Published in final edited form as:

Am J Sports Med. 2011 February ; 39(2): 384–391. doi:10.1177/0363546510381363.

Differences in Patellar Cartilage Thickness, Transverse Relaxation Time, and Deformational Behavior:

A Comparison of Young Women With and Without Patellofemoral Pain

Shawn Farrokhi, PT, PhD, DPT, Patrick M. Colletti, MD, and Christopher M. Powers, PT, PhD

Investigation performed at the Jacquelin Perry Musculoskeletal Biomechanics Research Laboratory, Division of Biokinesiology and Physical Therapy, University of Southern California, Los Angeles, California

Abstract

Background—The origin of patellofemoral pain (PFP) may be associated with the inability of the patellofemoral joint cartilage to absorb and distribute patellofemoral joint forces.

Hypothesis—When compared with a pain-free control group, young active women with PFP will demonstrate differences in their baseline patellar cartilage thickness and transverse (T2) relaxation time, as well as a less adaptive response to an acute bout of joint loading.

Study Design—Controlled laboratory study; Level of evidence, 3.

Methods—Ten women between the ages of 23 to 37 years with PFP and 10 sex-, age-, and activity-matched pain-free controls participated. Quantitative magnetic resonance imaging of the patellofemoral joint was performed at baseline and after participants performed 50 deep knee bends. Differences in baseline cartilage thickness and T2 relaxation time, as well as the postexercise change in patellar cartilage thickness and T2 relaxation time, were compared between groups.

Results—Individuals with PFP demonstrated reductions in baseline cartilage thickness of 14.0% and 14.1% for the lateral patellar facet and total patellar cartilage, respectively. Similarly, individuals with PFP exhibited significantly lower postexercise cartilage thickness change for the lateral patellar facet (2.1% vs 8.9%) and the total patellar cartilage (4.4% vs 10.0%) when compared with the control group. No group differences in baseline or postexercise change in T2 relaxation time were found.

Conclusion—The findings suggest that a baseline reduction in patellar cartilage thickness and a reduced deformational behavior of patellar cartilage following an acute bout of loading are associated with presence of PFP symptoms.

Keywords

cartilage thickness; transverse relaxation time; cartilage deformation

*Department of Physical Therapy, University of Pittsburgh, Pittsburgh, Pennsylvania. Keck School of Medicine, University of Southern California, Los Angeles, California. Jacquelin Perry Musculoskeletal Biomechanics Research Laboratory, Division of Biokinesiology and Physical Therapy, University of Southern California, Los Angeles, California.

The authors declared that they had no conflicts of interest in their authorship and publication of this contribution.

Patellofemoral pain (PFP) is one of the most common disorders of the knee, with as many as 22% of the general population reporting symptoms.³² Despite the high incidence of PFP, the pathophysiology of this disorder remains unclear. One hypothesis regarding the cause of PFP is related to the failure of the articular cartilage to adequately dissipate contact forces in response to patellofemoral joint loading.^{22,41} Because articular cartilage is aneural,³ changes in patellofemoral joint cartilage characteristics (ie, structural and material properties), as well as impaired deformational behavior, could affect the biomechanical load transfer through the articular cartilage, placing greater stress on the highly innervated subchondral bone.^{3,21,22}

From a mechanical perspective, altered patellar cartilage characteristics could play a significant role in the genesis of patellofemoral joint disorders. Because articular cartilage acts as a deformable medium, its load-bearing capacity is directly related to its thickness.⁴⁶ Patellar cartilage also has a high degree of compliance and permeability to fluid flow.²⁰ Thus, alterations in the biochemical balance of the tissue could impair its energy absorption capacity.

Quantitative in vivo investigations of the morphologic and biochemical properties of the articular cartilage can provide useful insight related to patellar cartilage health and dysfunction. It has been reported that quantitative imaging techniques are able to detect cartilage changes that reflect degenerative processes.^{11,13} For example, transverse (T2) relaxation time has been proposed as a noninvasive method to assess the mechanical properties of the articular cartilage in vivo.³⁶ The potential diagnostic value of T2 relaxation time is in its ability to detect early changes in cartilage properties, such as changes in the compressive stiffness of the tissue.^{30,40} Elevated T2 relaxation time has also been shown to be associated with cartilage damage and disease.

