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Patellofemoral joint contact area increases with knee flexion and weight-bearing

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Abstract

Patellofemoral pain is a common and debilitating disorder. Elevated cartilage stress of the patellofemoral joint is hypothesized to play a role in the onset of pain. Estimating cartilage stress requires accurate measurements of contact area. The purpose of this study was to estimate patellofemoral joint contact areas in a group of healthy, pain-free subjects during upright, weight-bearing conditions. Sixteen subjects (8 female, 8 male) were scanned in a GE Signa SP open configuration MRI scanner, which allowed subjects to stand or squat while reclining 25° from vertical with the knee positioned at 0°, 30°, or 60° of flexion. A custom-built backrest enabled subjects to be scanned without motion artifact in both weight-bearing (0.45 body weight per leg) and reduced loading conditions ('unloaded' at 0.15 body weight) at each knee flexion posture. Male subjects displayed mean unloaded patellofemoral joint contact areas of 210, 414, and 520 mm^2 at 0°, 30° and 60° of knee flexion, respectively. Female subjects' unloaded contact areas were similar at full extension (0°), but significantly smaller at 30° and 60° ($p < 0.01$), with mean values of 269 and 396 mm^2, respectively. When normalized by patellar dimensions (height × width), contact areas were not different between genders. Under weight-bearing conditions, contact areas increased by an average of 24% ($p < 0.05$). This study highlights the differences in patellofemoral joint contact area between gender, knee flexion postures, and physiologic loading conditions.

Keywords: Contact area; MRI; Cartilage; Patellofemoral joint

Introduction

Elevated cartilage stress has the potential to increase subchondral bone stress and is a plausible cause of pain in the patellofemoral joint. Elevated cartilage stress is also likely to play a role in chondromalacia patellae and long-term cartilage degeneration [9,15]. Cartilage stress is influenced by the joint contact force, the contact area, and the thickness and material properties of the articular cartilage. To test the hypothesis that pain is related to elevated cartilage stress requires accurate measurement of patellofemoral joint contact area under physiologic loading conditions.

Estimates of patellofemoral joint contact area have been made previously using pressure-sensitive film and cadaveric specimens [4,5,12,13,16,18]. These experiments provided valuable information regarding the mechanics of the patellofemoral joint and showed that contact area generally increases with knee flexion as the patella shifts distally in the trochlear groove. Contact area increases by 50% or more when the knee flexes

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from 20° to 60° [5,13,18], illustrating improved joint congruity with increased knee flexion. However, cadaveric experiments may not accurately reflect physiological loading of a young, healthy patellofemoral joint.

Magnetic resonance imaging (MRI) has been used to estimate patellofemoral joint contact area in living subjects [1,17,19]. These studies confirmed the increase in joint contact area with increased angles of knee flexion and showed little increase in contact area with increased quadriceps contraction [19]. Previous imaging studies were limited by the physical constraints imposed by closed-bore MR scanners, which do not permit images to be taken throughout a large range of motion in an upright, load-bearing posture. Previous measurements of patellofemoral joint contact area may therefore underestimate the contact area in the loaded in vivo joint, and the role of increased contact area to attenuate cartilage stress, as suggested by Clark et al. [3], remains unclear.

Previous studies used MRI to assess gender differences in the patellofemoral joint, including differences in total cartilage surface area [7,8]. However, gender differences in patellofemoral joint contact area under in vivo, upright weight-bearing conditions have not been previously studied using MRI. Previous MRI studies estimating contact area included both male and female subjects [1,19], but did not address issues related to scaling between genders. Differences in contact area may account for the observation that patellofemoral disorders are more common in the female population [6]. Absolute contact areas between genders are expected to be different, given that males are generally larger than females and have ~20% greater overall patella cartilage surface area [8]. However, whether patellofemoral joint contact areas scale in proportion to patella size remains unknown.

