Mechanisms Underlying Patellofemoral Pain: Lessons Learned over the Past 20 Years

Christopher M. Powers, PT, PhD, FASCM, FAPTA

Although recognized as one of the most common lower extremity disorders encountered in the general population, the etiology and treatment of patellofemoral pain (PFP) remains controversial. Over the past 20 years, our group has taken a multidisciplinary approach to better understand the pathogenesis of patellofemoral joint dysfunction. To gain insight into this complicated clinical condition, our studies have included the use of dynamic imaging, kinematic and kinetic analyses, cadaveric measurements, biomechanical modeling, and clinical assessments. This lecture will touch upon some of our contributions in these areas.

It has been hypothesized that abnormal loading of the patellofemoral joint is an important factor with respect to the genesis of PFP.[7] This premise is supported by the clinical observation that PFP typically is reproduced with activities that require quadriceps contraction (i.e. squatting, stair ascent/descent, etc). To test this hypothesis, we developed a patient specific, imaging based biomechanical model of the patellofemoral joint to quantify patellofemoral stress during functional tasks.[13] We were able to demonstrate that females with PFP exhibit higher patellofemoral stress during walking when compared to pain-free controls. Interestingly, the higher patellofemoral stress in the PFP group was the result of diminished contact area as opposed to an increase in the joint reaction force.[13] Based on these findings, we concluded that diminished contact area may be an important etiologic factor underlying PFP.

Evidence in support of the concept that reduced contact area may play contributory role with respect to elevated patellofemoral stress and PFP is provided by previous research evaluating the mechanism by which patellofemoral braces reduce patellofemoral symptoms.[21,23] Given the fact that kinematic MRI has revealed that patellofemoral bracing does not improve patella tracking under dynamic, loaded conditions,[22] we proposed that patellofemoral braces may achieve symptom reduction by increasing contact area. In theory, the compressive forces applied to the patella by means of sleeves and stabilizing straps may serve to better seat the patella in the femoral tochlea, thereby increasing contact area. We were able to demonstrate that application of a patellofemoral bracing resulted in significant increases in contact area (30-40%) without an appreciable change in patella alignment.[21] Importantly, this translated to a 27% reduction in patellofemoral stress during walking and a 56% reduction in pain.[23]

Over the past 5 years, our modeling efforts have expanded to examine the influence of excessive joint loading on patella cartilage stress. Using a subject-specific 3D model to quantify patellofemoral joint reaction forces,[2] and finite element methods to quantify stress,[9] we have been able to show that females with PFP exhibit elevated hydrostatic and shear stress in articular cartilage. We also have reported that females with PFP exhibit thinner cartilage and reduced deformational behavior following an acute bout of loading.[10] Given the cross-sectional nature of these studies however, it is not possible to ascertain if reduced cartilage thickness was a cause or an effect of high cartilage stress. However these findings suggest that elevated joint stress is associated with cartilage changes consistent with initial pathologic findings in the development of patellofemoral osteoarthritis.

Given the lack of nerve fibers, articular cartilage cannot be a source of PFP. However, subchondral bone is innervated and is thought to be the primary source of retropatellar pain. Ongoing research in our laboratory is focused on evaluating the transfer of stress from the articular cartilage to the subchondral bone. Preliminary findings are showing that persons with PFP and high cartilage stress also exhibit high bone stress.[14] We are now evaluating the responses of bone to abnormal loading including elevated patella water content (i.e. bone marrow edema) and the presence of bone marrow lesions.[15]

Given that elevated joint stress appears to underlie, at least in part, the development of PFP, it is important to identify the biomechanical factors that contribute to elevated patellofemoral stress. As mentioned above, stress is defined as force per unit area. As such, increased patellofemoral stress could be the result diminished contact area, elevated joint reaction force, or a combination of the two.

