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QUANTIFICATION OF MENISCAL VOLUME BY SEGMENTATION OF 3T MAGNETIC RESONANCE IMAGES

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Abstract

Meniscal injuries place the knee at risk for early osteoarthritis (OA) because they disrupt their load-bearing capabilities. Partial resection is routinely performed to alleviate symptomatic meniscal tears. While the removal of meniscal tissue may not be the only factor associated with partial meniscectomy outcome, the amount removed certainly contributes to functional loss. It is unknown, however, whether there is a critical amount of meniscal tissue that can be removed without diminishing the structure's chondroprotective role. In order to examine the existence of such a threshold, it is necessary to accurately quantify meniscal volume both before and after partial meniscectomy to determine the amount of meniscal tissue removed. Therefore, our goal was to develop and validate an MR-based method for assessing meniscal volume. The specific aims were: (1) to evaluate the feasibility of the MR-based segmentation method; (2) to determine the method's reliability for repeated measurements; and (3) to validate its accuracy in situ. MR images were obtained on a 3T magnet, and each scan was segmented using a biplanar approach. The MR-based volumes for each specimen were compared to those measured by water displacement. The results indicate that the biplanar approach of measuring meniscal volumes is accurate and reliable. The calculated volumes of the menisci were within 5% of the true values, the coefficients of variation were 4%, and the intraclass correlation coefficients were greater than 0.96. These data demonstrate that this method could be used to measure the amount of meniscal tissue excised during partial meniscectomy to within 125.7mm³.

Keywords

Knee; Meniscus; Meniscectomy; Biomechanics; MRI

1. Introduction

The menisci of the knee are crescent-shaped fibrocartilagenous washers that protect articular cartilage by maximizing contact area and minimizing contact stress within the tibiofemoral joint. When a meniscus is torn, the contact mechanics of the tibiofemoral joint are altered, which disrupts the homeostasis of articular cartilage metabolism, placing the knee at risk for early osteoarthritis (OA). Biomechanical studies have clearly shown that joint contact mechanics are altered following meniscectomy and meniscal transplantation (Haut Donahue,

et al., 2002; Donahue, et al., 2003; Haut Donahue, et al., 2004; Huang, et al., 2002; Huang, et al., 2003; Wilson, et al., 2003; Fairbank, 1948).

Total meniscectomy was once the standard treatment for symptomatic meniscal tears. This procedure decreases tibiofemoral contact area by 50–70%, a change which significantly increases contact stress on the articular cartilage (Ahmed and Burke, 1983) and reduces its shock-absorbing capabilities (Voloshin and Wosk, 1985). The link between meniscectomy and OA has been well-documented (Englund and Lohmander, 2004; McNicholas, et al., 2000; Roos, H., et al., 1998). Thus, partial resection, in which the undamaged portion of the meniscus is preserved, is now routinely performed to eliminate symptoms while attempting to preserve cartilage integrity (Andersson-Molina, et al., 2002; Chatain, et al., 2001; Englund, et al., 2001; Englund, et al., 2003; Englund and Lohmander, 2004). However, partial meniscectomy may not eliminate the risk of early OA (Andersson and Gillquist, 1990; Andersson-Molina, et al., 2002; Chatain, et al., 2001; Chatain, et al., 2003; Cicuttini, et al., 2002; Englund, et al., 2001; Englund, et al., 2003; Higuchi, et al., 2000; Hoser, et al., 2001; Hulet, et al., 2001; Rangger, et al., 1995; Rockborn and Messner, 2000; Roos, H., et al., 1995; Roos, E.M., et al., 2001; Roos, H., et al., 1998).

To date, no clinical studies have objectively measured the amount of meniscus that can be removed following acute meniscal injury without placing the knee at risk of OA. In order to examine whether a critical threshold exists, it is necessary to quantify the amount of meniscal tissue removed during surgery. Quantitative magnetic resonance imaging (MRI) has been used to assess dimensional changes of articular cartilage (Eckstein and Glaser, 2004), and could be used to construct models of the meniscus before and after partial meniscectomy; the difference between the two volumes would indicate the amount of tissue removed.

This study's objective was to validate an MR-based approach to document meniscal size and assess changes in meniscal volume following surgery. The specific aims were: (1) to evaluate the method's feasibility (phantom model); (2) to determine the technique's reliability (cadaver model); and (3) to validate the technique's accuracy in situ (cadaver model).

