**	1.43
PFPS	Submax	Non-Affected	2.62	**Medial**	3.27
Normal	Submax	Right	3.14	**Lateral**	1.41
Normal	Submax	Left	2.51	**Lateral**	2.00
PFPS	Maximal	Affected	0.99	**Lateral**	2.16
PFPS	Maximal	Non-Affected	1.70	**Lateral**	2.98
Normal	Maximal	Right	2.18	**Lateral**	2.01
Normal	Maximal	Left	0.41	**Lateral**	2.87
Legs Combined					
PFPS	No Load	Combined	2.23	**Medial**	1.95
Normal	No Load	Combined	0.75	**Lateral**	1.49
PFPS	Submax	Combined	1.32	**Medial**	2.46
Normal	Submax	Combined	2.82	**Lateral**	1.70
PFPS	Maximal	Combined	1.24	**Lateral**	2.46
Normal	Maximal	Combined	1.30	**Lateral**	2.57

Summary

Within and between group comparisons have been summarized in Table 8 with relationships of significance identified including the involved angles.

Table 8: Summary of Within and Between Group Comparisons

Group	Load Condition	Leg Condition	Significant Relationship	
			Yes/No	Angles (Degrees)
Within Group				
PFPS vs. PFPS	No Load	A leg vs. NA	**NO**	
PFPS vs. PFPS	Submax	A leg vs. NA	**NO**	
PFPS vs. PFPS	Maximal	A leg vs. NA	**NO**	
PFPS vs. PFPS	Combined Legs	No load verses Submax load	**NO**	
PFPS vs. PFPS	Combined Legs	No Load vs. Maximal Load	**YES**	**20,35***
PFPS vs. PFPS	Combined Legs	Submax Load vs. Maximal Load	**YES**	**20,35***
Normal vs. Normal	No Load	Right leg vs. Left	**NO**	
Normal vs. Normal	Submax	Right leg vs. Left	**NO**	
Normal vs. Normal	Maximal	Right leg vs. Left	**NO**	
Normal vs. Normal	Combined Legs	No load verses Submax load	**YES**	**10,15,20,25,40**
Normal vs. Normal	Combined Legs	No Load vs. Maximal Load	**YES**	**20**
Normal vs. Normal	Combined Legs	Submax Load vs. Maximal Load	**NO**	
Between Groups				
PFPS vs. Normal	Combined Legs	No Load vs. No Load	**YES**	**20,25,30,35,40**
PFPS vs. Normal	Combined Legs	Submax vs. Submax	**YES**	**15,20,25,30,35,40**
PFPS vs. Normal	Combined Legs	Maximal vs. Maximal	**NO**	

*** Please note that for the maximal load condition data for both groups was collected only at the knee joint angles of 5, 20 and 35 degrees.**

Patellar Position

The patellar positions were calculated for both the PFPS and the Normal control groups across all three-load conditions at the 5 and 35 degree angles. The5 degree angle represents the last position of the patella, completing the displacement pattern with the 35 degree angle utilized to represent the onset position of the patella, defining the initiation of the displacement pattern. The 35 degree angle was utilized verses the 40 degree angle to allow for comparisons across all load conditions. Figure 16 depicts the mean patellar positions expressed as percentages relative the medial condyle across all groups both at the 5 and 35 degree angles. The associated standard deviations are also included

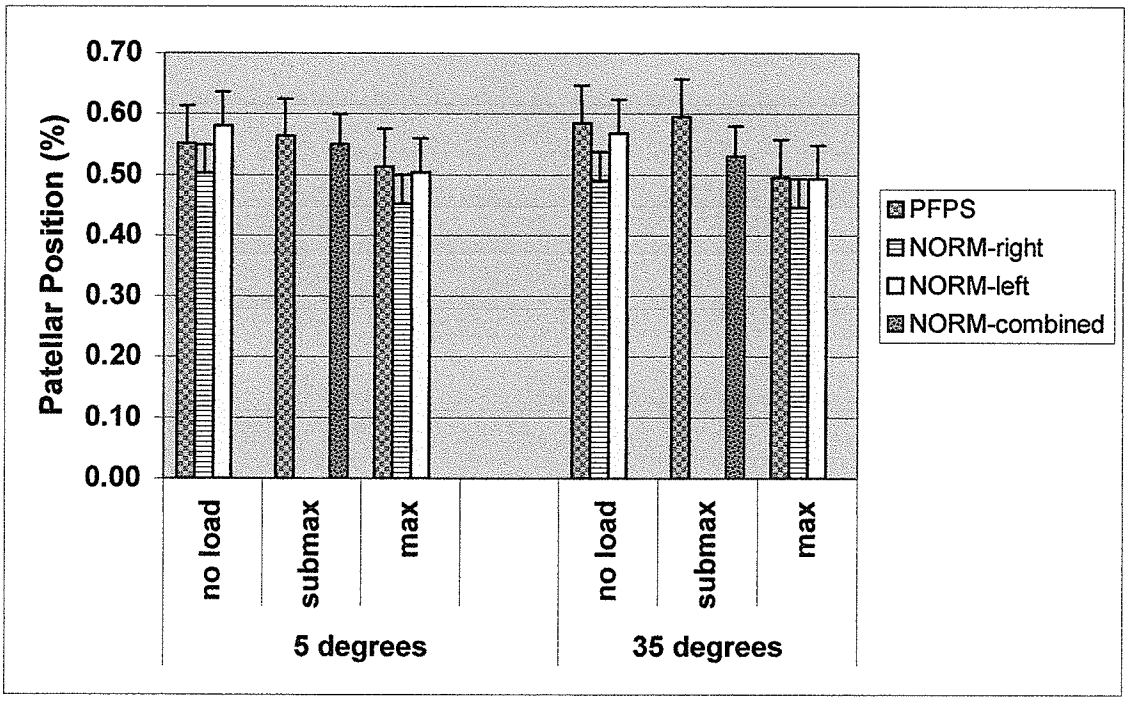


Figure 16: Comparison of Patellar Position at the Knee Joint Angles of 5 °and 35 °with Knee Extension across all 3 Load Conditions

Preliminary within and between group comparisons were performed utilizing t-tests to compare the position of the patella at the knee joint angles of 5 and 35 degrees across all three load conditions to identify any significant differences that may aid in defining the tracking pattern associated with the Normal control and PFPS groups.