Aside from baseline cartilage properties (ie, thickness and T2 relaxation time), knowledge of the in vivo tissue behavior in response to loading is important to understanding cartilage health and pathologic abnormalities. Recent studies suggest that healthy human patellar cartilage deforms 2% to 3% during everyday weightbearing activities such as walking.¹⁴ Intense exercise has been reported to result in an additional 2% to 3% deformation beyond that encountered during normal daily activity.^{12,14,16} For example, Eckstein and colleagues¹⁸ reported a 6% reduction in patellar cartilage volume following 50 knee bends in healthy volunteers. However, performing 100 repetitions or multiple sets of 50 knee bends did not increase the magnitude of patellar cartilage deformation, suggesting that an optimal level of in vivo deformation exists for healthy tissue.¹⁷

A recent investigation of the patellar cartilage response to loading has provided evidence of reduced deformational behavior in the elderly.²⁷ Hudelmaier and colleagues²⁷ reported that patellar cartilage deformation after 30 knee bends was 2.6% and 2.2% in elderly women and men, respectively. This deformation was significantly lower than that observed in young women (4.5%) and young men (6.2%), leading the authors to theorize that cartilage deformation may be influenced by tissue material properties. The observation of a reduced cartilage deformation has important implications for cartilage biology; that is, a decrease in

mechanical stimulation of chondrocytes under physiologic loading conditions may be linked to decreases in proteoglycan synthesis and cartilage injury.^{4,45} To date, no study has compared differences in patellar cartilage deformation between individuals with PFP and those who are pain-free. It is conceivable that alterations in the deformational behavior of the patellar cartilage may be responsible for the activity-induced symptoms commonly reported in this patient population.

Apart from cartilage deformation, the interstitial fluid flow during physiologic loading has been suggested to be a potent regulator of the biosynthetic activity of chondrocytes, thus influencing cartilage tissue properties.^{28,50} To that end, T2 relaxation time has been suggested as a sensitive in vivo biomarker of cartilage interstitial fluid movement.^{34,35} Because the solid phase of the articular cartilage can be assumed as incompressible,³⁹ the morphologic changes of the tissue following a bout of loading could be attributed to the loss of interstitial fluid from its extracellular matrix.¹⁶ To date, no study has evaluated differences in T2 relaxation time of the patellar cartilage in young active women with PFP after an acute bout of loading.

The purpose of the current investigation was to compare patellar cartilage thickness and T2 relaxation time between a group of young active women with PFP and a group of age-, height-, weight-, and activity-matched pain-free controls. A second objective of our study was to evaluate whether the patellar cartilage of individuals with PFP demonstrates a less adaptive response to an acute bout of lower extremity exercise, when compared those who are pain-free. We hypothesized that women with PFP would demonstrate decreased patellar cartilage thickness, along with an elevated cartilage T2 relaxation time, when compared with a pain-free control group. We also hypothesized that individuals with PFP would demonstrate less patellar cartilage deformation as well as less change in cartilage T2 relaxation time postexercise.

MATERIALS AND METHODS

Participants

Twenty participants were recruited for this study: 10 women with PFP constituted the experimental group, whereas 10 pain-free women served as the control group (Table 1). Individuals with PFP were admitted to the study if their pain originated from behind the patella (ie, retropatellar pain). Participants were accepted if they reported an insidious onset of symptoms of at least 3 months in duration and no history of previous trauma or subluxation. Before participation, all participants were informed of the nature of the study and signed a human subjects consent form approved by the Health Sciences Institutional Review Board of the University of Southern California.

Participants were screened through physical examination to rule out evidence of large knee effusion, crepitus, and peripatellar pain. This process included palpation of the soft tissues around the patellofemoral joint to identify the location of pain. If the source of pain was localized to the quadriceps tendon, patellar tendon, patella bursa, patella fat pad, tibiofemoral joint, or the lateral and medial menisci, the participant was disqualified from the study. The screening process also included a functional assessment of activities

commonly associated with PFP (squatting, stair climbing, isometric quadriceps contraction). Participants were included in the study if they reported pain of at least 3 out of 10 (based on a visual analog scale) with one or more of the aforementioned functional tasks. The PFP participants were also excluded from participation if they reported having any of the following: (1) history of knee surgery, (2) history of traumatic patellar dislocation, (3) neurologic involvement that would influence performance of various functional activities, or (4) implanted biological devices that could interact with the magnetic field.

Participants in the control group were age, height, weight, and activity matched (610%) to those in the PFP group. Participants' physical activity levels were determined based on the World Health Organization's Global Physical Activity Questionnaire. This questionnaire has been reported to provide a valid and reliable estimate of physical activity.² Participant selection in the control group was based on the same criteria as the experimental group except that the former had no history or diagnosis of knee disorder, trauma, or pain with the activities listed above. Participants were recruited from the University of Southern California's campus community through advertisement flyers and personal communication with the primary investigator.

Image Acquisition and Analysis

Imaging was performed with a 3.0-T magnetic resonance (MR) scanner with an 8-channel knee coil (General Electric Healthcare, Milwaukee, Wisconsin). Axial images were obtained with a fat-suppressed 3-dimensional fast spoiled gradient-echo sequence with the following parameters: repetition time, 16.3 milliseconds; echo time, 2.8 milliseconds; flip angle, 10°; matrix, 512 × 512; field of view, 16 × 16 cm; slice thickness, 2 mm; scan time, 1 minute, 59 seconds. In addition, T2 relaxation times were obtained from a 9-section, 4-echo sequence with a repetition time of 1800 milliseconds and 4 echo times evenly spaced over a range of 20 to 80 milliseconds (matrix, 384 × 192; field of view, 16 × 16 cm; slice thickness, 4.0 mm; intersection gap, 2.0 mm; scan time, 3 minutes 14 seconds). For all scans, participants were positioned supine with their knees fully extended and quadriceps relaxed.