The advent of MR scanners with an open vertical gap permits images to be taken with subjects in a weight-bearing standing or squatting posture [11]. This configuration allows for a comprehensive investigation to understand how patellofemoral joint contact area changes with weight-bearing in different knee postures. The aims of this study were to determine in vivo contact areas during upright weight-bearing conditions and to test the following hypotheses: males display greater absolute patellofemoral joint contact area than females in similar knee flexion postures; when normalized to patellar dimensions (height and width), patellofemoral joint contact area is not different between genders; and contact area increases under weight-bearing conditions.

Methods

Eight males (age: 29 ± 6 years, height: 1.77 ± 0.06 m, mass: 72.6 ± 6.0 kg) and eight females (age: 29 ± 5 years, height: 1.65 ± 0.05 m, mass: 57.4 ± 5.1 kg) participated in this study. All subjects were physically active, free of knee pain, and had no history of anterior knee pain or knee surgery. Prior to scanning, subjects were informed about the nature of the study and provided consent according to the policies of the Institutional Review Board of Stanford University.

All imaging was performed at the Stanford University Hospital using a GE Signa 0.5T SP/i MR scanner (GE Medical Systems, Milwaukee, WI). This scanner has an open magnet configuration with a 58 cm vertical gap, allowing for imaging in an upright, weight-bearing posture (Fig. 1A). A custom-built, MR-compatible backrest was developed to enable the subjects to maintain a standing or squatting position within the magnet with their upper body supported by the device (Fig. 1B). The backrest was inclined to 25° from vertical, such that the subjects supported ~90% of their body weight (BW), or 0.45 BW per leg. This loading was confirmed for several subjects using a set of bathroom scales. An adjustable toggle at the base of the backrest could be deployed to enable subjects to sit on a small padded seat, minimizing the load on each lower limb in what was termed the 'unloaded' condition. Due to the mass of the lower leg, a small amount of load was still present in this unloaded position. With the subject supported on the padded seat, the load measured at each foot (using the bathroom scales) was approximately 0.15 BW. To transition from unloaded to loaded state, the seat was folded away using the adjustable toggle at the back of the device, and the cleat restraining the backrest was unlocked, allowing the backrest to slide on low-friction rollers. This transition did not require the subject to change his/her position in the scanner, allowing the knee flexion angle to remain exactly the same for both the unloaded and loaded conditions. A large handheld goniometer was used to ensure that the desired angle of knee flexion was attained. The plastic goniometer was long enough to extend from the subjects greater trochanter to the knee center and then to the lateral malleoli of the ankle to improve the estimation of knee flexion angle.

Images were acquired with the knee at full extension (0°) and at 30° and 60° of knee flexion. At each flexion angle, images were acquired in both unloaded and loaded conditions. A 3D fast spoiled gradient echo (SPGR) sequence was employed to obtain 2 mm contiguous sagittal plane images of the subject's patellofemoral joint at each posture. Sagittal views were chosen to maximize the number of images across the patellofemoral joint contact area. Each scan took ~2:13 min using the following parameters: TR = 33 ms, TE = 9 ms, flip angle = 45°, NEX = 1, field of view = 20 cm × 20 cm, matrix dimensions = 256 × 160, interpolated to 256 × 256.

Contact area was determined by measuring the length of visible contact between the patella and femur in each slice (Fig. 2), multiplying this length by the slice thickness (2 mm), and then summing these values to obtain total contact area (mm^2) [1]. This method is highly reproducible and comparable to established pressure sensitive film techniques [2]. One examiner performed all the contact area measurements, repeating each measure three times per scan, to obtain an average contact area for each knee position and condition.

Due to varying gray-scale intensities in the MR image, we expected a certain amount of observer interpretation in what was considered contact. To train the observer to make accurate contact area measurements, an MRI-compatible contact 'phantom' was imaged using the same scan parameters outlined above, and the contact area was estimated using the same method as the in vivo contact area measurements. The phantom consisted of a nylon compression screw with a hemisphere attached to one end, to which a layer of gelatin-doped urethane was attached [10]. The screw was tightened to create a circular contact patch between the urethane hemisphere and the urethane base of the phantom. The phantom was filled with a manganese chloride solution, which, when absorbed into the urethane base and hemisphere, was intended to mimic cartilage and synovial fluid. Immediately following imaging, the manganese chloride solution was removed and replaced by silicone. Once set, this silicone created an accurate mould of the contact area patch, which could be removed from the phantom and measured using digital calipers.