Patellar Position at 5 Degrees

1. Patellar Femoral Pain Syndrome – Within Group Comparisons

The patellar positions of the affected and non-affected legs in the PFPS group were compared across all 3-load conditions with no significant differences being identified. Consequently the affected and non-affected legs were combined to form a PFPS group comprised of 14 legs. The respective means and standard deviations are as follows:

- No load condition: 0.55 (0.06)
- Submaximal load condition: 0.56 (0.07)
- Maximal load condition: 0.51 (0.046)

The no load condition was compared with the submaximal load condition with no significant relationship being identified. The no load condition was then compared with the maximal load condition with a significant relationship being identified with a p value of 0.03. The submaximal load condition was then compared with the maximal load condition with a significant difference also being identified with a p value of 0.02.

2. Normal - Within Group Comparison

The patellar positions of the right and left legs in the Normal control group were also compared across all 3-load conditions. The right and left legs were combined in the submaximal load condition as no significant difference was identified between the 2 groups. The legs could not be combined in the no load condition as well as the maximal load condition as significant differences were identified with respective p values of 0 .004 and 0 .01. The means and associated standard deviations are as follows:

- No load condition, right leg: 0.50 (0.06)
- No load condition, left leg: 0.58 (0.07)
- Submaximal load condition: 0.55 (0.05)
- Maximal load condition, right leg: 0.45 (0.04)
- Maximal load condition, left leg: 0.50 (0.04)

No significant difference was identified in comparing the patellar position of the right no load condition and the left no load condition with that of the combined group in the submaximal load condition. A significant difference was identified in comparing the patellar position of the right no load condition with that of the right maximal load condition with a p value of 0.03. No significant difference was identified in comparing the left no load condition with that of the left maximal load condition. A significant difference was also identified in comparing the combined leg group under the submaximal load condition with that of the right leg group under the maximal load condition with a p value of 0 .002. No significant relationship was identified in comparing the submaximal load condition with that of the left maximal load condition.

3. PFPS Verses Normal - Between Group Comparisons

In comparing the PFPS group with that of the Normal control groups across all 3-load conditions a significant relationship was identified between the combined PFPS group and the Normal control right leg group under the no load condition with a p value of 0.01 with a significant relationship also being identified under the maximal load condition in comparing the Normal control right leg group with that of the combined PFPS group with a p value of 0.01. No other significant relationships were established between the PFPS and Normal control groups.

Patellar Position at 35 Degrees

1. Patellar Femoral Pain Syndrome – Within Group Comparisons

The patellar positions of the affected and non-affected legs in the PFPS group were compared across all 3-load conditions with no significant differences being identified. Consequently the affected and non-affected legs were combined to form a PFPS group comprised of 14 legs. The respective means and standard deviations are as follows:

- No load condition: 0.58 (0.06)
- Submaximal load condition: 0.60 (0.05)
- Maximal load condition: 0.50 (0.05)

The no load condition was then compared with the submaximal condition with no significant relationship being identified. The no load and maximal load comparison identified a significant difference with a p value of 0.0001 with a significant difference also identified in comparing the submaximal load condition with that of the maximal load condition with a p value less than 0.0001.

2. Normal-Within Group Comparison

The patellar positions of the right and left legs in the Normal control group were also compared across all 3-load conditions. The right and left legs were combined in the submaximal load condition only with a right and left leg group created for the no load and maximal load conditions as significant differences were identified with respective p values less than 0.0001 and 0.05. The means and associated standard deviations are as follows:

- No load condition, right leg: 0.49 (0.04)
- No load condition, left leg: 0.57 (0.05)
- Submaximal load condition: 0.53 (0.05)
- Maximal load condition, right leg: 0.45 (0.03)
- Maximal load condition, left leg: 0.49 (0.04)

The no load right and no load left leg conditions were then compared with the submaximal load condition with no significant differences identified. The no load right and maximal load right groups were compared with a significant difference identified with a p value of 0.02. The no load left and maximal load left groups were also compared with a significant difference noted with a p value of 0.03 identified. Comparisons were also made between the submaximal load conditions and the maximal right and left leg groups with a significant relationship identified between the submaximal and maximal right leg group with a p value of 0.002. No significant difference was identified between the submaximal and left leg group.

3. PFPS Verses Normal-Between Group Comparisons

In comparing the PFPS group with that of the Normal control groups across all 3-load

conditions significant differences were identified. A significant difference was identified under the no load condition between the normal control right leg group and the combined PFPS group with a p value of 0.01. A significant difference was also identified between the 2 groups in the submaximal load condition with a p value of 0.003. A significant difference was identified in the maximal load condition between the 2 groups in comparing the Normal control right leg group with that of the combined PFPS group with a p value of 0.05. No other relationships were identified.

Strength

The maximum isometric knee extensor moment was recorded at the joint angles of 5, 20 and 35 degrees for both legs of all subjects in the PFPS group as well as the Normal control group. All values, expressed in Newton meters (Nm) are outlined in Table 9. The data was also normalized to account for gender differences to allow for greater accuracy in comparing the maximum isometric knee extensor moments between the two groups across the 3 angles of 5, 20 and 35 degrees. The normalized values have also been included in Table 9 with the unit of measure being Nm/kg.

