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In Vivo Assessment of Patellofemoral Joint Contact Area in Individuals Who are Pain Free

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Magnetic resonance imaging was used to quantify in vivo patellofemoral joint contact area and to determine if contact area is affected by quadriceps muscle contraction. Ten subjects without pain (six women, four men) had their right patellofemoral joint imaged. Cartilage-enhanced, axial plane images were obtained at 0°, 20°, 40°, and 60° knee flexion under quadriceps loaded (contracted) and quadriceps unloaded (relaxed) conditions. Medial and lateral facet contact area measurements were obtained on each image, and then summed across all images in a series to yield facet contact area measurements for each knee angle. Total contact area was computed as the sum of medial and lateral facet contact areas. Consistent with in vitro studies, progressive increases in patellofemoral joint contact area were observed from 0° to 60° knee flexion. The lateral facet comprised a greater percentage of total contact area compared with the medial facet at each knee flexion angle, suggesting increased load-bearing potential. Quadriceps contraction did not affect patellofemoral joint contact area indicating that the addition of a compressive load to the joint did not alter the area of the load-bearing surfaces. In vivo assessment of patellofemoral joint contact area could provide insight into mechanisms of patellofemoral joint disorders.

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Determination of the location and magnitude of joint contact area is a necessary step toward understanding the effects of loading on articular cartilage.[2] For example, accurate assessment of patello-femoral joint contact area is needed for various methods used to quantify joint stress (such as mathematical modeling or finite element analysis). Traditionally, such data have been obtained from cadaver specimens using dye-staining,[6,13] casting techniques,[1,4,5,17] and pressure-sensitive film.[3,8,10–12,14,16] More recently, magnetic resonance imaging (MRI) was shown to be a valid method of quantifying patellofemoral joint contact area, indicating the potential for in vivo assessment.[9]

The use of cadaver specimens for contact area measurements is limited as the true physiologic loading behavior of the quadriceps muscles (muscle forces produced during weightbearing and nonweightbearing activities) cannot be reproduced. Although methods of quadriceps loading have evolved from central tendon loading to multiplanar loading,[11,16] knowledge of the location of in vivo patellofemoral joint contact area with the quadriceps muscles contracted would provide additional insight into normal patellofemoral joint mechanics. In addition, such information could be used to understand pathologic features, as comparisons of specific patterns of joint contact could be made between persons with and without patellofemoral joint dysfunction.

To address the issues associated with quadriceps muscle loading and contact area, a MRI protocol was developed in which human subjects were imaged with the quadriceps muscles in a contracted state. Using this protocol, the primary purpose of the current study was to quantify medial and lateral patellar facet contact area and total contact area through a range of knee flexion. A secondary purpose was to determine if patellofemoral joint contact area is affected by quadriceps muscle contraction by comparing the magnitude and location of contact area between loaded and unloaded conditions.

MATERIALS AND METHODS

Subjects

Ten healthy individuals with no pain (six women, four men) with a mean age of 29.6 ± 4.1 years, mean height of 167.1 ± 6.8 cm, and mean body mass of 60.5 ± 11.0 kg participated in this study. Subjects were excluded if they had a current or previous history of patellofemoral pain, patellar subluxation, or prior knee surgery. Approval for this study was obtained from the institutional review board of our institution. Informed consent was obtained from all subjects before testing.

Procedures

Axial plane images of the patellofemoral joint were obtained with a 1.5T scanner (GE Medical Systems, Milwaukee, WI), using a fast spoiled gradient echo pulse sequence with spectral inversion (TE 1.5, TR 8.2, flip angle 10°, slice thickness 1 mm). The image field of view was 10 cm × 10 cm with a 256 × 256 matrix (interpolated to 512 × 512), giving a pixel size of 0.20 mm × 0.20 mm. Using this pulse sequence, the patellar and femoral cartilage was observed to be bright (white), and any separation between the cartilage surfaces appeared as a dark line.

Each subject was imaged at four knee flexion angles (0°, 20°, 40°, 60°) with the quadriceps contracted (loaded) and relaxed (unloaded). Resistance to the extensor mechanism was accomplished using a custom-built, nonferromagnetic loading apparatus that resembled a leg press machine (Captain Plastic, Seattle, WA). This device allowed subjects to do unilateral knee extension in the supine position (Fig 1). Resistance to knee extension was accomplished by pushing against a footplate that was connected (through a pulley system) to a moveable carriage containing nonferromagnetic (epoxy) weights (Fig 1).