Before imaging, participants were brought to the imaging center and instructed to lie supine (ie, non weight bearing) for 1 hour. This was done to control for load-induced compression of the articular cartilage.¹² Only the painful side was imaged in the PFP group. The side evaluated in the control participants was matched to that of their counterparts in the PFP group. Imaging was performed before exercise (baseline) and immediately after each volunteer performed 50 deep knee bends (post exercise). Participants performed the knee bends within a period of 100 seconds (0.5 Hz) while wearing a weighted vest equal to 25% of their body weight. Under the visual monitoring of the principal investigator, participants performed the knee bends with heels resting on the floor, to a depth where the thighs were parallel to the floor (approximately 110° of knee flexion). Immediately after completion of the 50 knee bends, participants were repositioned within the scanner, and the follow-up scans were obtained. A post exercise scan was performed within 2 minutes of completing the exercise session.

With use of a commercial software package (Sliceomatic, Tomovision, Montreal, Quebec, Canada), the axial MR images were manually segmented to distinguish the patellar cartilage

from the surrounding bone and soft tissues (Figure 1A). With a custom MATLAB code (Mathworks, Natick, Massachusetts), pixels representing the cartilage surfaces were identified, and the mean thickness of the patellar cartilage was then determined as the average length of the perpendicular vectors connecting the pixels representing the subchondral bone surface to the joint surface (Figure 1B). T2 relaxation times were calculated from the axial multiecho images of the patella using a linear least squares curve fitting routine (ImageJ software, National Institutes of Health, Bethesda, Maryland). The analysis was performed on a pixel-by-pixel basis (Figure 2).

T2 relaxation times of the pixels representing the major weight bearing portion of the patellar cartilage plate were averaged from the middle 3 axial slices of the patella (ie, the image containing the largest patella cross section and the slices immediately superior and inferior).

The post exercise variables of interest, including the percentage change in patellar cartilage thickness and T2 relaxation time, were quantified with the following equation: percentage change = [(baseline 2 post exercise)/baseline] 3 100. In addition, the baseline and post exercise change in cartilage thickness and T2 relaxation time were evaluated for the medial and lateral facets. The median ridge of the patella served as the point of separation between the medial and lateral facets.

A single investigator performed all MR measurements. To determine whether reliable data could be obtained with respect to cartilage thickness and T2 relaxation time, measurements were repeated on 5-image sets. Repeated measurements were made on 2 days at least 7 days apart. The coefficient of variation and the standard error of measurement for each variable are reported in Table 2.

Differences in the baseline patellar cartilage thickness and T2 relaxation time, as well as the post exercise change in cartilage thickness and T2 relaxation time, were compared between groups with independent-sample t tests. All analyses were performed with SPSS 15.0 using a significant level of $P < .05$.

RESULTS

Baseline Patellar Cartilage Thickness

Compared with the control group, participants with PFP demonstrated statistically significant reductions in total patellar cartilage thickness (2.37 mm vs 2.76 mm, $P = .04$; Table 3) and lateral patellar facet cartilage thickness (2.40mmvs 2.79 mm, $P = .02$; Table 3). No significant differences were observed for the medial facet cartilage thickness. Baseline Patellar Cartilage T2 Relaxation Time No significant group differences were observed for the baseline T2 relaxation time of the total patellar cartilage(Table 3). In addition, T2 relaxation time did not differ between groups for the lateral and medial facets.

Post exercise Change in Patellar Cartilage Thickness

When compared with the control group, participants with PFP demonstrated a significantly lower percentage change in cartilage thickness for the total patellar cartilage (4.44% vs

10.00%, $P < .01$; Figure 3) and the lateral patellar facet cartilage (2.10% vs 8.91%, $P < .01$; Figure 3). No difference in the percentage change in cartilage thickness was found for the medial patellar facet.

Post exercise Change in Patellar Cartilage T2 Relaxation Time

No significant group differences were observed for the post exercise percentage change in T2 relaxation time of the total patellar cartilage. In addition, the percentage change in T2 relaxation time did not differ between groups for the lateral and medial patellar facet cartilage (Figure 4).

DISCUSSION

To absorb and distribute the joint reaction forces, which can approximate several times body weight,^{1,44} the patellar cartilage must maintain a unique set of morphologic features and mechanical properties. The first objective of the current study was to test the hypothesis that young women with PFP exhibit reductions in patellar cartilage thickness, along with an increased T2 relaxation time, when compared with a group of age-, height-, weight-, and activity-matched controls. Consistent with our hypothesis, participants with PFP demonstrated significant reductions in average patellar cartilage thickness when compared with those who were pain free. However, no differences in T2 relaxation times were observed between the 2 groups.