Table 9: Maximal Isometric Knee Extensor Moments Across the Knee Joint Angles of 5, 20, and 35 Degrees for the PFPS and Normal Control Groups

SUBJECT		5 Degrees		20 Degrees		35 Degrees	
PFPS		**Nm**	**Nm/kg**	**Nm**	**Nm/kg**	**Nm**	**Nm/kg**
1 Female	A-Right**	47.5	0.63	47	0.63	48	0.64
	A-Left	61	0.81	77	1.03	89	1.19
2 Female	A-Right**	55	0.69	68	0.86	83	1.04
	NA-Left	73	0.92	83	1.04	115	1.45
3 Female	A-Left	67	1.18	90	1.58	109	1.92
	NA-Right**	57	1.00	73	1.29	84	1.48
4 Male	A-Left	106	1.12	136	1.43	158	1.66
	NA-Right**	100	1.05	129	1.36	162	1.71
5 Female	A-Right**	47	0.86	72	1.32	97.5	1.79
	A-Left	61.5	1.13	82	1.50	102	1.87
6 Female	A-Left	64	1.10	111	1.91	129	2.22
	NA-Right**	66	1.14	104	1.79	131	2.25
7 Female	A-Left	62	1.12	79	1.43	100	1.81
	NA-Right**	61	1.10	84	1.52	123	2.22
NORMAL		**Nm**	**Nm/kg**	**Nm**	**Nm/kg**	**Nm**	**Nm/kg**
8 Male	Right	48	0.62	66	0.85	87	1.13
	Left**	53	0.69	81	1.05	104	1.35
9 Male	Right**	66	1.00	109	1.65	145.5	2.21
	Left	75	1.14	117	1.78	138	2.09
10 Female	Right	50	0.62	67	0.83	81.5	1.01
	Left**	93	1.15	127	1.57	165.5	2.04
11 Female	Right	64	1.17	82	1.50	114	2.09
	Left**	90	1.65	101	1.85	116	2.13
12 Male	Right**	106	1.34	135	1.71	161	2.04
	Left	109	1.38	137	1.73	155	1.96
SUMMARY		**Mean (Nm/kg)**	**SD**	**Mean (Nm/kg)**	**SD**	**Mean (Nm/kg)**	**SD**
PFPS		**0.99**	**0.18**	**1.33**	**0.35**	**1.66**	**0.47**
NORMAL		**1.08**	**0.35**	**1.45**	**0.39**	**1.80**	**0.46**

** Dominant Leg

T-test were performed comparing the normalized maximal isometric knee extensor moments from the PFPS group across the angles of 5, 20 and 35 degrees with those from the Normal control group. No significant differences were identified between the two groups across all three angles. Although significant differences were not identified between the two groups, the trend noted in comparing the means from both groups was for the Normal control group to be associated with a slightly higher normalized mean

knee extensor moment primarily at the 35 degree angle. Figure 17 depicts the mean and associated standard deviations of the normalized knee extensor moments for both groups across all three angles of 5, 20 and 35 degrees.

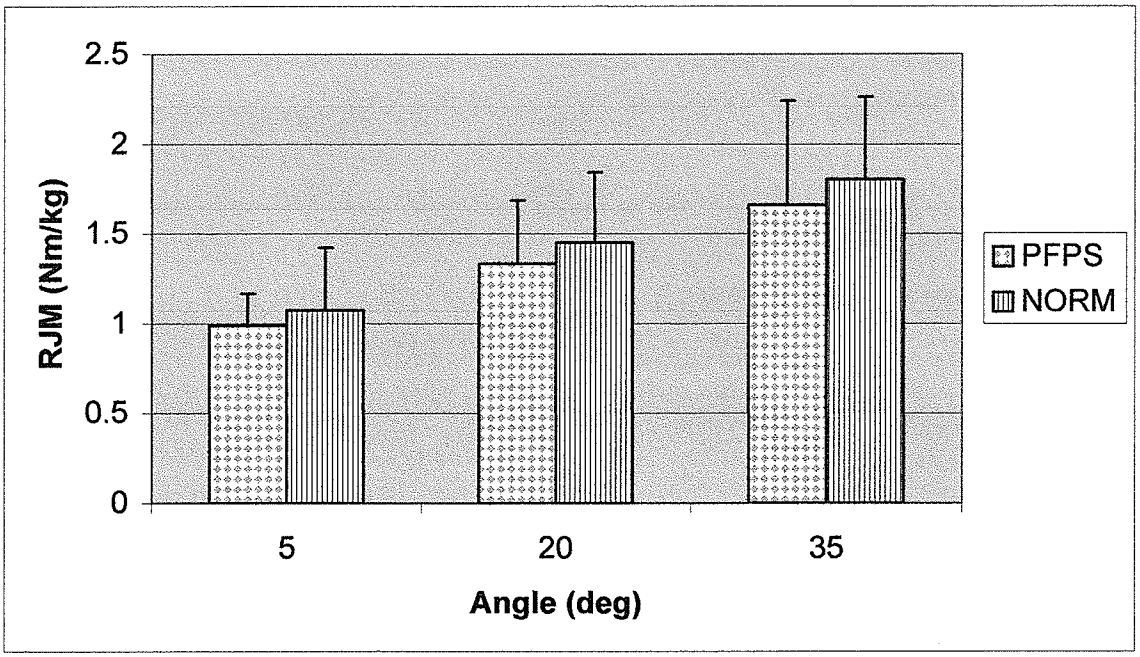


Figure 17: Mean Maximal Isometric Knee Extensor Moments Across the Knee Joint Angles of 5, 20, and 35 Degrees for Both the PFPS and Normal Control Groups

Discussion

Patellar femoral pain syndrome has been associated with an "abnormal" tracking or "maltracking" pattern of the patella as the knee flexes and extends. Currently there is a paucity of research to support this theory with a specific tracking pattern not as yet identified and clearly defined for the PFPS population. Studies across deferring mediums have only recently identified a reasonably consistent tracking pattern for the normal population.

