Weight-Bearing MRI of Patellofemoral Joint Cartilage Contact Area

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Purpose: To measure contact area of cartilage in the patellofemoral joint during weight bearing using an open MRI scanner.

Materials and Methods: We developed an MR-compatible back support that allows three-dimensional imaging of the patellofemoral cartilage under physiologic weight-bearing conditions with negligible motion artifact in an open MRI scanner. To measure contact areas, we trained observers using a phantom of known area and tested intra- and interobserver variability. We measured in vivo contact areas between the patella and femoral cartilage with the knee in 30 degrees of flexion, loaded and unloaded, in six volunteers.

Results: We were able to measure the contact area of the patellofemoral cartilage with small interobserver (CV 7.0%) and intraobserver (CV 3.0%) variation. At 30 degrees of knee flexion, mean contact area increased from 400 mm² (unloaded) to 522 mm² (loaded to 0.45 times body weight per leg).

Conclusion: Using an open magnet and specially designed apparatus, it is possible to image the patellar cartilage during physiologic loading. Knowledge of patellar cartilage contact area is needed to assess patellofemoral stress, which may be increased in patients with patellofemoral pain syndrome.

Key Words: MRI; cartilage; loading; contact area; stress


Published 2004 Wiley-Liss, Inc.

PATELLOFEMORAL PAIN SYNDROME (PFPS) is a common cause of knee pain. Pain typically occurs during activities that load the patellar cartilage, such as running and climbing stairs. Thus, accurate measurement of patellofemoral cartilage contact area under loaded conditions is essential for a physiologically relevant determination of patellofemoral joint stress (1). Knowledge of patellofemoral joint stress may, in turn, provide new insight into the etiology of PFPS.

Examination of the patellofemoral joint cartilage with MRI is commonly done in horizontal, closed-bore systems without load. Spoiled gradient echo imaging is a standard imaging sequence used to look for cartilage defects and estimate cartilage thickness and volumes (2,3). Measurement of patellofemoral cartilage volume using MRI has been done immediately after exercise, although not while under load (4). Patellofemoral joint kinematics have also been studied with MRI using minimal load (5–7).

Measurement of patellofemoral joint contact area has been performed using MRI in vivo under limited load (1,8). Contact area has also been measured in cadavers using pressure-sensitive film (9–14). MR imaging of cadavers under load has been used to measure contact area (15). Recent measurements in the patellofemoral joint of cats have shown that contact areas increase with applied force (16).

Data obtained in vivo for patellofemoral contact area in humans during weight-bearing has been difficult to obtain. Noninvasive tests like MR imaging are typically performed with minimal load and the subject is subject to motion artifacts. The purpose of this study was to develop and evaluate an MR imaging protocol that could be used to provide accurate and repeatable estimates of in vivo patellofemoral cartilage contact area during weight-bearing.

MATERIALS AND METHODS

Phantom Studies

Validation of the contact area analysis was performed first, using a phantom model with known contact areas. Measurement of contact area was performed by three independent observers on a cartilage phantom of known area (Fig. 1) (17). The phantom was constructed using a nylon screw with a hemisphere attached to one end, which was coated with gelatin-doped urethane. The gelatin was doped to simulate cartilage relaxation.
times. The screw was tightened to create a circular contact patch between the urethane hemisphere and the urethane base of the phantom.

The phantom was placed in a solution of 0.15 mmol manganese chloride to mimic synovial fluid and MR imaging was performed in a 0.5-T GE Signa SP (General Electric Medical Systems, Milwaukee, WI). The phantom was imaged with a transmit–receive surface coil with a sagittal three-dimensional spoiled gradient echo sequence (three-dimensional-SPGR) and a 20-cm field-of-view (FOV). The imaging matrix was 256 × 160, with a TR/TE of 33 msec/9 msec and a 45-degree flip angle. We acquired 32 sections of 2-mm thickness in a scan time of 2:13 minutes.

Immediately following imaging, the phantom contact area was calculated using a silicone casting technique and compared to the value obtained from the MRI. All three observers compared their image-based results to the known area obtained from the silicone casting. The phantom was imaged at two settings, low contact area (347 mm²) and high contact area (638 mm²). The low contact area setting simulated patellofemoral contact areas without load, and the high contact area setting simulated patellofemoral contact area under load.

Contact area measurements of the cartilage phantom were useful to train our observers. After an initial attempt to gauge contact area, the observers were told whether their contact area measurements from the images were high or low as compared with the silicone casting. Once our observers provided accurate, reproducible measurements of contact area in the phantom, they proceeded to measure contact areas from the human subjects.

**In Vivo Studies**

Six healthy, physically active, male subjects participated in this study (age: 32 ± 6 years; height: 1.78 ± 0.05 m; mass: 74 ± 6 kg). Subjects were free of knee pain and had no history of 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.

We imaged our volunteers at 30 degrees of knee flexion in loaded and unloaded conditions. MR scanning was performed in a 0.5-T GE Signa SP open MRI scanner using a custom back support device (Fig. 2) that allows subjects to remain motion-free for the duration of the scan. An adjustable toggle at the base of the backrest enabled subjects to sit on a small padded seat while in the unloaded state. In the loaded state, the seat was removed and the backrest was allowed to slide on low-friction rollers. This required the subject to bear his/her own weight while maintaining a desired knee flexion angle. A handheld goniometer was used to ensure that 30 degrees of knee flexion was attained. A water-filled counterweight supported the weight of the sliding portion of the backrest. The counterweight was used to offset the weight of the sliding backrest, and was not used to generate a load.