The second objective of our study was to evaluate whether the patellar cartilage of individuals with PFP demonstrates a less adaptive response to an acute bout of lower extremity exercise when compared with that of those who are pain-free. Consistent with our hypothesis, women with PFP demonstrated significantly less cartilage deformation than the control group, as reflected by less pronounced changes in the post exercise patellar cartilage thickness. Contrary to our hypothesis, however, no group differences in post exercise T2 relaxation time change were identified.

Differences in Baseline Patellar Cartilage Characteristics

Although changes in patellar cartilage thickness have been reported with advancing age^{24,27,49} and as a hallmark of patellofemoral joint osteoarthritis,^{5,8} the possible role of such morphologic changes with respect to the causes of PFP has not been studied in detail. In general, articular cartilage plays an important role in the distribution of contact loads within the patellofemoral joint. To that end, it has been suggested that thinner cartilage experiences higher peak stresses when compared with thicker cartilage under the same loading conditions.³³ In our study, we observed an average reduction of 14% in total patellar cartilage thickness for participants in the PFP group. Specifically, the reduction in cartilage thickness in the PFP group was the result of thinner cartilage on the lateral patellar facet, given that no differences in medial facet cartilage thickness were observed. We believe that the observed differences in cartilage thickness in the PFP group are relevant because it has been reported that a 10% reduction in cartilage thickness can result in an 8% to 10% increase in peak cartilage stress.³³ It is conceivable that higher stresses resulting from the

diminished cartilage thickness may contribute to the propensity for retropatellar pain during various weight bearing activities in this population.

Our finding of reduced cartilage thickness in our PFP group is inconsistent with the results of Draper and colleagues,⁹ who reported no differences in mean patellar cartilage thickness between women with PFP and pain-free controls. However, it is interesting to note that the decreased cartilage thickness observed in our females with PFP was similar in magnitude to that of the male participants with PFP reported by Draper and colleagues.⁹ One possible explanation for the inconsistency between the 2 investigations may be related to the fact that the control participants in the current study were matched on the basis of a set of stringent a priori criteria known to influence cartilage morphologic characteristics. For example, patellar cartilage thickness can be influenced by age,^{24,27} body mass index,^{5,25} and level of physical activity.^{23,25,49} Failure to control for these factors may limit the ability to detect morphologic differences between groups. Furthermore, the current study evaluated cartilage thickness across the entire patellar surface, as opposed to distinct locations. Given that the entire patellar cartilage surface is loaded as the knee moves through its full range of motion, we thought that assessment of the entire retropatellar surface would provide a more comprehensive analysis of patellar cartilage changes.

The development of quantitative MR imaging techniques to assess changes in the extracellular matrix of articular cartilage provides a unique opportunity to noninvasively evaluate the biomechanical environment of joints. T2 relaxation time has been shown to be a sensitive parameter for the evaluation of cartilage water and collagen content changes as well as tissue anisotropy.³⁶ On the basis of the observation of elevated T2 relaxation times in the presence of cartilage damage,^{10,37} we hypothesized that the patellar cartilage of participants with PFP would exhibit elevated T2 relaxation times when compared with the control group. However, our results revealed that the baseline patellar cartilage T2 relaxation times were similar between the 2 groups. The lack of group differences in T2 relaxation time suggests that alterations in cartilage morphologic characteristics may precede changes in cartilage water content in relatively young persons with no clinical evidence of osteoarthritis (ie, crepitus or effusion). This finding is in contrast to what has been reported in older individuals with end-stage osteoarthritis.^{10,36} Alternatively, it could be argued that T2 relaxation time may not be sensitive enough to detect early cartilage pathologic changes owing to its limited dynamic range.⁴³ Because loss of proteoglycans from the extracellular matrix is one of the earliest events in the development of cartilage degeneration,⁴⁸ future studies should consider imaging techniques that provide information on the proteoglycan content of the cartilage (ie, T1ρ-weighted imaging).

Differences in Patellar Cartilage Deformation

The deformational behavior of the patellar cartilage in response to lower extremity exercise has been reported to be 6% in healthy volunteers.^{16,18} In the current study, we observed patellar cartilage thickness changes of approximately 10% in our pain-free participants. The greater patellar cartilage deformation observed in our control group compared with that of previous studies may be explained in 2 ways. First, as opposed to previous investigations that reported average patellar cartilage deformation for men and women combined, our study

included only women. Thus, the greater patellar cartilage deformations reported in the current study may reflect the known sex differences in cartilage relaxation properties in women.^{19,31} Second, while performing the deep knee bends, the participants in our study wore a weighted vest equivalent to 25% of body weight. Because patellar cartilage deformation is proportional to loading,¹⁵ it is conceivable that the higher loading condition utilized in the current study could have been responsible for greater observed changes in post exercise patellar cartilage thickness.