Before imaging, subjects were positioned supine on the loading device and straps were placed across the hips and shoulders to stabilize the trunk and pelvis. Two 5-inch receive-only coils were placed on each side of the knee (with the patella centered between) and secured with tape.

Subjects were instructed to place the right foot on the footplate, and the knee was positioned in either 0° or 60° flexion (see randomization procedures described below). For the quadriceps-loaded condition the carriage was loaded to 25%

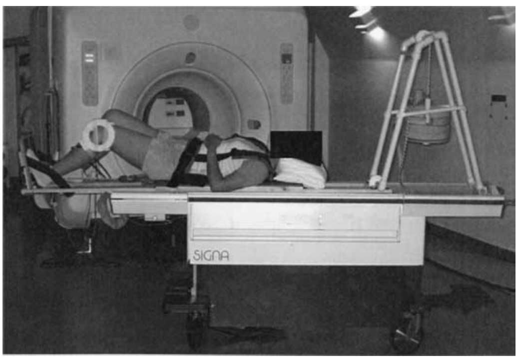

Fig 1. The quadriceps loading apparatus consisted of a rigid base and footplate connected (through a pulley system) to a moveable body carriage containing nonferromagnetic weights. Under the loaded condition, quadriceps contraction was required to prevent movement of the body carriage (resistance equal to 25% body weight). A brake was applied to the carriage during the unloaded imaging sequences, allowing the quadriceps to remain relaxed.

bodyweight, and subjects were instructed to push against the footplate while maintaining a fixed knee position. For the unloaded condition a brake was applied to the device, which allowed maintenance of knee flexion without quadriceps muscle contraction. After the limb placement procedure, the device was moved into the MRI bore and imaging commenced. After data acquisition at the first knee angle, the patient was removed from the MRI bore and repositioned on the loading device. The order of loading conditions was randomized for each subject, and the sequence of knee flexion angles was partially randomized (either increasing from 0°–60° or decreasing from 60°–0°). Total imaging time was 60 seconds (30 seconds per axial sequence) at each knee flexion angle.

Data Analysis

Contact area was measured from the sequential axial plane images of the patellofemoral joint. Images were displayed for analysis using Scion Medical Imaging Software (GE Medical Systems). The section of the image containing the patella and surrounding portion of the femur was enlarged to 1.5 times normal view to enhance observation of the articular cartilage. Contact was defined as areas of patella and femur approximation in which no distinct separation could be found between the cartilage borders of the two joint surfaces. Because cartilage is relatively bright on images obtained with a fast spoiled gradient echo pulse sequence, the definition of contact area was operatively defined as white on white.[9] The line of contact between the patella and femur was measured and recorded using the electronic calipers feature in the software. This measurement tool was calibrated for each image series to output measurements in millimeters.

To obtain medial and lateral facet contact area for each slice, the length of each respective line of contact was multiplied by the 1-mm slice thickness (the median ridge of the patella served as the point of separation between the medial and lateral facets) (Fig 2). The areas of contact from each sequential image were summed to obtain the patellofemoral joint contact area for each facet. Total contact area was calculated by summing the medial and lateral facet contact areas at each knee flexion angle. Contact area measurements were made twice by the same investigator and averaged for final analysis.

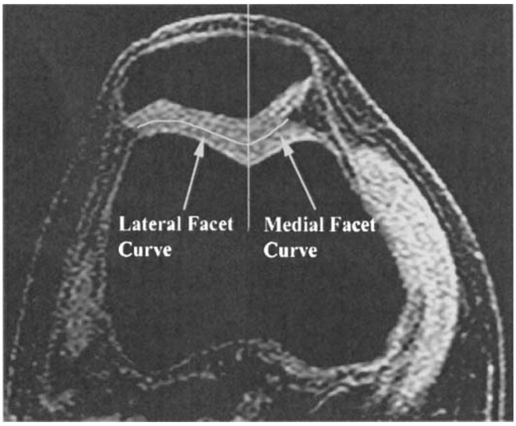

Fig 2. The vertical line on this axial image of the patellofemoral joint indicates the location of the median ridge, which distinguishes the medial and lateral patellar facets. Curvilinear lines indicate location of cartilage contact. The length of each line multiplied by the 1-mm slice thickness yielded contact area. The areas of contact from each sequential image were summed to obtain the patellofemoral joint contact area for each facet. Total contact area was calculated by summing the medial and lateral facet contact areas at each knee flexion angle.