The primary purpose of this study was to determine if a tracking pattern specific to the patellar femoral pain syndrome group could be identified across multiple angles (5 to 40 degrees) and load conditions comparing affected and non-affected extremities. The secondary purpose was to compare the results from the PFPS group with those from the Normal control group to determine if significant differences between the two groups could be identified. Given the literature to date comprised primarily of one study with subjects having a history of subluxation of the patella (Brossmann et al, 1994) and three studies on subjects with symptoms consistent with PFPS (O'Donnell et al, 2004; Harman et al, 2001; Witonski et al, 1999), a greater degree of lateralization was expected to be identified in the PFPS group. Other possibilities identified include a possible change in trajectory and /or an offset in the position of the patella.

Within Study Comparisons

Within group comparisons for the PFPS group under the no load and submaximal load conditions across all angles did not identify the presence of a significant difference, although a trend of difference at the angles of 20, 25, 30, 35 and 40 degrees is apparent in viewing the mean patellar displacement patterns across all angles for both load conditions. This trend may have become significant if a larger sample size was available. The mean patella displacement patterns for both the no load and submaximal load conditions are defined by the patella shifting medially as the knee extends from 40 to 5 degrees.

A significant difference was identified between the no load and maximal load condition and the submaximal and maximal load condition at the angles of 20 and 35 degrees. The mean patellar displacements for the 3 conditions of no load, submaximal load and maximal load are similar in their magnitudes, with the significant difference attributed to the disparate directions of the displacement. The patella displaces medially in the no load and submaximal load conditions and laterally in the maximal load condition. As noted the only angles assessed for the maximal load condition were 0, 20 and 35 to avoid symptom exacerbation in the PFPS population. Given the disparate directions of displacement it is not unreasonable to expect that the trend for the maximal load condition would continue to be defined by lateralization and therefore significant differences would also be identified across the other angles. Findings for the one male PFPS subject were consistent with the mean direction of displacement for the female PFPS subjects with the patella displacing medially through knee extension under the no load and submaximal load conditions with the maximal load condition being associated with a lateral shift.

Within group comparisons for the normal population identify significant differences between the no load and submaximal load condition at the angles of 10,15, 20, 25 and 40 degrees as well as the no load and maximal load conditions at 20 degrees. The direction of the patellar displacement is consistent across all 3-load conditions and is characterized by a lateral shift (lateralization). This trend was identified in both genders in the Normal control group.

Between group comparisons identify a significant difference in comparing the 2 groups under the no load condition at the angles of 20, 25, 30, 35 and 40 degrees. A significant difference was also established between the groups under the submaximal load condition at the angles of 15, 20, 25, 30, 35 and 40 degrees. The significant differences identified between both of the groups across the two load conditions of no load and submaximal load are not unexpected given the disparate directions of displacement characterizing the two groups with the PFPS group displacing medially and the Normal control group displacing laterally. No significant difference was identified between the 2 groups under the maximal load condition with the patellar displacement patterns for both groups

defined by a lateral shift. In comparing the pattern of patellar displacement between the groups, utilizing both the direction of the displacement as well as the magnitude, the values from each group at each angle under this maximal load condition virtually overlap. Although digital images for the maximal load condition were only obtained during data collection at 5, 20 and 35 degrees, given the direction of displacement it would be reasonable to expect a continuation of this trend of lateral displacement for both groups across all angles.

Comparisons with Literature

Tracking Pattern

Direction of Patellar Displacement

A reasonably consistent trend has been identified in the literature for the patellar tracking pattern of the normal population with respect to the direction of the patellar displacement. Although there is general consensus regarding the direction of the displacement, the magnitude is not consistent across the studies nor is the response of the patella under no load verses loaded conditions.

Patellar motion is generally defined in response to the movement of the knee as it flexes or extends or the moment about the knee represented by a flexor or extensor moment. Consequently flexion of the knee is associated with medial patellar displacement with extension of the knee associated with lateral patellar displacement. Literature for in vitro and in vivo studies identify a fairly consistent trend associated with patellar motion in the initial stages of knee flexion (0 to 40 degrees). The literature identifies the trend of lateralization of the patella in the last 15 to 40 degrees of knee extension or medialization in the initial 15 to 40 degrees of flexion with the range varying depending upon the study (Shih et al, 2004; Katchburian et al, 2003; Moro-oka et al, 2002; Suchak et al, 2000; Powers et al, 1998, Brossmann et al, 1993; Koh et al, 1992; Hefzy et al, 1991; van Kampen and Huiskes, 1990; Kujala et al, 1989). Medialization of the patella in the initial

stages of knee flexion has also been identified in recent weight bearing studies utilizing CT-scans and MRI (Asano et al, 2003; Patel et al's, 2003). Brossmann et al (1993) as well as Suchak at al (2000) identify the trend of lateralization during the last 30 degrees of knee extension, but only under loaded conditions with no significant mediolateral displacement identified under the no load condition.