The phantom was scanned on two separate occasions with different torques applied to the compression screw to simulate different contact areas (638 mm^2 and 347 mm^2). The examiner was then trained on the phantom by making repeated measurements from the MR images. If a measurement was too high or too low, the measure was repeated until three results were obtained within 3% of the value measured by the casting. Using this phantom, the observer could adjust the interpre-

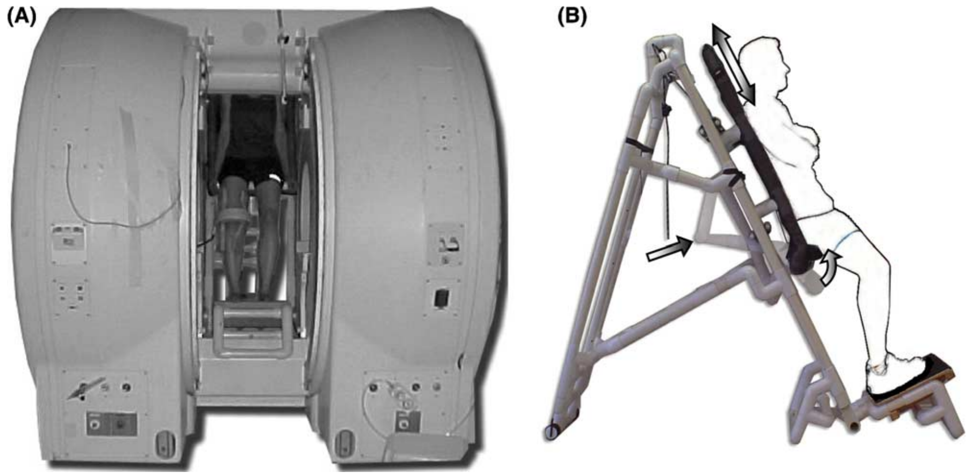

Fig. 1. Custom-built MR-compatible backrest and subject within the Signa 0.5T SP open MRI scanner (A). Backrest illustrating adjustable toggle to facilitate unloaded and loaded conditions (B). The toggle can be pushed forward such that a seat rest moves upward, allowing the subject to sit down and support their body weight. The backrest can slide up and down on rollers to enable the subject to assume different knee postures. A pulley and cleat system can be used to lock the backrest in one position.

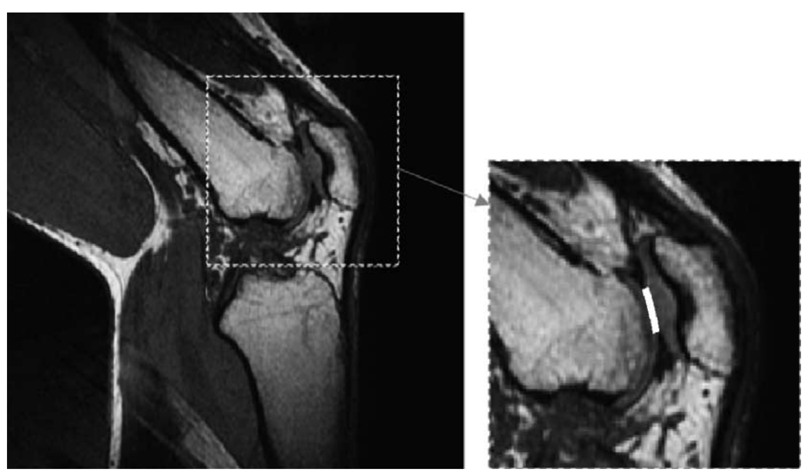

Fig. 2. Typical sagittal MR image used to calculate contact area. Zoomed view shows the region of contact between the femur and patella that was manually defined.

tation of what was considered contact in the MR image, which was typically an adjustment of only a few pixels in each image slice. Initial estimates of the phantom contact areas (prior to training) were within 10% of the actual value. After training, contact area estimates were accurate to within 3% of the MRI phantom. It was assumed that this training would help the observer to interpret contact within the in vivo patellofemoral joint scans. The contact area measurements at each knee flexion angle and loading condition were performed three times by a single examiner and were found to be repeatable, with a coefficient of variation of 3.8%.