This MRI method of assessing contact area has been shown to be reliable and comparable with contact area measurements obtained using Fuji pressure sensitive film in cadaver specimens.[9] Intratester reliability was excellent for medial facet, lateral facet, and total contact area measurements with intraclass correlation coefficients ranging from 0.92 to 0.98.

Statistical Analysis

To determine whether contact area varied between loading conditions and knee flexion angles, an analysis of variance (ANOVA) with repeated measures was done for each dependent variable (medial facet contact area, lateral facet contact area, and total contact area). Because measurements at 60° were not obtainable for two subjects, each ANOVA was a 2 × 3 repeated measures design: loading condition (loaded, unloaded) knee flexion angle (0°, 20°, 40°). Significant main effects (after appropriate post hoc testing) were reported if there were no significant interactions. If a significant interaction was identified, individual main effects were analyzed separately. For measurements at 60° (n = 8), t tests were done comparing loaded versus unloaded contact area, and comparing contact area measurements at 60° and 40° (collapsed across loading conditions). All statistical analyses were done using SPSS statistical software (SPSS Inc, Chicago, IL) with a probability less than 0.05 considered significant.

RESULTS

Total Contact Area

When averaged across loading conditions, total contact area increased from 143.7 mm^2 at 0° knee flexion to 334.2 mm^2 at 60° knee flexion (Fig 3). Differences between knee flexion angles were observed (significant angle effect, no interaction), with post hoc analysis revealing statistical significance between each knee flexion angle (0°–20°, p = 0.03; 20°–40°, p < 0.001; 40°–60°, p = 0.001; Table 1). There was no significant difference in total contact area between loaded and unloaded conditions at any knee flexion angle (Table 1).

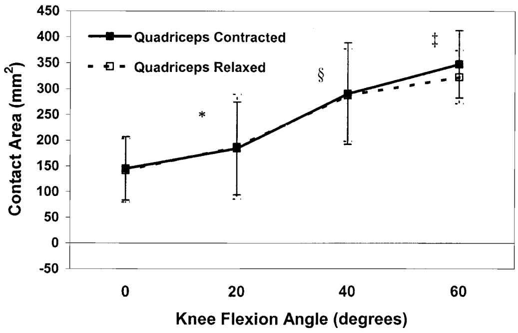

Fig 3. The graph shows average total patellofemoral joint contact area as a function of knee flexion angle (n = 10, except at 60° where n = 8). The solid line indicates the quadriceps contracted condition, and the dashed line indicates the quadriceps relaxed condition. The error bars represent one standard deviation. No difference in total contact area was detected between loading conditions when collapsed across all knee flexion angles. Significant differences ($p < 0.05$) were detected between 0° and 20°(*), 20° and 40°(§), and 40° and 60°(‡) when averaged across loading conditions.

TABLE 1. Patellofemoral Joint Total Contact Area

Knee Angle (degrees)	Total Contact Area (mm^2)						
	Quadriceps Contracted			Quadriceps Relaxed			
	Mean	*Standard Deviation*	*Range*	*Mean*	*Standard Deviation*	*Range*	*p Value*[a]
0 (n = 10)	145.5	61.7	73.2–272.4	141.9	61.9	74.7–262.2	
20 (n = 10)	184.0	90.1	81.9–355.9	187.1	101.7	80.7–361.4	0.03[b]
40 (n = 10)	290.4	98.2	166.7–440.3	287.3	89.4	161.5–401.8	<0.001[c]
60 (n = 8)	346.6	65.1	279.6–466.2	321.8	51.2	257.0–403.6	0.001[d]

[a]significance of t tests for pairwise comparisons between knee angles, collapsed across quadriceps condition; No significant main effect for quadriceps condition

[b]Comparison with 0°

[c]Comparison with 20°

[d]Comparison with 40°

Medial Facet Contact Area

When averaged across loading conditions, medial facet contact area increased from 0 mm^2 at 0° knee flexion to 102.8 mm^2 at 60° knee flexion (Fig 4). Differences between knee flexion angles were observed (significant angle effect, no interaction), with post hoc analysis revealing statistical significance between each knee flexion angle (0°–20°, $p = 0.03$; 20°–40°, $p = 0.006$; 40°–60°, $p = 0.002$; Table 2). There was no significant difference in medial facet contact area between loaded and unloaded conditions at any knee flexion angle (Table 2).