2. Methods

2.1 MR imaging

Specimens were imaged on a 3T scanner (Siemens Trio, Erlangen, Germany) using a surface coil. The T2*-weighted 3D-CISS sequence [constructive interference in the steady state; TR/TE/FA, 14.5/7.3/35°; FOV, 160mm; matrix, 512x512, slice length/gap, 1mm/0; avg, 1] was utilized. Preliminary testing determined that this sequence provided high contrast between meniscal tissue and adjacent structures.

2.2 Segmentation technique

The phantom model and cadaver menisci were manually segmented from both sagittal and coronal plane image reconstructions using commercial software (Mimics 9.11; Materialise, Ann Arbor, MI). Three-dimensional voxel models were generated from the biplanar segmentations and wrapped with a triangular mesh to create a solid model of each structure. The solid models captured both meniscal volume and morphology (Figure 1). Each model's volume was calculated by surface integration.

2.3 Water volume technique

The volume of each MR-based model was compared to its water displacement volume (Stone, et al., 1994). After imaging, the menisci were carefully dissected from the joint. Each meniscus was placed in a 25cc graduated cylinder containing 25cc of isotonic saline. The displaced saline

was removed from the cylinder, using a micropipette, until the fluid level was restored to 25cc. Each water volume measurement was repeated three times, and the values averaged. Previous testing determined that the coefficient of variation for repeated water displacement measurements was 1.5%.

2.4 Feasibility study (Aim 1)

The feasibility of the segmentation method was evaluated using a plastic phantom model. A single intact fresh human cadaver knee with no evidence of knee pathology was imaged as described above. The menisci were segmented using MR-based biplanar segmentation, and 3-D models of the menisci were generated. Using rapid prototyping technology, plastic prototypes of these menisci were created. The volumes of the model menisci (medial = 4352.67mm³; lateral = 3741.38mm³) were confirmed by water displacement. The plastic models were then embedded within 1.7% agarose gel. The gel was created within a plastic cylinder (diameter 11cm, height 10cm) similar in size to a human knee cross-section. The phantom was imaged as described, and the plastic produced a contrast similar to that seen between menisci and surrounding tissues. The plastic menisci were segmented, and the MR-based volumes were compared with the known model volumes to establish a percent error in volume.

2.5 Reliability study (Aim 2)

The reliability of the MR-based segmentation method for multiple scans was evaluated using a fresh human cadaver knee. The knee was scanned 7 times; the specimen was removed and repositioned within the coil between scans. After imaging, the cadaver menisci were carefully excised, and their water displacement volumes were measured. After the menisci were segmented and reconstructed, the MR-based volumes were compared to the water displacement volumes. The coefficients of variation for both the medial and lateral menisci were calculated.

2.6 In situ validation (Aim 3)

The MR-based segmentation method was then validated in situ. 10 fresh-frozen human cadaver knees (5 pairs; mean age=56; range=52–60) with no gross evidence of knee pathology were imaged, after which one knee from each pair underwent a partial medial meniscectomy. Partial meniscectomies were performed within the inner rim of the medial meniscus. Resection size was not standardized between specimens. All knees were then rescanned. The “pre-operative” and “post-operative” MR images of each knee were segmented, and the volumes of the medial and lateral menisci were calculated. The MR-based volume of meniscal tissue removed during each resection was determined by subtracting the post-operative volume from the pre-operative volume. This value was compared to the water displacement volume of the portion of meniscus removed. The post-operative scans of the medial meniscus of the contralateral knee and the lateral menisci from both knees served as “repeated standards” to assess reliability. Because these menisci did not undergo meniscectomy, no volume changes were expected between scans. Both menisci were then removed from all 10 knees, and their water displacement volumes were determined. Reliability was quantified by calculating intraclass correlation coefficients (ICCs) for the repeated standards. Accuracy was assessed by calculating the absolute error between the MR-based volume and water displacement volume for each meniscus. Variation between right and left medial and lateral meniscal volumes was examined for these five pairs of cadaver specimens (Figure 2).

3. Results

3.1 Feasibility study (Aim 1)

When compared to the known volumes, the errors for the plastic medial and lateral menisci were 0.3% and 3.3%, respectively. The phantom MR-based volumes overestimated the intact model volumes for the medial and lateral menisci at 4363.8mm³ (versus 4352.7mm³) and 3863.1mm³ (versus 3741.4mm³), respectively.

3.2 Reliability study (Aim 2)

The mean absolute errors between MR-based and water displacement volumes of the medial and lateral menisci were 4.6% and 7.9%, respectively (Table 1). The coefficients of variation were 4% for both compartments.