The findings for the Normal control group (n=10) in the no load condition are fairly consistent with the pattern identified in the literature for the last stages of knee extension with a lateral shift defining the mean displacement pattern from 35 to 15 degrees followed by minimal to no mediolateral displacement from 15 to 5 degrees. The mean displacement pattern of the patella in the submaximal load condition is characterized by a medial shift from 35 to 25 degrees followed by a lateral shift from 25 to 5 degrees. The patella also lateralizes in the maximal load condition with a specific lateral shift noted from 20 to 5 degrees. The trend of lateralization of the patella especially under loaded conditions is consistent with the dynamic studies performed by Brossmann et al (1993) and Suchak et al (2000)

It was theorized that the findings from the PFPS group would identify a greater degree of lateral displacement relative the Normal control group. Findings do not support this theory across all 3 load conditions with the mean patellar displacement patterns identified for the no load and submaximal load conditions characterized by medialization of the patella. This pattern of medial patellar displacement was identified during extension of the knee from 40 to 15 degrees in the no load condition and 40 to 20 degrees in the submaximal load condition with minimal to no mediolateral translation being identified in both displacement patterns from 15 to 20 degrees through to 5 degrees. This medial displacement pattern has been recognized in the literature as being associated with patellar femoral pain syndrome with both Witonski et al (1999) and Harmen at al (2001) having identified it as being one of the 5 tracking patterns associated with this condition. Witonski et al (1999) studied 12 women with PFPS, identifying this medial displacement pattern in 1 (8%) of the subjects. Harman et al (2001) studied the tracking pattern in 17 men (20 knees) with persistent anterior knee pain, identifying this pattern of

medialization in 5 (25%) of the subjects. Findings for the maximal load condition identify a mean patellar displacement pattern, characterized by lateralization that is virtually indistinguishable from the Normal control group. This pattern is consistent with the literature in across study comparisons with normal, symptomatic and/or subluxing knees under loaded conditions (Suchak et al, 2000; Witonski et al, 1999; Brossmann et al, 1994).

The most common tracking pattern identified by Witonski et al (1999) in the PFPS group was lateral tilt combined with lateralization with 5 (42%) of the subjects classified under this category. Harman et al (2001) list lateralization with no patellar tilt as the most common pattern with 10 (20%) of the subjects demonstrating this patellar movement pattern. The most recent study by O'Donnell et al (2004) also identify trends characterized by lateralization with this pattern defining the patellar displacement patterns of both the symptomatic and asymptomatic groups. Across all three PFPS studies a large percentage of the subjects in each study were classified as demonstrating "normal" patterns of patellar displacement with no significant differences identified in comparisons with the control groups. O'Donnell et al (2004) classify 57% of the anterior knee pain subjects as "central" which is similar to the findings for the control group at 62%. Witonski et al (1999) report that 32 –44% of the PFPS subjects present with patellar displacement patterns consistent with the control group with Harman et al (2001) reporting a value representing 10 % of the PFPS group with consistent patterns.

In reviewing the patella displacement patterns for PFPS subjects that participated in the study, it is recognized that some individuals demonstrated patterns of displacement that are consistent with the normal control group. One subject in the PFPS group demonstrated a lateral pattern of displacement for both legs across all three load conditions. Two subjects demonstrated minimal mediolateral displacement under the no load condition which is consistent with Brossmann et al (1994) and Suchak et als' (2000) findings for this load condition. One of these subjects then demonstrated a medial displacement pattern for the affected leg and a lateral displacement pattern for the non-affected leg under the submaximal load condition. Consequently in viewing the

individual patellar displacement patterns for each subject in the PFPS group 4 patterns or trends were identified:

1) Medialization under the no load and submaximal load conditions with lateralization under the maximal load condition.
2) Lateralization under all three load conditions
3) Minimal to no mediolateral displacement under the no load condition with medialization of the affected leg and lateralization of the non-affected leg under the submaximal load condition. Lateralization of both legs under the maximal load condition
4) Minimal mediolateral patellar displacement in the less affected side under the no load condition with medialization identified under the submaximal load condition. Medialization under both load conditions on the more affected side. Lateralization of both legs under the maximal load condition

Trajectory Change

A general trend is identified in the PFPS group in the no load condition in which a momentary (change in trajectory) directional shift in translation occurs at 20 degrees across 80% of the individuals in the non-affected group and 78% of the affected group at the angles of 15 or 20 degrees. This trend is also identified in the submaximal load condition in the PFPS population in 78% of the affected group again involving the angles of 15 and 20 degrees. There was no consistent trend identified in the non-affected group in the PFPS population in the submaximal load condition nor were their consistent trends identified across the no load and submaximal load conditions involving the normal population.

Magnitude of Patellar Displacement

Research indicates that the magnitude of displacement of the patellae during knee

extension from 90 to 0 degrees across all in vitro studies ranges from 2.9 to 18.5 mm with the range for in vivo studies across the angles of 50 to 0 identified as 3.37 to 9.3 mm. The magnitude of the resultant displacement values are somewhat less than those identified in the literature both for the patellar femoral pain syndrome group and the normal group with respective ranges across all load conditions of 0 .34 to 3.14 mm for the normal and 0.59 to 2.93mm for the PFPS population. In multiplying the values by the identified 15% underestimation the ranges at 0.51 to3.61 mm for the Normal control group and 0.68 to 3.37 for the PFPS group approximate those identified in the literature

The magnitude of displacement for the normal population for the maximal load condition was expected to be larger given the results from Suchak et al (2000). The results from their study indicate a larger lateral displacement associated with the maximal load condition compared to that of the submaximal load condition. This is not consistent with this study with findings indicating a larger mean patellar displacement for the sub maximal load condition verses the maximal load condition. As both studies utilized digital imagery with similar methodologies it was expected that the results would be consistent for the normal population. This inconsistency may be due to a discrepancy in the submaximal load condition as it is defined in both studies as a percentage of maximal load, but the method of determining the percentage values is not consistent. Suchak et al (2000) defines the submaximal load condition as 5 % of maximal load with the present study defining the submaximal load condition as 10 % of maximal load across the angles of 5 to 40 degrees.