When compared with the control group, participants with PFP demonstrated a lower post exercise percentage change in their patellar cartilage thickness. On average, persons with PFP exhibited a 4.4% change in their post exercise patellar cartilage thickness. The deformational behavior observed in our relatively young PFP group is similar to what has been reported in older adults.²⁷ Because the rates of cartilage morphologic change and fluid flux are highly correlated with the amount of deformation,^{16,17} the stiffer patellar cartilage behavior in our PFP participants may be indicative of differences in cartilage material properties. This observation has potential implications with regard to the causes of PFP, given that increased cartilage stiffness has been associated with elevations in the peak cartilage stress.²⁶ It is conceivable that higher stresses resulting from the reduced deformational behavior of the articular cartilage may contribute to activity-induced retropatellar pain commonly observed in this population.

To evaluate whether post exercise patellar cartilage deformation was associated with the reduced baseline cartilage thickness, a post hoc analysis was performed. Results revealed no association between the baseline total patellar cartilage thickness and the change in total cartilage thickness after exercise for both groups combined ($r = .04$, $P = .86$). Similarly, baseline lateral and medial patellar facet cartilage thickness was not associated with post exercise changes in lateral facet cartilage thickness ($r = 2.28$, $P = .23$) and medial facet cartilage thickness ($r = 2.08$, $P = .74$). As such, the amount of cartilage deformation after exercise cannot be explained by the initial thickness of the patellar cartilage.

Despite a significant difference in the percentage change in cartilage thickness between groups, no differences were observed in the percentage change in T2 relaxation time. This finding was unexpected because it has been reported that cartilage deformation reflects a net loss of fluid from the cartilage tissue.¹⁷ That the control group demonstrated a greater percentage change in cartilage thickness without a concurrent greater percentage change in T2 relaxation time suggests that the relative rate of cartilage fluid flux was comparable between the 2 groups. Note, however, that the current study evaluated the residual change in T2 relaxation time after exercise as opposed to the actual change that would occur owing to joint loading during exercise. Given that the post loading scans were obtained several minutes after completion of the deep knee bends, it is unclear whether the rate of fluid reuptake after exercise may have had an influence on the reported post exercise values. Future studies should consider evaluating changes in the T2 relaxation time during loaded conditions to better describe the deformational behavior of patellar cartilage in response to loading.

Study Limitations

With respect to the findings of the current study, several inherent limitations must be taken into account. First, unavoidable deviations from orthogonality in the axial plane images may have produced small out-of-plane variations in our cartilage thickness measurements. However, every effort was made to visually align the images perpendicular to the joint surface during MR acquisition. Although minor variations in the T2 values may have occurred owing to the collagen fibril anisotropy with respect to the main magnetic field (ie, magic angle effect),³⁶ it is unlikely that the “magic angle effect” accounted for the lack of group differences in patellar cartilage T2 relaxation time, given that the influence of cartilage orientation has been reported to be relatively small with respect to this parameter.³⁸

Another limitation of our study was the use of a 4-echo sequence to assess T2 relaxation times. Future investigations should consider using a higher number of echo times to improve accuracy of this measure. In addition, the fact that we evaluated T2 on only 3 slices as opposed to the entire articular surface may explain discrepancies with previous studies that reported changes in T2 relaxation times post exercise. Finally, our findings may not be generalized to the entire PFP population, because our study included only a subset of patients with retropatellar pain based on a set of stringent criteria. Patellofemoral symptoms will vary considerably in intensity and location depending on the duration of symptoms and the structures involved.⁴² As such, our results may be relevant to only a specific subgroup of patients.

CONCLUSION

Women with PFP exhibited significant reductions in patellar cartilage thickness and less post exercise patellar cartilage deformation when compared with pain-free controls. In light of these findings, it is reasonable to assume that the observed differences in the PFP group may reflect differences in the structural and material properties of patellar cartilage in this population. We believe that the finding of thinner patellar cartilage in the presence of PFP symptoms is important because reductions in cartilage thickness are commonly considered the initial pathologic findings in development of osteoarthritis.^{6,7,40,41} In addition, a long term history of PFP has been linked to a higher incidence of patellofemoral joint osteoarthritis in older adults,⁴⁷ suggesting that the presence of PFP symptoms may be an indicator of abnormal patellofemoral joint loading and cartilage changes over one's lifetime. Our findings support the need for interventions aimed at improving patellofemoral joint mechanics and thus potentially decreasing the rate of cartilage changes in persons with PFP.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

ACKNOWLEDGMENT

This study was approved by the Health Sciences Institutional Review Board, University of Southern California, Los Angeles, California. We thank Samuel Valencerina and Adriane Harris for their technical support with the image acquisition portion of this study. Financial support for this investigation was provided by Promotion of Doctoral Studies level I and II awards from the Foundation for Physical Therapy. The funding source had no role in the study design, data collection, analysis, or writing of this article.

