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Quantification of patellofemoral joint contact area using magnetic resonance imaging

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Abstract

To describe a method for quantifying patellofemoral joint contact area using magnetic resonance imaging (MRI), we used a repeated measures design using cadaver specimens. The use of contact area obtained from cadaveric specimens for biomechanical modeling does not permit investigators to assess the inter-subject variability in contact area as a result of patellofemoral pathology or malalignment. Therefore, a method for measuring patellofemoral joint contact area in-vivo is necessary. Six fresh frozen unmatched human cadaver knees were thawed at room temperature and minimally dissected to permit insertion of a pressure sensitive film packet into the suprapatellar pouch. A custom loading apparatus was designed to apply a compressive load to the patellofemoral joint at 30 degrees of flexion. Simultaneous measurement of contact area was made using both the pressure sensitive film technique and MRI. The intraclass correlation coefficient (ICC) and coefficient of variation were used to compare the agreement between the two methods and to assess the repeatability of the MRI method. Good agreement was found between the MRI and pressure sensitive film techniques (ICC 0.91; CV 13%). The MRI technique also was found to be highly reproducible (ICC 0.98; CV 2.3%). MRI assessment of patellofemoral joint contact area was found to be comparable to the established pressure sensitive film technique. These results suggest that this method may be a valuable tool in quantifying patellofemoral joint contact area in-vivo. Quantification of the patellofemoral joint stress has been dependent on patellofemoral joint contact area obtained from cadaver specimens, thereby negating the potential influence of subject specific variability. Developing a non-invasive technique to evaluate contact area will assist researchers and/or clinicians in obtaining patient-specific contact area data to be used in biomechanical analyses and clinical decision making.

Keywords: Patellofemoral joint; Contact area; MRI

1. Introduction

Elevated patellofemoral joint stress has been hypothesized to contribute to articular cartilage wear and patellofemoral joint pain [1,2]. From a mechanical standpoint, patellofemoral joint stress may be defined as the patellofemoral joint reaction force divided by the area of contact between the patella and the trochlear surface of the femur. Using biomechanical methods and mathematical equations to derive the patellofemoral joint reaction force, several investigators have estimated patellofemoral joint stress during various activities [3-6]. In these studies, however, patellofemoral joint contact area was obtained from cadaveric specimens.

The use of cadaveric contact area data in estimating patellofemoral joint stress poses significant problems. For example, cadaveric specimens are generally from an older population and do not reflect the typical age ranges of persons with patellofemoral pain [7-13]. Perhaps more importantly, however, is that inter-subject variability in contact area as a result of patellar malalignment cannot be considered. This is of significant concern especially since malaligned patella can substantially alter contact area and joint stress [9].

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Given the limitations of using contact area from cadaver specimens to estimate patellofemoral joint stress, there is a need for an in-vivo method to obtain such data. The purpose of the present study was to describe a method for quantifying patellofemoral joint contact area using magnetic resonance imaging (MRI). The validity of this technique was established in cadaver specimens by comparing the contact area obtained from MRI with contact area obtained using pressure sensitive film. A secondary purpose of this study was to report on the reliability of the MRI method. Information obtained from this study will assist researchers and/or clinicians in obtaining patient specific contact area data to be used in biomechanical analyses and clinical decision making.

2. Materials and methods

Six fresh frozen unmatched human cadaver knees were used in this study. Each specimen consisted of an intact knee joint with 3/4 of the length of the tibia and femur retained. Prior to preparation, specimens were thawed at room temperature. Throughout preparation and testing, each specimen was kept moist using 4% saline solution.

2.1. Specimen dissection and loading

To expose the suprapatellar pouch, longitudinal incisions were made along the lateral borders of the central quadriceps tendon and the quadriceps muscle group was separated from the anterior aspect of the femur. A 5-cm incision was made in the superior patellofemoral joint capsule to accommodate the pressure sensitive film packets.

To simulate a compressive load across the patellofemoral joint, a custom loading apparatus (constructed of non-ferromagnetic material) was designed. Each specimen was supported on a base that held the knee in 30° of flexion (Fig. 1). The tibia and the femur were secured to the base with rubber tubing. To take up the slack in the quadriceps tendon, a plastic screw was inserted into the proximal femur and a small circle of surgical tubing (3-cm diameter) was sutured to the deep portion of the quadriceps tendon and looped around the plastic screw. Surgical tubing threaded through a plastic cap secured to the anterior patella, was looped around wooden dowels in the support base to provide a compressive force through the patellofemoral joint (Fig. 1).

2.2. Assessment of contact area

Patellofemoral joint contact area was assessed using the MRI and pressure sensitive film techniques. Both methods were employed simultaneously using the methods outlined below.