Scanning was done using a 9-inch transmit–receive surface coil with sagittal three-dimensional SPGR and a

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**Figure 1.** A: Sagittal MR image of the contact area phantom. The urethane simulates cartilage and the manganese chloride solution simulates joint fluid. B: Photograph from the top with the acrylic hemisphere of the phantom removed. This photograph was taken after the manganese chloride was replaced with silicone casting material. The actual contact area (contact patch) between the urethane coating the acrylic hemisphere and the urethane coating the base of the phantom (outlined by the cross-hatches) is surrounded by silicone casting material.

**Figure 2.** Schematic drawing of our custom MR-compatible back support. The support is made of plastic pipes, a sliding mesh backrest, and a water-filled counterweight. The entire back support fits between the two halves of the “double doughnut” GE Signa SP system. The knee is positioned at isocenter.
20-cm FOV. The imaging matrix was 256 × 160 with a TR/TE of 33 msec/9 msec and a 45-degree flip angle. We acquired 32 sections of 2-mm thickness in a scan time of 2:13 minutes. Subjects were first scanned at 30 degrees of flexion without load, and then under a load of approximately 0.45 times their body weight supported by each leg.

Three independent observers measured in vivo contact areas between the patella and femoral cartilage at a flexion angle of 30 degrees. Images were interpolated to 256 × 256 by the scanner, and analyzed in a custom program written in MATLAB (Mathworks, Inc.). The patellofemoral joint was magnified during image analysis to facilitate measurement of contact area. Contact area in vivo was determined from multiplying the length of gray-on-gray pixels in each image by the slice thickness and summing the values across the joint (1).

Total contact areas without load and with load were compared. Each observer measured the contact area three times in each subject. The observers were not blinded to the unloaded or loaded status of the scans. Using these data, we calculated the alpha coefficient and coefficient of variation for intra- and interobserver variability of our measurements. Alpha coefficient values above 0.9 indicate excellent agreement among the measurements (18).

RESULTS

Phantom Studies

After an initial 10-minute training period, all three observers were able to measure contact areas in the phantom with good accuracy. Our three observers were able to accurately measure contact areas in the phantom at both low contact area (347 mm²) and high contact area (638 mm²) settings. After training, all observers were able to measure contact areas for both low and high contact area settings to within a coefficient of variation (CV) of 3% of the silicone casting area.

In Vivo Studies

Images acquired during knee flexion without the back support device resulted in considerable motion artifact. Use of the back support resulted in loaded images with no apparent motion artifact in all subjects. Both loaded and unloaded images were free of artifact and patellar cartilage was visible to all observers. The contact area in both loaded and unloaded states was easily visible to all of the observers (Fig. 3).

Contact area measurements (Fig. 3) from three independent observers showed good intra- (mean CV of 3.0%) and interobserver agreement (mean CV 7.0%). The alpha coefficients for intra- and interobserver variability were excellent (0.99 and 0.94, respectively).
Mean contact area (Fig. 4) for our six subjects was greater when the limb was loaded (522 mm² ± 33) than when it was unloaded (400 mm² ± 21). Each subject increased in contact area under load, and the mean contact area increase under load was statistically significant (*P < 0.01). Intraobserver variation was low (alpha = 0.99, CV = 3.0%). Interobserver variation was also low (alpha = 0.95, CV = 7.0%).

DISCUSSION

MRI has great ability to image articular cartilage non-invasively; however, imaging under loaded conditions is challenging. Our study addressed the challenge of imaging during weight bearing by using an open-bore interventional MRI scanner and a custom apparatus that allows for physiologic loading. The use of the back support is limited to systems such as the double-doughnut GE Signa SP. Although horizontal systems will not allow standing load bearing, use of a footplate and harness has been described to simulate weight-bearing (8). Such systems will apply load across the knee, but may not capture all aspects of upright weight bearing.

One limitation of our study is the relatively low image resolution compared with studies using closed-bore systems (2,19,20). Image resolution was lower in this study due to the relatively limited signal-to-noise (SNR) of the 0.5-T system compared with 1.5-T systems. A relatively large transmit-receive surface coil was used in this study. Construction and use of a smaller, receive-only surface coil for the patella cartilage will be the subject of future work.

Another factor that limited the resolution of our images was the need for a short scan time in the loaded state. Imaging time was kept short to allow future studies of patients with PFPS to be performed with limited motion. Preliminary results on patients with patellofemoral pain show they can be successfully scanned during weight-bearing using the techniques described in this study.

The increase in patellofemoral cartilage contact area observed under load could be due to repositioning of the patella in the trochlear groove and to cartilage deformation from loading. Our results are consistent with results in the feline patella (16) and with calculations made in vitro (10). When combined with additional information about joint contact forces, these measurements of contact area will allow us to calculate patellofemoral cartilage stress during weight bearing. Knowledge of cartilage stress will provide new insights into the etiology of patellofemoral pain syndrome and enable us to evaluate the effects of treatment for this disorder.

ACKNOWLEDGMENTS

We thank Doug Schwanert for help with design and construction of the back support and Michael Fredericson for recruitment of subjects with patellofemoral pain. We also thank Christopher Powers for help with data analysis.

REFERENCES