REFERENCES

1. Ahmed AM, Burke DL, Yu A. In-vitro measurement of static pressure distribution in synovial joints: part II. Retropatellar surface. *J Biomech Eng.* 1983; 105(3):226–236. [PubMed: 6632824]
2. Armstrong T, Bull F. Development of the World Health Organization Global Physical Activity Questionnaire (GPAQ). *J Public Health.* 2006; 14:66–70.
3. Biedert RM, Sanchis-Alfonso V. Sources of anterior knee pain. *Clin Sports Med.* 2002; 21(3):335–347. [PubMed: 12365231]
4. Buschmann MD, Gluzband YA, Grodzinsky AJ, Hunziker EB. Mechanical compression modulates matrix biosynthesis in chondrocyte/agarose culture. *J Cell Sci.* 1995; 108(pt 4):1497–1508. [PubMed: 7615670]
5. Cicuttini F, Wluka A, Wang Y, Stuckey S. The determinants of change in patella cartilage volume in osteoarthritic knees. *J Rheumatol.* 2002; 29(12):2615–2619. [PubMed: 12465162]
6. Cicuttini FM, Wang YY, Forbes A, Wluka AE, Glisson M. Comparison between patella cartilage volume and radiological assessment of the patellofemoral joint. *Clin Exp Rheumatol.* 2003; 21(3): 321–326. [PubMed: 12846050]
7. Cicuttini FM, Wluka AE, Hankin J, Stuckey S. Comparison of patella cartilage volume and radiography in the assessment of longitudinal joint change at the patellofemoral joint. *J Rheumatol.* 2004; 31(7):1369–1372. [PubMed: 15229959]
8. Ding C, Garner P, Cicuttini F, Scott F, Cooley H, Jones G. Knee cartilage defects: association with early radiographic osteoarthritis, decreased cartilage volume, increased joint surface area and type II collagen breakdown. *Osteoarthritis Cartilage.* 2005; 13(3):198–205. [PubMed: 15727885]
9. Draper CE, Besier TF, Gold GE, et al. Is cartilage thickness different in young subjects with and without patellofemoral pain? *Osteoarthritis Cartilage.* 2006; 14(9):931–937. [PubMed: 16647278]
10. Dunn TC, Lu Y, Jin H, Ries MD, Majumdar S. T2 relaxation time of cartilage at MR imaging: comparison with severity of knee osteoarthritis. *Radiology.* 2004; 232(2):592–598. [PubMed: 15215540]
11. Eckstein F, Charles HC, Buck RJ, et al. Accuracy and precision of quantitative assessment of cartilage morphology by magnetic resonance imaging at 3.0T. *Arthritis Rheum.* 2005; 52(10): 3132–3136. [PubMed: 16200592]
12. Eckstein F, Faber S, Muhlbauer R, et al. Functional adaptation of human joints to mechanical stimuli. *Osteoarthritis Cartilage.* 2002; 10(1):44–50. [PubMed: 11795982]
13. Eckstein F, Glaser C. Measuring cartilage morphology with quantitative magnetic resonance imaging. *Semin Musculoskelet Radiol.* 2004; 8(4):329–353. [PubMed: 15643573]
14. Eckstein F, Hudelmaier M, Putz R. The effects of exercise on human articular cartilage. *J Anat.* 2006; 208(4):491–512. [PubMed: 16637874]
15. Eckstein F, Lemberger B, Gratzke C, et al. In vivo cartilage deformation after different types of activity and its dependence on physical training status. *Ann Rheum Dis.* 2005; 64(2):291–295. [PubMed: 15647438]
16. Eckstein F, Lemberger B, Stammberger T, Englmeier KH, Reiser M. Patellar cartilage deformation in vivo after static versus dynamic loading. *J Biomech.* 2000; 33(7):819–825. [PubMed: 10831756]
17. Eckstein F, Tieschky M, Faber S, Englmeier KH, Reiser M. Functional analysis of articular cartilage deformation, recovery, and fluid flow following dynamic exercise in vivo. *Anat Embryol (Berl).* 1999; 200(4):419–424. [PubMed: 10460479]
18. Eckstein F, Tieschky M, Faber SC, et al. Effect of physical exercise on cartilage volume and thickness in vivo: MR imaging study. *Radiology.* 1998; 207(1):243–248. [PubMed: 9530322]
19. Felson DT, Nevitt MC. Estrogen and osteoarthritis: how do we explain conflicting study results? *Prev Med.* 1999; 28(5):445–448. [PubMed: 10329332]
20. Froimson MI, Ratcliffe A, Gardner TR, Mow VC. Differences in patellofemoral joint cartilage material properties and their significance to the etiology of cartilage surface fibrillation. *Osteoarthritis Cartilage.* 1997; 5(6):377–386. [PubMed: 9536286]