Subjects' patellar height and width were measured from the sagittal MR images, and their product (height × width) was used to normalize the contact areas. To determine how patellar size scaled with subject height, such that a simple scaling measure could be determined to normalize patellar contact area, a regression was performed to relate patellar size (height × width) to subject height squared. Patellar ligament length and diagonal height of the patella were also measured from the 30° unloaded condition MR images to calculate the Insall–Salvati index for patella alta and patella baja [14]. To test the first hypothesis of the study, a two-factor ANOVA (gender × knee angle) with repeated-measures was performed to compare absolute contact area between males and females at each flexion angle. This analysis was repeated using the normalized patellofemoral contact areas to test the second hypothesis of the study. Finally, one-way ANOVA's were used to determine differences in the unloaded/loaded condition, using normalized contact areas at each knee flexion angle. Significance was set to $p < 0.05$, and Scheffe post-hoc tests were used to determine the significance of interactions in the two-factor ANOVA's.

Results

Male subjects had significantly greater patellofemoral joint contact area than females, in all knee postures for both unloaded (Fig. 3A) and loaded conditions (Fig. 3B), with the exception of the 0° unloaded condition, in which females had similar contact areas to males. Male subjects had, on average, patellar area (height × width) 34% greater than female subjects ($19.8 \pm 2.8\,cm^2$ versus $14.8 \pm 2.4\,cm^2$, respectively). A linear regression of patellar area (height × width) against subject height squared revealed that subject height was a strong

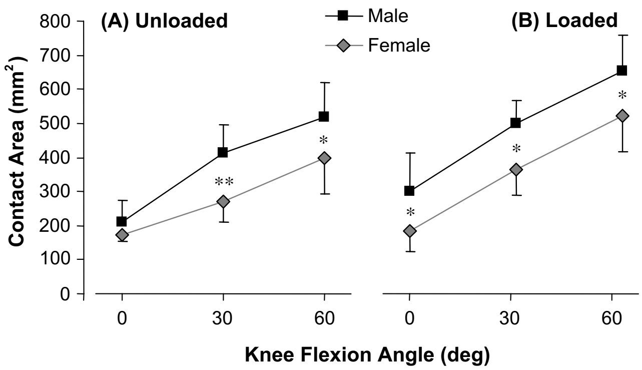

Fig. 3. Patellofemoral joint contact area at various knee flexion angles (0°, 30°, and 60°) in unloaded (A) and loaded (B) conditions. Significant differences between male and female subjects indicated with a *($p < 0.05$) or **($p < 0.01$).

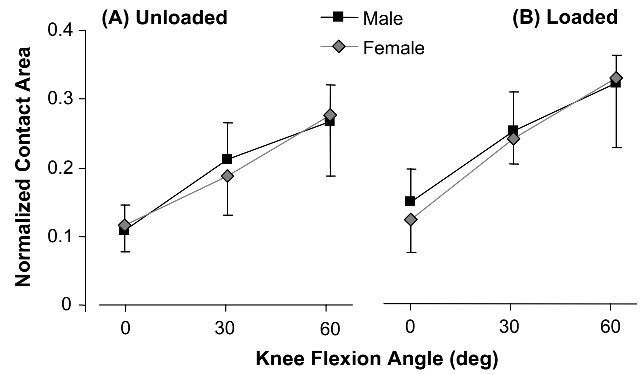

Fig. 5. Comparison of male and female normalized patellofemoral joint contact areas at different knee postures under unloaded (A) and loaded (B) conditions. Contact areas are normalized by patellar height × width. No significant gender differences existed in normalized contact areas.

predictor of patellar dimensions, accounting for 78% of the variation in patellar size (Fig. 4). Using the Insall–Salvati index of patella tendon length/patella height ratio, two males and one female subject had a ratio greater than 1.2 indicating patella alta, and one male subject had a ratio less than 0.8 indicating patella baja [14].