The factors that influence contact area are those that contribute to patella malalignment and/or maltracking. It is well established that patella tracking in non-weightbearing is dictated by bony structure, particularly the depth of the trochlear groove,[24] and the angle of inclination of the lateral anterior femoral condyle.[12] Conditions such as trochlear dysplasia (abnormal shape or depth of the trochlea) or patella alta (high riding patella) can lead to excessive lateral tilt and lateral displacement of the patella,[31] decreased contact area,[31] and a subsequent increase in patellofemoral stress.[32]

Historically, patella tracking has been viewed as the relative motion of the patella on a fixed femur. This assumption however is based on kinematic studies that were performed non-weightbearing or under conditions where the femur motion was constrained. Recent evidence from our group suggests that patellofemoral joint kinematics may be different during weightbearing tasks. For example, we have provided evidence that the primary contributor to lateral patella tilt and displacement during weightbearing is internal rotation of the femur underneath a stable patella.[25,29] These findings suggest that the control of femur rotation may be important in restoring normal patellofemoral joint kinematics. In addition, minimizing femoral rotation may impact patellofemoral joint stress as it has been shown that excessive internal rotation of the femur can result in decreased patellofemoral contact area and increased joint stress.[17]

Apart from the influence of diminished contact area on patellofemoral joint stress, a recent publication by our group has revealed that patient with PFP exhibit higher than normal laterally directed patellofemoral joint forces.[3] Importantly we identified that the main contributors to the lateral forces were frontal and transverse plane motions at the knee.[4] This lead to the conceptual framework of the dynamic quadriceps angle or Q-angle.[26] As the Q-angle reflects the frontal plane forces acting on the patella, frontal plane motion of the lower extremity would be expected to adversely affect patellofemoral joint loading. As noted in a previously published review article,[26] there are distal factors (i.e. those related to the foot & ankle) and proximal factors (i.e. those related to the hip & pelvis) that can influence the dynamic Q-angle.

With respect to the distal factors that can influence the patellofemoral joint, it is commonly believe that foot pronation and resulting tibia rotation contributes to PFP. This premise has formed the basis for the use of foot orthotics as a treatment for this condition. When relating excessive pronation to PFP however, an assumption is made that abnormal pronation results in excessive tibia internal rotation. This relationship however has been shown to be inconsistent at best.[28] More important is the fact that excessive tibia internal rotation caused by abnormal foot pronation would actually decrease the Q-angle as the tibial tuberosity would move medially.[26] Indeed, in-vitro studies have shown that tibia internal rotation has no influence on patellofemoral joint contact area or pressures.[18] Nonetheless, there is growing evidence that foot orthoses are efficacious for PFP, at least in the short-term (i.e. 6-8 weeks).[1,5] However the mechanism(s) by which these devices reduce PFP remain unclear.

With respect to proximal factors, excessive knee valgus resulting from hip adduction would be expected to have the largest influence on the dynamic Q-angle as this motion influences the frontal plane alignment of the lower extremity.[26] Excessive hip internal rotation also would contribute to an increase in the dynamic Q-angle however its influence on lower limb alignment would not be as great. Indeed, previous work by our group and others has shown that females with PFP exhibit greater degrees of hip adduction and internal rotation during dynamic tasks when compared to pain-free controls.[6,20,30,33]

There are an increasing number of studies suggesting that impaired hip strength (extensors, abductors and external rotators) may underlie the tendency of females with PFP to exhibit altered hip kinematics. In fact, a systematic review of the literature in this area concluded that there is strong evidence that these individuals exhibit impaired strength of the hip extensors, abductors, and external rotators.[27] From treatment standpoint, the focus on hip strength/control is logical from a biomechanical perspective as the control of hip rotation rotation can improve patella tracking (thereby improving contact area), and the control of hip adduction can reduce the laterally directed forces on the patellofemoral joint by minimizing the dynamic Q-angle. Indeed, clinical trials evaluating the influence of hip strength on pain and function in persons with PFP are emerging to support this premise.[8,11,16,19]

In summary, several important advances have emerged over the last decade that has advanced our understanding of the potential factors that may underlie PFP:

- Elevated patellofemoral stress appears to be an important biomechanical variable associated with PFP and perhaps PFJ osteoarthritis.
- The combination of reduced contact area and elevated joint reaction forces is most detrimental with respect to patellofemoral joint loading.
- There is evidence to suggest that in weightbearing, patellofemoral malalignment and/or maltracking may be the result of internal rotation of the femur as opposed to lateral tilt/displacement of the patella.