Patellar Offset

Patellar offset was evaluated utilizing the position of the patella (bisect) within the bicondylar distance (width) expressed as a percentage relative the medial condyle. The position of the patella associated with the 35 degree angle at the onset of knee extension and the 5 degree angle associated with completion of knee extension were utilized to make within and between group comparisons across all three load conditions to identify trends. A lateral offset of the patella is observed in the PFPS group with the mean patellar

position for both the 35 and 5 degree angles located lateral to center in the no load condition. Consequently although the displacement pattern identified is characterized by a medial shift, the displacement pattern is occurring lateral to the center of the bicondylar distance. A lateral offset is also identified for the Normal control left leg group with findings indicating a lateral shift from 35 to 5 degrees. The patellar position for the Normal control right leg group is centrally placed for both angles with no offset noted and minimal mediolateral translation identified from 35 to 5 degrees. A lateral offset is noted for both the PFPS and Normal control groups under the submaximal load condition across both angles with a lateral shift identified for the Normal control group from 35 to 5 degrees and a medial shift identified for the PFPS group. This trend of a medial shift of the patella characterizing the displacement pattern for the PFPS group with the displacement pattern occurring lateral to center is consistent with the findings for the no load condition. The mean patellar position in the maximal load condition for the Normal control left leg group and the PFPS group is centrally placed with no offset identified. A minimal shift in the mean patellar position in the lateral direction is noted from 35 to 5 degrees. The mean patellar position for the Normal control right leg group across both angles is medial to center with no offset noted and no mediolateral displacement noted.

Studies to date have not generally defined the absolute position of the patella relative the condyles at the onset of displacement with knee movement nor the position of the patella at the end range of knee movement. This information would allow for the identification of possible trends pertaining to the specific position of the patella as well as determine if significant within and between group differences exist. One study (Asano et al, 2002) assessing the tracking pattern of the patella in weight bearing, does consider the position of the patella in describing the pattern of displacement. The authors' indicate a medial shift in the initial 15 to 30 degrees of flexion but indicate that the center (bisect) of the patella is located laterally to the midpoint between the 2 condyles throughout knee movement of from 0 to 120 degrees. Therefore, although the direction of the displacement is medial, the centre of the patella is located laterally to the midpoint of the bicondylar space throughout range of motion of the knee. Consequently, defining the start and end position of the bisect of the patella in relation to the bicondylar space would

supply additional information to aid in further defining and identifying tracking pattern of the patella associated with various populations i.e. Normal, PFPS, as it will determine if the patella is centrally, laterally, or medially placed upon initiation of testing as well as upon completion. This will add an additional dimension when making within and between group comparisons.

Across study comparisons to identify consistent tracking patterns and /or trends is often difficult as the authors' often do not clearly define the knee moment (flexor verses extensor) about the knee or movement (flexion verses extension) associated with the pattern of displacement of the patella, nor does there appear to be a standardized coordinate system utilized. Occasionally the knee movement or moment is defined, but is then inconsistently utilized by the author(s) throughout the document. Other factors also need to be considered when making group comparisons across studies, including the average mean age and range of the group as well as the sex of the group (male verses female verses mixed). Limitations associated with across study comparisons also include the use of different methodologies with parameters associated with the study not always being clearly defined.

Clinical Implications

The mechanism of injury associated with the development of PFPS cannot be attributed to one specific cause as one has to consider whether it is a sudden onset associated with one event with immediate pain and swelling or insidious in its presentation. The sudden acute onset with no pre-existing history of knee and lower quadrant (back and lower extremity) symptoms is theorized to be due to a momentary loss or perturbation in neuromuscular control, which causes the patella to abut against the lateral condyle instigating the pain and swelling cycle. This may result, if not addressed, in the facilitation of the vastus medialis to guard against another such incident. Consequently, if this perturbation in neuromuscular control is the mechanism, it is not clear whether the displacement of the patella in a medial direction in the no load and submaximal load

conditions would be identified in individuals experiencing an acute, first time occurrence or if this pattern would only develop and be consistently identified in chronic cases with a long term history including multiple exacerbations. Based upon the findings, the pattern of medial patellar displacement was only identified in the PFPS group in both the affected and non-affected legs in subjects with a long-term history (>5yrs) of anterior knee pain. In the one PFPS subject with a fairly recent history (0.30 yrs), characterized by a single acute episode of knee pain, the pattern of medialization of the patella was only identified in the affected leg. The pattern of displacement for the non-affected leg was consistent with the Normal control group. As such a medial patellar tracking pattern, if present in both legs, may be developed in those PFPS subjects that have had the condition for a longer period of time with symptoms experienced only with certain activities such as stair climbing and running. It is also possible that the subjects that present with this medialized tracking pattern have always had this pattern due to biomechanical factors and are consequently predisposed to developing PFPS as a result.

The insidious onset is theorized to be a result of lower quadrant dysfunction (back and lower extremity) in which the subject may present with anterior knee pain with an insidious onset but also have signs and symptoms of hip/pelvis dysfunction with deficits in hip abductor and knee extensor strength as wellas reduced strength and endurance of the core and poor recruitment strategies identified. Recent literature (Mascal et al, 2003, McConnell et al, 2002) favor the model of global lower quadrant involvement, but it is difficult to determine the specifics regarding the timeline and sequencing of events. It is possible that the neuromuscular perturbation in the acute situation is pre-disposed to occur due to the presence of biomechanical factors including weak hip extensor and abductor musculature with poor core recruitment and deficits in strength and endurance also noted in the presence and/or absence of pronated feet and a Q-angle outside of the normal limits, but the subject may be asymptomatic and not identify any pre-existing problems. Therefore these variables would have to be assessed prior to the subject participating in a study with a standard format developed that could be replicated by other researchers.

The neuromuscular perturbation could also be an anomaly, occurring in isolation and not influenced by other lower quadrant variables with gait, recruitment and muscle sequencing being altered secondary to the pain and swelling associated with the event. This sequence of events lends itself to altered lower extremity function especially if the subject does not seek aid prior to the symptoms becoming chronic. As such we are somewhat caught up in the "chicken and egg" scenario as clinically it is the authors experience that the affected population does not attend promptly for assessment and treatment. It is also the authors experience that the above outlined deficits especially reduced hip abductor and extensor strength and poor core stability are consistently identified in the assessment of clients with PFPS. This clinical impression is supported by the results from the study conducted by Ireland et al (2003) who identified women with the diagnosis of PFPS as having a greater likelihood of weakness of the hip abductor and external rotator musculature.