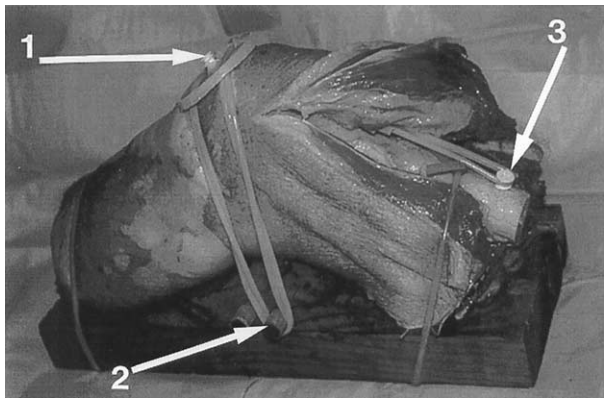


Fig. 1. Custom loading apparatus used to provide patellofemoral joint loading during assessment of contact area. The compressive force through the patellofemoral joint was provided by a plastic cap secured to the patella [1] and rubber tubing anchored to the base of support [2]. The slack in the quadriceps tendon was taken up by suturing rubber tubing to the quadriceps tendon and securing the tubing to a plastic screw inserted into the proximal femur [3].

2.3. Magnetic resonance imaging

Images of the patellofemoral joint were obtained using a 1.5T magnet (GE Medical Systems, Milwaukee, Wisconsin) using a three-dimensional spoiled gradient recalled echo (3D SPGR) imaging sequence. The following parameters were employed: TR 60 ms, TE 20 ms, Flip Angle 30°, NEX 1.5, matrix size 512 × 224 × 28, field of view: 20 cm × 20 cm and chemically selective fat suppression. Each slice was 2 mm thick and contiguous with the adjacent slices.

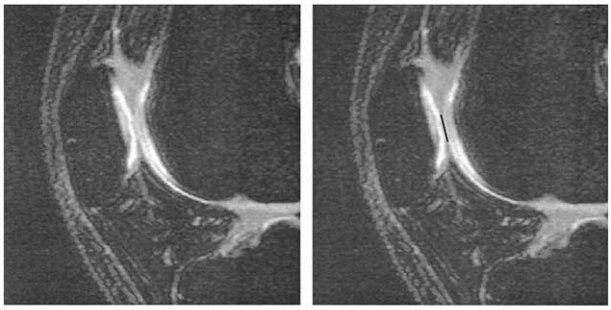
2.4. Pressure sensitive film

Contact pressure patterns were obtained using Fuji pressure sensitive film (Fuji Photograph Film Co., Tokyo, Japan) with a pressure range of 2-6 kgf/cm^2. The film was cut to size (5.0 cm × 5.0 cm) and placed inside a protective polyethylene envelope (250 μm thick). The polyethylene envelope prevented contamination and allowed contact area to be obtained within a fully lubricated joint.

2.5. Procedure

Following specimen dissection and mounting on the loading apparatus, a pressure sensitive film packet was inserted into the patellofemoral joint through the incision in the suprapatellar pouch. A compressive force was then applied to the specimen using the technique described above. One the average, the compressive force used in this study resulted in a peak patellofemoral joint stress of 5.5 ± 2.1 MPa. As the purpose of this study was to compare the two methods of assessing contact area, no attempt was made to control the magnitude of the compressive forces between specimens.

Prior to imaging, two five-inch receive only extremity



A B

Fig. 2. A) Representative sagittal plane image of the patellofemoral joint, magnified 2.5 times normal size. B) The black line indicates contact between the patella and femur.

coils were secured vertically on either side of the patella. Sequential images were then obtained, ensuring that the entire patellofemoral joint was imaged. Total imaging time was approximately 11 min. Upon completion of scanning, the patellofemoral joint was unloaded and the pressure sensitive film packet removed. Films with evidence of crinkling artifact were discarded, a new film inserted, and the MRI procedure repeated.

Imaging was performed with the pressure sensitive film packet in the joint to ensure identical loading conditions between the two measurement techniques. Pilot data demonstrated that the presence of the film packet did not influence the MRI measurement of contact area, as measurements with the film packet in the joint and without the film packet in the joint were highly comparable (Intraclass correlation coefficient (ICC) 0.94; Coefficient of Variation (CV) 2.8%).

To determine the measurement reliability for both the MRI and pressure sensitive film techniques, the procedures (as outlined above) were repeated three times in one specimen. A new pressure sensitive packet was used for each of these three trials.