- The lateral forces acting on the patella are largely influenced by abnormal motions of the lower extremity.
- Compared to abnormal foot pronation, altered hip kinematics (i.e. excessive hip adduction and internal rotation) appear to have the greatest influence on the dynamic Q-angle.
- Individuals with PFP may benefit from interventions aimed at improving hip muscle performance.

Future work should be directed to understand whether hip strengthening is superior to traditional quadriceps strengthening for the treatment of PFP. Although not addressed specifically in this lecture, emerging research in the area of patellofemoral joint pathomechanics calls into question the practice of vastus medialis oblique (VMO) strengthening as the gold standard treatment for PFP. It is my hope that this keynote address will promote new ideas for future research and advancements in clinical practice.

References

1. Barton CJ, Menz HB, Crossley KM. Effects of prefabricated foot orthoses on pain and function in individuals with patellofemoral pain syndrome: a cohort study. *Phys Ther in Sport.* 2011;12:70-75.
2. Chen YJ, Scher I, Powers CM. Quantification of patellofemoral joint reaction forces during functional tasks: A subject specific, three dimensional model. *J Appl Biomech*. 2010;26:415-423.
3. Chen YJ, Powers CM. Comparison of three dimensional patellofemoral joint reaction forces in persons with and without patellofemoral pain. *J Appl Biomech* (in press)
4. Chen YJ, Powers CM. The dynamic Q-angle: A comparison of persons with and without patellofemoral pain. Proceedings of the *North American Congress on Biomechanics*. 2008 [Abstract]
5. Collins NJ, et al. Foot orthoses and physiotherapy in the treatment of patellofemoral pain syndrome: randomised clinical trial. *BMJ.* 2008;337:a1735.
6. Dierks TA, Manal KT, Hamill J, Davis IS. Proximal and distal influences on hip and knee kinematics in runners with patellofemoral pain during a prolonged run. *J Orthop Sports Phys Ther.* 2008;38:448-456.
7. Dye SF. The pathophysiology of patellofemoral pain: a tissue homeostasis perspective. *Clin Orthop Relat Res.* 2005;436:100-110.
8. Earl JE, Hoch AZ. A proximal strengthening program improves pain, function, and biomechanics in women with patellofemoral pain syndrome. *Am J Sports Med.* 2011;39:154-163.
9. Farrohki S, Keyak JH, Powers CM. Individuals with patellofemoral pain exhibit greater patellofemoral joint stress: A finite element analysis study. *Osteoarthritis & Cartilage*. 2011;19:287-294.
10. Farrohki S, Colletti PM, Powers CM. Differences in patella cartilage thickness, T_2 relaxation time and cartilage deformational behavior: A comparison of young females with and without patellofemoral pain. *Am J Sports Med*. 2011;39:384-391.