The pattern of medialization identified in the PFPS group may be due to the facilitation of the quadriceps (VM), which splints or guards the patella to prevent further contact with the lateral condyle. Taping has been utilized in the treatment of patellar femoral pain syndrome with studies indicating a decrease in pain and possible improvement in function but with no significant change in the kinematics of the patella identified especially in loaded or dynamic conditions (Pfeiffer et al, 2004; Gigante et al, 2001; Bockrath et al, 1993). The effect of the tape in current literature has been theorized to be due to afferent stimulation with improvements in proprioception about the knee also identified (Callaghan et al 2002). It is possible that the application of the tape may provide feedback to inhibit the body from splinting the patella medially, which in turn would facilitate a quicker recovery with less opportunity for the body to develop poor adaptation strategies that may lend themselves to the development of the identified medialized tracking pattern in the PFPS population.

Given the findings from this study as well as in reviewing the available studies on PFPS the application of tape to medialize the patella may not be appropriate for all individuals with PFPS. Various tracking patterns have recently been identified and associated with

this condition including the medial pattern defined by this study. Consequently patients need to be assessed prior to the application of the tape to ensure that it is an appropriate intervention.

Limitations

This study identified a tracking pattern for the PFPS under the conditions of no load, submaximal load and maximal load with knee extension across the angles of 40 to 5 degrees and compared it to the tracking pattern of the normal population with significant differences identified. Although it has been informative, allowing for a platform for further study, it is considered to be preliminary as it is limited in its power with a small sample size. It also only addresses one component of the tracking pattern, that of mediolateral translation (shift) that can be compared to the literature. It also only allows for within and between groups comparisons involving the maximal load condition at the 3 angles of 5, 20 and 35 degrees with the tracking pattern associated with this load only being defined by these 3 angles. Testing under this load condition was limited to avoid exacerbating symptoms in the PFPS group to prevent the subjects from discontinuing testing and withdrawing from the study. The study is also limited as the load conditions are static verses dynamic. The assessment of patellar displacement under load was performed with isometric contractions at fixed angles as opposed to dynamic with either isovelocity testing or assessment of patellar displacment during weight bearing. Consequently this study provides some insight, into the behavior of the patella under static loaded conditions only.

Conclusion

Further research is needed to accurately define and quantify the tracking pattern of the normal population as well as the amount of expected variability associated with this population. This will allow for a baseline of comparison for the tracking pattern associated with patellar femoral pain syndrome. This is an important first step in defining the tracking pattern of the PFPS population, as the general terminology utilized to

describe the etiology of PFPS is that it is an "abnormal" tracking or "maltracking" problem related to the patellar femoral joint. Maltracking of the patellar femoral joint, although discussed in the literature and commonly utilized by health care professionals to describe the condition to their patients, has not been extensively researched. A clear definition of the tracking pattern or patterns associated with patellar femoral pain syndrome has not occurred as yet. In fact there has been only recent consensus in the literature over components of the tracking pattern of the normal population primarily with patellar flexion (lag) and the direction of mediolateral translation (shift) with the magnitude of the displacement associated with the translation continuing to be highly variable. Less consistent and highly variable are the results for the component of the tracking pattern defined by patellar tilt and rotation.

Consensus across studies is apparent regarding the necessity of studying the components of patellar lag, mediolateral shift, patellar tilt and patellar rotation to fully define the patellar tracking pattern. The diversification leading to the variability across the studies and therefore differing results is attributed to the lack of standardization of the methodology. This lack has only recently been identified and addressed in the literature with a study performed by Ward et al (2002) utilizing Kinematic MRI to compare qualitative (visual analysis) and quantitative (objective measurements utilizing osseus landmarks) as well as 2 review articles one by Bull et al (2002) and the other by Katchburian et al (2003). Bull et al focus on the importance of consistency across the studies in the definitions of patellar femoral motion i.e. shift, tilt, rotation, flexion as well as the axes of motion. Katchburian et al (2003), identify 11 points in their review of the literature that affects the measurement of the tracking pattern of the patella. These like Bull et al (2002) include the coordinate system and reference points utilized to obtain the data, as well as the type and accuracy of the measurement system utilized, whether the measurements were taken under static or dynamic conditions, the presence of quadriceps loading including the magnitude and direction as well as type of muscle contraction if any as well as whether the loading was active or passive. The presence or lack of tibial rotation, varus angulation as well as the direction of knee range of motion (flexion or extension), reporting of the actual knee range of motion measured, subject data and

presentation of the data were also listed by the authors as effecting the tracking pattern of the patella. All of these factors may vary in one or more areas across the studies and therefore need to be considered, as differences will lend itself to variability when comparing results.

It is expected that there would be some inherent variability in the normal population but without some standardization, across study comparisons will be difficult making it challenging to determine the amount of variability in the tracking pattern that would be expected and considered to be representative of the tracking pattern associated with the normal population. This principle also apples to the study of the tracking pattern in the PFPS population. Standardization needs to be considered to allow for within group comparisons across studies to determine the degree of inherent variability in the tracking pattern associated with this group as well as determine if more than one tracking pattern can consistently be identified. Standardization will also facilitate across group comparisons with the normal population to determine if there are significant differences in the tracking patterns associated with the two groups under different conditions. Katchburian et al (2003) recommend, for standardization purposes, that researchers should minimally utilize consistency in the coordinate system and terminology utilized to define it, ensure that the knee angles and the direction of the movement i.e. extension verses flexion is defined as well as provide specifics regarding other parameters utilized i.e. load

In researching the tracking pattern associated with the PFPS population, it is also important to stringently define the subject population as based upon the results from the study, it is theorized that the tracking pattern for the chronic population with a long term history and multiple exacerbations would differ from the pattern of the acute or subacute population especially in comparing legs. This theory was identified prior to data collection but has been strengthened based upon the findings from the one PFPS subject with the recent history of a sudden onset of pain and swelling whose tracking pattern for the non-affected leg was inconsistent with the trend developed from the results for the PFPS group with all others, based upon their histories classified as chronic. Difficulties

are also inherent in studying subjects with an acute onset of PFPS with signs and symptoms of pain and swelling as it is not expected that they would be able to tolerate testing involving maximal load conditions whether in non-weight bearing or in weight bearing conditions especially involving the last 5 to10 degrees of knee extension though the affected extremity.