2.6. Data analysis

2.6.1. Quantification of contact area using MRI

Sequential sagittal plane images were displayed for analysis using Signa Advantage Medical Imaging Software (GE Medical Systems, Milwaukee, Wisconsin). The section of the image containing the patella and surrounding portion of the femur was isolated and magnified (Fig. 2A). Patellofemoral joint contact was defined as areas of patella and trochlear surface approximation in which no distinct separation could be found between the cartilage borders of the two structures. Since cartilage brightness is enhanced on fat suppressed images, the definition of contact area was operatively defined as ‘white on white’.

The line of contact between the patella and femur was measured and recorded using the same software used to display the images (Fig. 2B). When the line of contact was curved, separate straight-line segments were measured. To obtain the contact area for each slice, the length of the line of contact was multiplied by the 2-mm slice thickness. Contact areas calculated from each image were summed to obtain the total patellofemoral joint contact area, with values reported in units of cm^2. Measurements were made twice and averaged for final analysis. All MRI measurements were made by the same investigator.

2.6.2. Quantification of contact area using pressure sensitive film

The exposed pressure sensitive film was scanned on a Hewlett Packard Scan Jet IIc Color Scanner and analyzed using National Institute of Health IMAGE (Bethesda, MD, USA.) version 1.6 software. Using a scale provided by the manufacturer, the software was calibrated for the film sensitivity, temperature during data collection, and for the hardware used in processing. This program converted the film pressure image into a scaled image with 256 levels of gray, which was used for the determination of the contact area. The contact area was identified, and the number of pixels in the image were counted. The pixels were converted into area and reported in units of cm^2. A preliminary study revealed the accuracy of the color scanner to be within 0.5% for quantification of contact area.

2.6.3. Statistical analysis

The reliability of contact area measurements obtained from MRI and the pressure sensitive film technique was assessed using the ICC [14] and CV [15]. The ICC and CV were also used to assess the level of agreement between the MRI and pressure sensitive film methods. All statistical analyses were performed using SPSS statistical software (SPSS Inc., Chicago, Ill., USA)

3. Results

For the reliability portion of this study, the ICC and CV values for the repeated MRI trials were 0.98 and 2.3% respectively, while the ICC and CV values for the repeated pressure sensitive film trials were 0.95 and 3.2%. The ICC and CV values indicating the level of agreement between the MRI and pressure sensitive film techniques was 0.91 and 13% respectively. When averaged across all specimens, the contact area obtained through MRI was 2.94 ± 1.01 cm^2 while the contact area obtained using the pressure sensitive film technique was 3.05 ± 0.95 cm^2. The average individual specimen difference between the two methods was 10.9%. (Fig. 3).

4. Discussion

The reliability of both techniques was found to be excellent. The higher CV using pressure sensitive film reflects

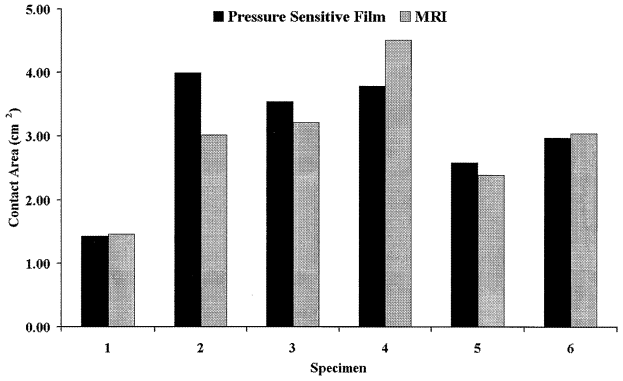


Fig. 3. Comparison of the mean contact area measurements between pressure sensitive film and MRI for all six specimens.

greater measurement error, however, this value falls well within the acceptable range for clinical/experimental methods [15]. Whether or not the same level of reproducibility for both measurements would be obtained between different investigators (inter- rater reliability) has yet to be determined.

Comparison of the patellofemoral joint contact area between the MRI and pressure sensitive film techniques was found to be good, with the overall average difference across all specimens being less than 5%. In comparison, the average within specimen difference was 10.9%. The lower overall average difference across all specimens was the result of the MRI measurement being greater than the pressure sensitive film measurement in three of the specimens and less than the pressure sensitive film in the remaining three specimens. The lack of consistency in the direction of the differences between the MRI and pressure sensitive film techniques (i.e., MRI greater or less than pressure sensitive) indicates that the MRI method did not apply a consistent bias to measurement of contact area. In other words, the MRI technique did not consistently overestimate or underestimate contact area when compared to the pressure sensitive film technique.

The magnitude of the individual specimen differences is reflective of the intrinsic error or variability associated with measuring contact area using MRI. Such variability is directly related to image quality and the quality of the articular cartilage within the specimen. Although every effort was made to externally lubricate each specimen with saline solution during the study, several of the specimens evaluated demonstrated varying degrees of cartilage degeneration based on visual inspection. In some images, this degeneration resulted in gaps in the contacting surfaces, making evaluation of the contact area difficult. However, the use of multiple line segments to quantify this contact area may provide a more accurate representation of contact area in comparison to methods using mathematical representations of the shape of the articular surfaces, which tend to smooth over such surface defects.