11. Fukada TY, Rossetto FM, Magalhaes E, Bryk FF, Lucareli PR, de Almeida Aparecida Carvalho N. Short term effects of hip abductor and lateral rotator strengthening in females with patellofemoral pain syndrome: A randomized controlled clinical trial. *J Orthop Sports Phys Ther*. 2010;40:736-742.
12. Harbaugh CM, Wilson NA, Sheehan FT. Correlating femoral shape with patellar kinematics in patients with patellofemoral pain. *J Orthop Res*. 2010;28:865-872.
13. Heino-Brechter JH, Powers CM. Patellofemoral stress during walking in persons with and without patellofemoral pain. *Med Sci Sports Exerc*. 2002;34:1582-1593.
14. Ho KY, Yang NH, Farrokhi S, Powers CM. The influence of patella cartilage thickness on patella bone stress in females with and without patellofemoral pain. Proceedings of the Annual Meeting of the American Society of Biomechanics. 2010 [Abstract]
15. Ho KY, Hu HH, Collett PM, Powers CM. Patella water content and bone marrow lesions in individuals with patellofemoral pain: Evaluation using Water-Fat MRI. Proceedings of the International Society of Magnetic Resonance in Medicine Fat-Water separation. 2012 [Abstract]
16. Khayambashi K, Mohammadkhani Z, Ghaznavi K, Lyle MA, Powers CM. The effects of isolated hip abductor and external rotator muscle strengthening on pain, health status, and hip strength in females with patellofemoral pain. *J Orthop Sports Phys Ther*. 2012;42:22-29.
17. Lee TQ, Anzel SH, Bennett KA, Pang D, Kim WC. The influence of fixed rotational deformities of the femur on the patellofemoral contact pressures in human cadaver knees. *Clin Orthop*. 1994;302:69-74.
18. Lee TQ, Morris G, Csintalan RP. The influence of tibial and femoral rotation on patellofemoral contact area and pressure. *J Orthop Sports Phys Ther*. 2003;33:686-693.
19. Nakagawa TH, Muniz TB, Baldon RM, Maciel D, de Menezes Reiff RB, Serrao FV. The effect of additional strengthening of hip abductor and lateral rotator muscles in patellofemoral pain syndrome: A randomized controlled pilot study. *Clin Rehab*. 2009;22:1051-1060.
20. Noehren B, Davis I. The effect of real-time gait retraining on hip kinematics, pain and function in subjects with patellofemoral pain syndrome. *Br J Sports Med.* 2011;45:691-696.
21. Powers CM, Ward SR, Chan L, Chen Y, Terk MR. The effect of bracing on patella alignment and patellofemoral joint contact area. *Med Sci Sports Exerc*. 2004;36:1226-1232,
22. Powers CM, Shellock FG, Beering TV, Garrido DE, Goldback RM, Molnar T. The effect of bracing on patellar kinematics in patients with patellofemoral pain. *Med Sci Sport Exerc*. 1999:31:1714-1720
23. Powers CM, Ward SR, Chen Y, Chan L, Terk MR. The effect of bracing on patellofemoral joint stress during free and fast walking. *Am J Sports Med*. 2004;32:224-231.
24. Powers CM. Patellar kinematics, Part II: The influence of the depth of the trochlear groove in subjects with and without patellofemoral pain. *Phys Ther*. 2000;80:965-973.
25. Powers CM, Ward SR, Fredericson M, Guillet M, Shellock FG. Patellofemoral kinematics during weightbearing and non-weightbearing knee extension in persons with patellar subluxation: A preliminary study. *J Orthop Sports Phys Ther.* 2003;33:677-685Ward SR, Terk MR, Powers CM. Patella alta: Association with patellofemoral alignment and changes in contact area during weight bearing. *J Bone & Joint Surg Am.* 2007; 89:1749-1755.
26. Powers CM. The influence of altered lower extremity kinematics on patellofemoral joint dysfunction: A theoretical perspective *J Orthop Sports Phys Ther*. 2003;33:639-646.

27. Prins MR, van der Wurff P. Females with patellofemoral pain syndrome have weak hip muscles. a systematic review. *Aust J Physiother.* 2009;55:9-15.
28. Reischl SF, Powers CM, Rao S, Perry J. The relationship between foot pronation and rotation of the tibia and femur during walking. *Foot and Ankle International.* 1999;20:513-520.
29. Souza RB, Draper CE, Fredericson M, Powers CM. Femur rotation and patellofemoral joint kinematics: A weight-bearing MRI analysis. *J Orthop Sports Phys Ther*. 2010;40:277-285.
30. Souza RB, Powers CM. Differences in hip kinematics, muscle strength, and muscle activation between subjects with and without patellofemoral pain. *J Orthop Sports Phys Ther.* 2009;39:12-19.
31. Ward SR, Terk MR, Powers CM. Patella alta: Association with patellofemoral alignment and changes in contact area during weight bearing. *J Bone & Joint Surg Am. 2007;*89:1749-1755.
32. Ward SR, Powers CM. The influence of patella alta on patellofemoral joint stress during normal and fast walking. *Clin Biomech*. 2004;19:1040-1047.
33. Willson JD, Davis IS. Lower extremity mechanics of females with and without patellofemoral pain across activities with progressively greater task demands. *Clin Biomech.* 2008;23:203-211.