Lateral Facet Contact Area

When averaged across loading conditions, lateral facet contact area increased from 143.7 mm^2 at 0° knee flexion to 231.4 mm^2 at 60° knee flexion (Fig 4). Differences between knee flexion angles were observed (significant angle effect, no interaction), with post hoc analysis revealing statistical significance between 20° and 40° ($p = 0.002$) and 40° and 60° ($p = 0.008$) (Table 3). There was no difference in lateral facet contact area between 0° and 20° knee flexion. In addition, there was no significant difference in lateral facet contact area between loaded and unloaded conditions at any knee flexion angle (Table 3).

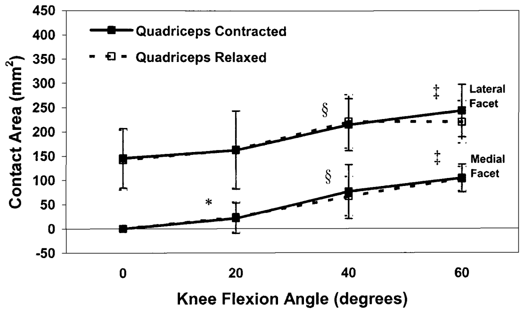

Fig 4. The graph shows average medial and lateral facet contact area as a function of knee flexion angle ($n = 10$, except at 60° where $n = 8$). The solid line indicates the quadriceps contracted condition, and the dashed line indicates the quadriceps relaxed condition. The error bars represent one standard deviation. No differences in medial or lateral facet contact area were detected between loading conditions when collapsed across all knee flexion angles. Significant differences ($p < 0.05$) were detected between 0° and 20° (* medial only), 20° and 40°(§), and 40° and 60°(‡) when collapsed across loading conditions.

DISCUSSION

Total patellofemoral joint contact area significantly increased with knee flexion angle, which corresponds to the findings of previous investigations despite use of different methodologies.

TABLE 2. Patellofemoral Joint Medial Facet Contact Area

	Medial Facet Contact Area (mm^2)						
	Quadriceps Contracted			Quadriceps Relaxed			
Knee Angle (degrees)	*Mean*	*Standard Deviation*	*Range*	*Mean*	*Standard Deviation*	*Range*	*p Value*[a]
0 (n=10)	0.0	0.0	0.0–0.0	0.0	0.0	0.0–0.0	
20 (n=10)	21.7	31.6	0.0–71.6	23.8	31.3	0.0–82.6	0.03[b]
40 (n=10)	76.0	55.7	0.0–174.7	66.31	40.47	0.0–125.7	0.006[c]
60 (n=8)	103.5	28.9	56.6–147.5	102.12	25.05	73.6–137.1	0.002[d]

[a]significance of t tests for pairwise comparisons between knee angles, collapsed across quadriceps condition; No significant main effect for quadriceps condition

[b]Comparison with 0°

[c]Comparison with 20°

[d]Comparison with 40°

TABLE 3. Patellofemoral Joint Lateral Facet Contact Area

Knee Angle (degrees)	Lateral Facet Contact Area (mm^2)						
	Quadriceps Contracted			Quadriceps Relaxed			
	Mean	*Standard Deviation*	*Range*	*Mean*	*Standard Deviation*	*Range*	*p Value*[a]
0 (n = 10)	145.5	61.7	73.2–272.4	141.9	61.9	74.7–262.2	
20 (n = 10)	162.3	80.8	57.5–291.4	163.3	79.9	76.0–301.2	0.12[b]
40 (n = 10)	214.5	54.1	146.9–307.0	221.0	55.5	156.0–302.3	0.002[c]
60 (n = 8)	243.2	54.3	175.2–345.6	219.6	44.0	155.5–278.9	0.008[d]

[a]significance of t tests for pairwise comparisons between knee angles, collapsed across quadriceps condition; No significant main effect for quadriceps condition

[b]Comparison with 0°

[c]Comparison with 20°

[d]Comparison with 40°

Using cadaver limbs and pressure sensitive film, Powers et al[16] reported a 68% increase in contact area between 15° and 60° knee flexion, whereas D'Agata et al[3] reported an 81% increase between 20° and 60°. Through a comparable range of knee flexion angles, 20° and 60°, an 80% increase in total contact area was observed in the current subjects.