The magnitude of the contact area obtained in this study compares favorably with that previously reported in the literature [4,16-19]. This suggests that the loading apparatus used in this current investigation was capable of producing compressive loads comparable to other in- vitro studies. Although forces used may not represent those forces experienced during activities of daily living (i.e., during stair climbing) the static load in this study permitted adequate comparison of the two contact area measurement techniques.

5. Conclusion

MRI assessment of patellofemoral joint contact area was found to be highly reproducible, and comparable to the established pressure sensitive film technique, suggesting that this method may be a valuable tool in evaluating the patellofemoral joint contact area. Future investigations should consider assessment of normal and pathologic joints for etiologic studies of patellofemoral joint disease. This method also may be utilized to determine age specific, pathology specific, or activity level specific contact areas for relevant study populations. Finally, assessment of patellofemoral joint contact area following patellofemoral joint surgery may allow surgeons to assess the impact of specific procedures on patellofemoral joint mechanics.

References

[1] Fulkerson JP, Shea KP. Mechanical basis for patellofemoral pain and cartilage breakdown. In: Ewing JW, editor. Articular Cartilage and Knee Joint Function: Basic Science and Arthroscopy. New York: Raven Press, 1990. p. 93–101.
[2] Heino-Brechter J, Powers CM. Patellofemoral stress during walking in persons with and without patellofemoral pain. Med Sci Sports Exerc 2002;34:1582–1593.
[3] Hungerford DS, Barry M. Biomechanics of the patellofemoral joint. Clin Orthop 1979;144:9–15.
[4] Matthews LS, Sonstegard DA, Henke JA. Load bearing characteristics of the patello-femoral joint. Acta Orthop Scand 1977;18:511–516.
[5] Scott SH, Winter DA. Internal forces at chronic running injury sites. Med Sci Sports Exerc 1990;22:357–369.
[6] Steinkamp LA, Dillingham MF, Markel MD, Hill JA, Kaufman KR. Biomechanical considerations in patellofemoral joint rehabilitation. Am J Sports Med 1993;21:438–444.
[7] Callaghan MJ, Baltzopoulos V. Gait analysis in patients with anterior knee pain. Clin Biomech (Bristol, Avon) 1994;9:79–84.
[8] Cohen ZA, McCarthy DM, Ateshian GA, Kwak SD, Peterfy CG, Alderson P, Grelsamer RP, Henry JH, Mow VC. Knee joint cartilage topography, thickness and contact areas: validation of measurements from MRI. 1996.
[9] Fujikawa K, Seedhom BB, Wright V. Biomechanics of the patello-femoral joint. Part II: a study of the effect of simulated femoro-tibial varus deformity on the congruity of the patello-femoral compartment and movement of the patella. Eng Med 1983;12:13–21.
[10] Gilleard W, McConnell J, Parsons D. The effect of patellar taping on the onset of vastus medials obliquus and vastus lateralis muscle activity in persons with patellofemoral pain. Phys Ther 1998;78:25–32.

[11] van Eijden TMGJ, Kouwenhoven E, Verburg J, Weijs WA. A mathematical model of the patellofemoral joint. J Biomech 1986;19:219–229.
[12] Witvrouw E, Sneyers C, Lysens R, Victor J, Bellemans J. Reflex response times of vastus medialis oblique and vastus lateralis in normal subjects and in subjects with patellofemoral pain syndrome. J Orthop Sports Phys Ther 1996;24:160–166.
[13] Yates C, Grana WA. Patellofemoral pain-a prospective study. Orthopedics 1986;9:663–667.
[14] Bartko JJ. On various intraclass correlation reliability coefficients. Psychol Bull 1976;83:762–765.
[15] Portney L, Watkins M. Foundations of clinical research: applications to practice. Norwalk, CN: Appleton & Lang, 1993.
[16] Hefzy MS, Jackson WT, Saddemi SR, Hsieh Y-F. Effects of tibial rotations on patellar tracking and patello-femoral contact areas. J Biomed Eng 1992;14:329–343.
[17] Hehne H-JM. Biomechanics of the patellofemoral joint and its clinical relevance. Clin Orthop 1990;258:73–85.
[18] Huberti HH, Hayes WC. Patellofemoral contact pressures: the influence of Q-angle and tendofemoral contact. J Bone Joint Surg 1984; 16A:715–723.
[19] Seedhom BB, Tsubuku M. A Technique for the study of contact between visco-elastic bodies with special reference to the patellofemoral joint. J Biomech 1977;10:253–260.