In conclusion patellar femoral pain syndrome appears to be associated with a number of different patellar displacement patterns with more than one trend identified. Further standardized research needs to occur to improve the definition of the patellar tracking pattern in the normal and PFPS populations as well as aid in determining the amount of inherent variability associated with each group. Additional parameters such as a measure of the position of the patella in relation to the bicondylar width with the onset of knee movement as well as with completion of knee range of motion should be considered to aid in further defining the displacement or tracking pattern of the patella.

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Appendix

Appendix A: Recruitment/Written Request

"Load and Angle Dependent Patellar Kinematics in the Patellofemoral Pain Syndrome Population"

Human Performance Lab
School of Medical Rehabilitation
University of Manitoba

To whom it may concern,

We are currently seeking subjects for a study regarding atraumatic anterior knee pain. The study will focus on determining the kinematics (tracking) pattern of the patella in the Patellofemoral Pain Syndrome population under unloaded and loaded conditions, comparing the results with the non-affected lower limb and to the normal population. If you have any cases of atraumatic anterior knee pain please inform these patients of this study.

If there are any questions or if you would like further information please contact one of the names below. Thank you for your consideration in this matter.

Contacts
Dr. Dean Kriellaars -
Donna Sarna -

Appendix B: Paraphrase

"Load and Angle Dependent Patellar Kinematics in the Patellofemoral Pain Syndrome Population"

Paraphrase and Informed Consent Form
University of Manitoba 2003

Contact: Dr. Dean Kriellaars -

Paraphrase

Many people suffer from knee pain. One source of this pain may be that the knee cap does not travel properly through a groove on the thigh bone as the knee bends and straightens. This pattern of travel is often referred to as tracking. To date the tracking pattern in people with and without knee pain has not been determined. It is important to determine the tracking pattern of the kneecap to aid in developing treatment techniques to decrease the pain and improve function in daily life.

Procedure

As a subject in this study you will be asked to participate in an examination and questionnaire. You will be asked to perform 3 tests on a special machine (isovelocity dynamometer) that is used to measure strength of the knee muscles. The first test will require you to relax as the machine moves your lower leg through a range or arc of movement. The second test involves maximally pushing your lower leg against a pad for a period of 5 seconds with the test to be repeated at 3-7 different knee positions. The third test involves pushing your lower leg with sub maximal force, against a pad for a period of 5 seconds with the test to be repeated at 7 different knee positions Pictures of your knee will be taken during each test at all knee positions. Testing will take place on both legs. The approximate time to complete the tests is 2 hours. You may be asked to return another day to repeat some tests. Any and all information provided for this study will be kept confidential.

Risks
The risks associated with the strength testing are minimal and include:

A. **You may experience an increase in pain during the testing. Testing may be stopped if needed at any time.**

B. You may experience some discomfort in the muscles surrounding the knee joint, which may last up to 72 hours after the test. This is a normal result of the exercise and will resolve on its own.

C. You may experience some swelling about the knee joint

You will not be identified in any published report of this study. Your participation is voluntary, and you are free to withdraw at any time without prejudice. You will not receive reimbursement for participation in this study, nor will you be responsible for any costs directly related to the study.

If you have any questions or do not understand any aspect of this form, please contact,

Dr. Dean Kriellaars
School of Medical Rehabilitation
University of Manitoba

Appendix C: Consent Form

"Load and Angle Dependent Patellar Kinematics in the Patellofemoral Pain Syndrome Population"

Paraphrase and Informed Consent Form
University of Manitoba 2003

Contact: Dr. Dean Kriellars

Consent Form

I have read the paraphrase and understand the nature of the study including the potential benefits and risks. I have satisfied any questions that I may have had with respect to this study. I agree to participate in this study and abide by the procedural requirements.
I understand that I may withdraw from this study at any time without prejudice.

Subject_____ Date_____

Witness_____ Date_____

Investigator_____ Date_____

Appendix D: Screening Assessment

Screening Assessment for Anterior Knee Pain

Name: _____
Date: _____
Date of Birth: _____
Thigh length: _____
Q-Angle: R_____L_____
Weight: _____

1) What leg would you kick a ball with? R or L

2) In which knee do you have anterior knee pain? R or L

3) Is this your first bout of anterior knee pain? Yes/No
If no how many previous occurrences over what time span?

_____
_____

4) How long have you had anterior knee pain? _____

5) Any restriction in movement in the painful knee?_____

6) Pain with: Ascending Stairs Yes/No
Descending Stairs Yes/No
Which is worse? A / D
Sitting? Yes/No.

7) Medications for your knee? _____

8) Have you had any traumatic injury to the painful knee including injury to the ligaments, injury to the cartilage, dislocations or previous surgery? Yes/No

9) Do you have any cardiovascular problems (e.g. Dizziness, high blood pressure, pain in the chest, heart or lung problems) or other medical conditions that may affect your ability to participate in this study? _____

10) Do you have osteoarthritis, rheumatoid arthritis or have you ever been given the diagnosis of chondramalacia patella? _____

11) Have you been diagnosed with having a neurological condition? _____
_____