21. Fulkerson, JP.; Buuck, DA. Disorders of the Patellofemoral Joint. Lippincott Williams & Wilkins; Philadelphia, PA: 2004.
22. Goodfellow J, Hungerford DS, Woods C. Patello-femoral joint mechanics and pathology: 2. Chondromalacia patellae. J Bone Joint Surg Br. 1976; 58(3):291–299. [PubMed: 956244]
23. Hanna F, Teichtahl AJ, Bell R, et al. The cross-sectional relationship between fortnightly exercise and knee cartilage properties in healthy adult women in midlife. Menopause. 2007; 14(5):830–834. [PubMed: 17413649]
24. Hanna F, Wluka AE, Ebeling PR, O'Sullivan R, Davis SR, Cicuttini FM. Determinants of change in patella cartilage volume in healthy subjects. J Rheumatol. 2006; 33(8):1658–1661. [PubMed: 16881121]
25. Hanna FS, Bell RJ, Davis SR, et al. Factors affecting patella cartilage and bone in middle-aged women. Arthritis Rheum. 2007; 57(2):272–278. [PubMed: 17330276]
26. Huber-Betzer H, Brown TD, Mattheck C. Some effects of global joint morphology on local stress aberrations near imprecisely reduced intra-articular fractures. J Biomech. 1990; 23(8):811–822. [PubMed: 2384493]
27. Hudelmaier M, Glaser C, Hohe J, et al. Age-related changes in the morphology and deformational behavior of knee joint cartilage. Arthritis Rheum. 2001; 44(11):2556–2561. [PubMed: 11710712]
28. Kim YJ, Bonassar LJ, Grodzinsky AJ. The role of cartilage streaming potential, fluid flow and pressure in the stimulation of chondrocyte biosynthesis during dynamic compression. J Biomech. 1995; 28(9):1055–1066. [PubMed: 7559675]
29. Kujala UM, Jaakkola LH, Koskinen SK, Taimela S, Hurme M, Nelimarkka O. Scoring of patellofemoral disorders. Arthroscopy. 1993; 9(2):159–163. [PubMed: 8461073]
30. Lammentausta E, Kiviranta P, Nissi MJ, et al. T2 relaxation time and delayed gadolinium-enhanced MRI of cartilage (dGEMRIC) of human patellar cartilage at 1.5 T and 9.4 T: Relationships with tissue mechanical properties. J Orthop Res. 2006; 24(3):366–374. [PubMed: 16479569]
31. Larbre JP, Da Silva JA, Moore AR, James IT, Scott DL, Willoughby DA. Cartilage contribution to gender differences in joint disease progression: a study with rat articular cartilage. Clin Exp Rheumatol. 1994; 12(4):401–408. [PubMed: 7955604]
32. Levine J. Chondromalacia patellae. Phys Sportsmed. 1979; 7:41–49.
33. Li G, Lopez O, Rubash H. Variability of a three-dimensional finite element model constructed using magnetic resonance images of a knee for joint contact stress analysis. J Biomech Eng. 2001; 123(4):341–346. [PubMed: 11563759]
34. Liess C, Lusse S, Karger N, Heller M, Gluer CC. Detection of changes in cartilage water content using MRI T2-mapping in vivo. Osteoarthritis Cartilage. 2002; 10(12):907–913. [PubMed: 12464550]
35. Lusse S, Claassen H, Gehrke T, et al. Evaluation of water content by spatially resolved transverse relaxation times of human articular cartilage. Magn Reson Imaging. 2000; 18(4):423–430. [PubMed: 10788720]
36. Mosher TJ, Dardzinski BJ. Cartilage MRI T2 relaxation time mapping: overview and applications. Semin Musculoskelet Radiol. 2004; 8(4):355–368. [PubMed: 15643574]
37. Mosher TJ, Dardzinski BJ, Smith MB. Human articular cartilage: influence of aging and early symptomatic degeneration on the spatial variation of T2—preliminary findings at 3 T. Radiology. 2000; 214(1):259–266. [PubMed: 10644134]
38. Mosher TJ, Smith H, Dardzinski BJ, Schmithorst VJ, Smith MB. MR imaging and T2 mapping of femoral cartilage: in vivo determination of the magic angle effect. AJR Am J Roentgenol. 2001; 177(3):665–669. [PubMed: 11517068]
39. Mow VC, Holmes MH, Lai WM. Fluid transport and mechanical properties of articular cartilage: a review. J Biomech. 1984; 17(5):377–394. [PubMed: 6376512]
40. Nieminen MT, Toyra J, Laasanen MS, Silvennoinen J, Helminen HJ, Jurvelin JS. Prediction of biomechanical properties of articular cartilage with quantitative magnetic resonance imaging. J Biomech. 2004; 37(3):321–328. [PubMed: 14757451]
41. Outerbridge RE. The etiology of chondromalacia patellae. J Bone Joint Surg Br. 1961; 43:752–757. [PubMed: 14038135]