Normalizing contact area by patellar area (width × height) showed no statistical difference between males and females in unloaded (Fig. 5A) or loaded conditions (Fig. 5B). Similar results were obtained if patellar width [2] was used to normalize contact area instead of patellar width × height. Because the normalized patellofemoral contact areas were not different between males and females, contact areas were pooled to evaluate the overall effect of loading (Fig. 6). On average, the loaded condition increased contact area by 24% compared to the unloaded condition at each knee posture. Although the loaded condition always resulted in significantly greater contact area than the unloaded condition, the percentage increase was highly variable between individuals. Some subjects' contact areas increased by as much as 100% from unloaded to loaded conditions, whereas others increased by only 10%. Contact area also increased significantly with knee flexion, with a mean increase of 79% from 0° to 30° and an increase of 34% from 30° to 60° of knee flexion.

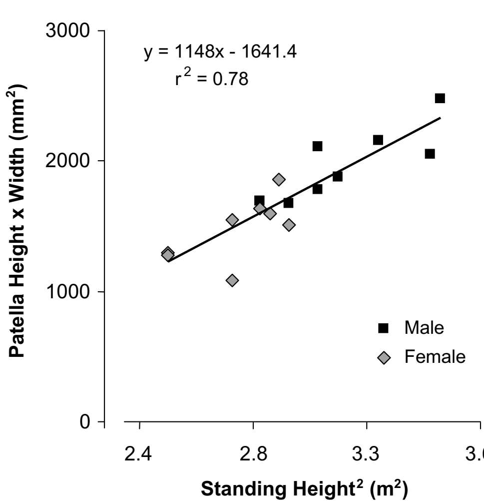

Fig. 4. Patellar height × width plotted against subject standing height squared for all subjects.

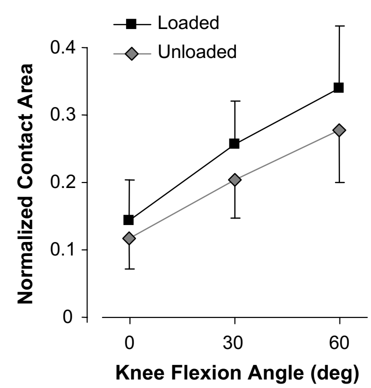

Fig. 6. Comparison of patellofemoral joint contact area in unloaded and loaded condition. Contact areas are normalized by patella height × width and include both male and female subjects.

Discussion

The aim of this study was to evaluate changes in patellofemoral joint contact areas in different knee postures under weight-bearing conditions in both male and female subjects. We hypothesized that males would have greater contact areas than females, given that they are likely to have larger patellae. This first hypothesis was supported by the current study. Normalizing patellofemoral joint contact area by patellar dimensions of height and width eliminated the differences between male and female subjects, which supported the second hypothesis of this study. Our third hypothesis, that patellofemoral joint contact area would increase when the joint was exposed to weight-bearing, was also supported by the data.

It may be argued that the static 0.45 body weight loading condition used in this study does not accurately represent physiologic loading of the patellofemoral joint. Dynamic activities, such as running or stair climbing, place much greater load on the patellofemoral joint than the loading protocol used in this study and the resulting contact areas might also differ from the values reported here. The loading protocol used in this study was limited by the length of time that our subjects could maintain a stationary squatting position and the speed of the scanning sequence used to obtain clear, motion-free images. New MR pulse sequences might, in the future, provide measurement of cartilage deformation and patellofemoral joint contact areas under larger dynamic loads.