In addition to similar percent increases, the actual in vivo contact area values obtained in the current study were within the ranges reported in previous in vitro investigations. The current average total contact area measurements ranged from 186 mm^2 at 20° to 334 mm^2 at 60°. D'Agata et al[3] reported contact area values ranging from 160 mm^2 at 20° to 290 mm^2 at 60°, whereas Huberti and Hayes[11] reported measurements of 260 mm^2 at 20° and 390 mm^2 at 60°.

Another similarity between the results of the current study and those reported by previous investigators was that the greatest increase in contact area occurred before 40° to 45° flexion. In the current study 76% of the total increase in contact area was achieved by 40°, whereas Powers et al[16] reported a 100% increase in contact area by 45° knee flexion. This pattern of contact can be explained by the anatomy and kinematics of the patellofemoral joint. As the knee flexes from full extension (0°), the patella glides inferiorly in the femoral trochlea, which deepens distally. By 45°, the patella is fully engaged in the femoral trochlea, resulting in less dramatic changes in contact area with greater knee flexion angles.

Substantial patellofemoral joint contact area was seen at 0° (143.7 mm^2). This finding is consistent with that of Powers et al[16] who used anatomically based, multiplane loading of the extensor mechanism in cadaver specimens. In vitro models that load the extensor mechanism via the central tendon (as opposed to loading the individual vasti along the respective principal muscle fiber directions) are incapable of documenting contact area at 0° as the application of force parallel to the femur would not create sufficient joint reaction force to compress the patella against the femur.

As with total contact area, medial and lateral facet contact area increased with knee flexion angle. In addition, lateral facet contact area contributed substantially more to total contact area than did medial facet area. Between 0° and 60° knee flexion, the average contribution from the lateral facet was 70%, whereas only 30% came from the medial facet. Additionally, no subject had medial facet contact at 0° knee flexion under either loading condition. This pattern of contact suggests that the articular cartilage of the flateral facet absorbs most of the forces transmitted through the patellofemoral joint at this knee flexion angle.

Patellofemoral joint contact area did not differ between quadriceps contracted and relaxed conditions. Although this was somewhat unexpected, there are several possible explanations for this finding. One is that the applied resistance did not require a quadriceps contraction of sufficient magnitude to compress the patella and induce a change in contact area. Another possible reason is that the subjects in the current study were pain-free with no history of patellofemoral joint dysfunction, therefore a quadriceps contraction probably would not have resulted in malalignment of the patella. Although patellofemoral alignment was not measured in the current study, none of the subjects had a history of patellar subluxation, which is one of the most cosistent variables associated with observable patellar malalignment.[7,15,18,19] In the absence of patellar malalignment, changes in contact area attributable to compression and deformation of the patellofemoral joint articular cartilage may have been too subtle to detect with the methodology used.

There are several study limitations. Because of the configuration of the loading apparatus in the MRI bore, subjects were not able to flex their knees beyond 60°. As a result contact area measurements at greater knee flexion angles were not obtained. Another limitation involves the number of subjects (n = 10) in this study. Although the sample size was small, it was sufficient to detect differences in average contact area across knee flexion angles. No differences in contact area were detected between loading conditions, however, a post hoc power analysis ($\beta = 0.80$, $\alpha = 0.05$ two-tailed) indicated that greater than 780 subjects would be required to detect such differences. Even if it were feasible to do a study with a sample of that size, the clinical significance of such a small difference in contact area (3–4 mm^2 from 0°–40°) could be challenged. Nonetheless, a more definitive statement of statistical significance could be made with a larger sample size.

Consistent with in vitro studies, progressive increases in patellofemoral joint contact area were observed from 0° to 60° knee flexion. The greater lateral facet contact area compared with the medial facet contact area at each knee flexion angle suggests increased load-bearing potential. Quadriceps contraction did not affect patellofemoral joint contact area indicating that the addition of a compressive load to the joint did not alter the area of the load-bearing surfaces.

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