42. Outerbridge RE, Dunlop JA. The problem of chondromalacia patellae. Clin Orthop Relat Res. 1975; 110:177–196. [PubMed: 1098819]
43. Regatte RR, Akella SV, Lonner JH, Kneeland JB, Reddy R. T1rho relaxation mapping in human osteoarthritis (OA) cartilage: comparison of T1rho with T2. J Magn Reson Imaging. 2006; 23(4): 547–553. [PubMed: 16523468]
44. Reilly DT, Martens M. Experimental analysis of the quadriceps muscle force and patello-femoral joint reaction force for various activities. Acta Orthop Scand. 1972; 43(2):126–137. [PubMed: 5079747]
45. Sah RL, Kim YJ, Doong JY, Grodzinsky AJ, Plaas AH, Sandy JD. Biosynthetic response of cartilage explants to dynamic compression. J Orthop Res. 1989; 7(5):619–636. [PubMed: 2760736]
46. Simon WH. Scale effects in animal joints: I. Articular cartilage thickness and compressive stress. Arthritis Rheum. 1970; 13(3):244–256. [PubMed: 5423816]
47. Utting MR, Davies G, Newman JH. Is anterior knee pain a predisposing factor to patellofemoral osteoarthritis? Knee. 2005; 12(5):362–365. [PubMed: 16146626]
48. Wheaton AJ, Borthakur A, Dodge GR, Kneeland JB, Schumacher HR, Reddy R. Sodium magnetic resonance imaging of proteoglycan depletion in an in vivo model of osteoarthritis. Acad Radiol. 2004; 11(1):21–28. [PubMed: 14746398]
49. Wijayaratne SP, Teichtahl AJ, Wluka AE, et al. The determinants of change in patella cartilage volume: a cohort study of healthy middle-aged women. Rheumatology. 2008; 47(9):1426–1429. [PubMed: 18641040]
50. Yellowley CE, Jacobs CR, Li Z, Zhou Z, Donahue HJ. Effects of fluid flow on intracellular calcium in bovine articular chondrocytes. Am J Physiol. 1997; 273(1, pt 1):C30–C36. [PubMed: 9252439]

Figure 1.

Quantitative magnetic resonance imaging of the patella showing cartilage segmentation (A) (green, lateral facet; blue, medial facet) of the patellar cartilage and thickness measurements (B) of the patellar cartilage, represented as the average per-pendicular distance of vectors between the subchondral bone and the cartilage surface. The red line indicates the separation between the medial and lateral facets at the median ridge.

Figure 2.
A representative multiecho image (left) and a color-scale T2 relaxation time map (right) of a control participant.

Figure 3. Mean percentage changes in patellar cartilage thickness after exercise. Asterisk (*) denotes statistically significant differences ($P < .05$) from the control group. PFP, patellofemoral pain.

Figure 4.

Mean percentage changes in patellar cartilage T2 relaxation time after exercise. PFP, patellofemoral pain.

TABLE 1

Patients' Characteristics

	Patellofemoral Pain Group (n, 10)	Control (n, 10)	<i>P</i>
Age, y	27.7 ± 4.3	27.0 ± 4.4	.72
Height, m	1.7 ± 0.1	1.6 ± 0.1	.53
Weight, kg	63.3 ± 8.4	61.9 ± 8.7	.72
Activity level, MET.min/week	2804.0 ± 1830.1	2564.0 ± 1900.1	.77
Anterior Knee Pain Scale ^a	73.8 ± 10.5		
Duration of patellofemoral pain symptoms, years	7.3 ± 3.4		

^a A score of 100 on the Anterior Knee Pain Scale indicates no anterior knee pain or disability.²⁹

TABLE 2

Coefficient of Variation and the Standard Error of Measurement for Cartilage Thickness and T2 Relaxation Time Variables

	Lateral Facet	Medial Facet	Total
Patellar cartilage thickness			
Coefficient of variation	.026	.013	.018
Standard error of measurement	.012	.011	.018
Patellar cartilage T2 relaxation time			
Coefficient of variation	.014	.018	.013
Standard error of measurement	.159	.216	.294

TABLE 3

Comparison of Baseline and Postexercise Patellar Cartilage Thickness and T2 Relaxation Time Between Groups^a

	Baseline		Postexercise		Percentage Change	
	PFP	Control	PFP	Control	PFP	Control
Patellar cartilage thickness, mm						
Lateral facet	2.40 ± 0.32 ^b	2.79 ± 0.36	2.35 ± 0.32	2.54 ± 0.37	-2.10 ± 3.99 ^b	-8.91 ± 4.14
Medial facet	2.33 ± 0.39	2.72 ± 0.57	2.18 ± 0.42	2.43 ± 0.58	-6.65 ± 5.41	-10.97 ± 7.33
Total	2.37 ± 0.33 ^b	2.76 ± 0.43	2.27 ± 0.36	2.48 ± 0.46	-4.44 ± 3.27 ^b	-10.00 ± 4.18
Patellar cartilage T2 relaxation time, ms						
Lateral facet	32.81 ± 1.33	32.46 ± 2.70	32.17 ± 1.71	32.34 ± 2.37	-1.92 ± 6.25	-0.38 ± 4.75
Medial facet	31.59 ± 1.96	30.80 ± 1.80	31.98 ± 2.31	31.27 ± 1.90	1.25 ± 6.25	1.50 ± 5.75
Total	32.50 ± 1.37	31.78 ± 2.22	31.76 ± 1.75	31.86 ± 2.31	-2.25 ± 5.50	0.25 ± 4.02

^aPFP, patellofemoral pain.

^b $P < .05$.