The contact areas measured in this study were larger than those reported in previous studies. For example, at 30° knee flexion, Csintalan et al. [4] reported mean patellofemoral joint contact areas of 284 mm^2 for females and 331 mm^2 for males. At 30° flexion, we found mean loaded contact areas of 362 mm^2 for females and 494 mm^2 for males. Huberti and Hayes [13], Powers et al. [18], and Salsich et al. [19] reported similar values to those of Csintalan et al. [4], which were 20–30% lower than the contact areas reported in this study. Several reasons may explain the discrepancy. One possible difference may be that the subjects recruited in the current investigation were larger than those from previous studies, and thus had larger patellae and, consequently, greater contact areas. Another explanation is that the upright, weight-bearing posture assumed by subjects in this study involved greater loading on the patellofemoral joint than what has previously been possible. Greater loading is likely to result in greater cartilage deformation and lead to increased contact area, as has been shown in the feline patellofemoral joint [3]. One other explanation is that the upright position of the subjects within the scanner improves the joint congruity compared to a static supine scanning posture. Even the relatively small load placed on the leg in the unloaded condition (0.15 BW) might be enough to alter the position of the patella in the trochlear groove and improve the congruence of the joint compared to a static supine position.

Another factor that will influence the position of the patella within the trochlea groove is the length of the patellar tendon. The Insall–Salvati ratio is one method used to determine the length of the patellar tendon in relation to the diagonal length of the patella, and it might account for some variation in patellofemoral contact areas [14]. However, we did not see a significant relationship between the Insall–Salvati index and patellofemoral contact area. For example, a regression between the Insall–Salvati index and contact area for the unloaded 30° flexion condition had a coefficient of determination of 0.06 and a p value of 0.37. Regressions for the loaded condition and at other flexion angles gave similar results. Some association between patellar position and contact area might be seen by directly comparing two groups, one with patella alta and one with patella baja.

The percentage increase in contact area due to loading was not consistent between subjects and varied between knee postures. Changes in contact area between the unloaded and loaded condition are due to either cartilage deformation, a reorientation of the patella in the trochlear groove, or some combination of the two. Clark et al. [3] showed increases in contact area of more than 50% with increasing load in the feline patellofemoral joint and attributed this increase to cartilage deformation. Hypothetically, if we assume an elliptical contact area, a 1 mm increase in the radii of this ellipse would result in a 20% increase in total contact area given the dimensions of the unloaded contact area in this study. This represents a reasonable amount of deformation of the patella and femoral articular cartilage from the unloaded to loaded condition. However, patellofemoral joint contact area increased by more than 50% in some subjects, which is more likely to result from a change of patellar orientation with respect to the femur. For example, the patella may contact only the lateral facet of the femur in an unloaded state, but applying a weight-bearing load may shift the patella medially with respect to the femur, such that it contacts both the medial and lateral facets, increasing the contact area.

Muscles controlling the position of the patella and femur play an important role in determining the contact area experienced under weight-bearing conditions. Salsich et al. [19] estimated patellofemoral joint contact areas in vivo and compared a quadriceps contracted condition with a quadriceps relaxed condition. They did not observe a significant increase in contact area with increased quadriceps loading. However, their 0.25 BW horizontal loading protocol may not have been sufficient to exhibit significant cartilage deformation. Csintalan et al. [4] used cadaver specimens to examine the effect of increasing vastus medialis muscle forces on patellofemoral joint contact area and found that contact area significantly increased between unloaded and loaded states. When simulated vastus medialis muscle loading increased from 0 to 100 N, the corresponding contact area increased by 38% with the knee in 30° of flexion [3]. Estimates of in vivo muscle loads and patellofemoral kinematics during dynamic activities would be required to understand the role of muscle in stabilizing the patellofemoral joint.

Increasing patellofemoral joint contact area with knee flexion has been well documented [4,5,13,18,19]. Increases in contact area due to knee flexion were consistent amongst subjects and gender in our study and can be explained by the increased congruence of the patella within the trochlear groove of the femur as the knee flexes from 0° to 60° [4].

Patellofemoral joint contact areas should be measured under loaded conditions to account for cartilage deformation and changes in patellar alignment that may occur with load. This is particularly relevant when trying to understand potential mechanisms of patellofemoral pain. Understanding the complex interaction between cartilage contact area, joint contact forces, and resulting cartilage stresses in the patellofemoral joint will help to define the mechanisms responsible for pain and establish more effective treatment strategies.

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