3.3 In situ Validation (Aim 3)

The ICCs for repeated standards were greater than 0.96, indicating that the technique was reliable. The mean absolute errors between MR-based and water displacement volumes across all specimens were less than 5.3% (Figure 3). The average volumes of the resected pieces were 522 (range 330–880) mm³ and 565 (range 325–1000) mm³ for the MR-based segmentation and water displacement methods, respectively (Figure 3). Excluding the volumes of the resected pieces, the mean absolute errors between MR-based volumes and water displacement volumes were 4.8% and 3.0% for the medial and lateral menisci, respectively (Figure 2). The 95% confidence interval of the difference between the calculated (MR) and actual (water displacement) volumes of the removed fragments was 125.7mm³.

4. Discussion

The amount of meniscus that can be removed following an acute meniscal injury without placing the knee at risk of OA is unknown. In order to examine whether there is a critical threshold, it is necessary to quantify the amount of meniscal tissue removed during surgery. Such a method could be used to design a clinical study of partial meniscectomy for simple acute tears, in which each patient's partial meniscectomy and residual meniscal tissue could be quantified. Each patient could then be tracked, and the mechanisms of OA development following partial meniscectomy could be better understood. We have shown that this MR-based approach is accurate and reliable for tracking changes in meniscal volume. This method may also be useful for sizing meniscal allografts, because the MR-based segmentation technique results in a 3-D model in which both meniscal morphology and volume can be examined.

In developing a technique to size meniscal allografts, Stone et al utilized a similar imaging approach (Stone, et al., 1994). They used a 3-D MR sequence on a 1.5T magnet. Images were segmented in the sagittal plane, and MR measurements were performed 6 times per cadaver specimen before the menisci were excised. The volumes of the menisci were then measured by water displacement. Stone reported that the MR technique was precise but consistently underestimated true meniscal volume by 20% and 44% for medial and lateral menisci, respectively.

Our MR-based segmentation approach has several improvements. Images were obtained on a 3T magnet using the T2*-weighted, 3D-CISS sequence. The protocol provided high-resolution images and high contrast between meniscal tissue and adjacent structures. Because meniscal contours are best seen in orthogonal images, segmentations were performed using both sagittal and coronal views of the same volume to optimize the central and anterior/posterior boundaries of the menisci, respectively. The reliability study (Aim 2), in which coefficients of variation

were less than 4% for both menisci, indicated that results were reproducible. The calculated volumes of the menisci for the in situ validation study were within 5% of their water displacement volumes, and the ICCs between methods were greater than 0.96. The method was accurate for detecting meniscal morphometry before and after partial meniscectomy to within 125.7mm³.

Some limitations should be noted. The evaluations were performed using phantom (Aim 1) and cadaver specimens (Aims 2 and 3). Motion and blood flow artifacts were not present; thus, a clinical evaluation of reliability is needed. The segmentations were performed manually. To minimize variation, the images were segmented by a trained examiner under a musculoskeletal radiologist's direction. Since meniscal segmentations were performed independently, the results of the repeatability (Aim 2) and accuracy (Aim 3) studies minimize this concern. Although MRI is a reasonable means of detecting displaced meniscal fragments (Wright, et al., 1995), the accuracy of this approach for more complicated tears (i.e. bucket handle tears) remains unknown. However, based on our results (Figure 2), it would be possible to use the respective meniscus of the uninjured contralateral knee as a baseline, or check, for complex tears. Despite these limitations, the MR-based biplanar segmentation method provides an accurate and reliable way to document meniscal volumes from 3-D segmented models.

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Figure 1.

The user interface of the commercial segmentation software (Mimics 9.11; Materialise, Ann Arbor, MI) used for this study. The top panes show coronal (left) and axial (right) views; the bottom panes show the sagittal view (left) and 3-D meniscal reconstructions (right).

Figure 2.

Mean (+1 standard deviation) MR-based and water displacement volumes for right and left medial and lateral menisci of specimens used in Aim 3. Water volumes of medial and lateral menisci for each pair of knees showed mean coefficients of variation (CV) of 5.78% and 4.95%, respectively. MR-based volumes of medial and lateral menisci for each pair showed mean CVs of 6.45% and 4.32%, respectively. Mean MR-based volumes of the medial menisci of the right and left knees were 3102mm³ and 2969mm³, respectively. Mean MR-based volumes of the lateral menisci of the right and left knees were 2913mm³ and 2859mm³, respectively.

Figure 3.

Mean (+1 standard deviation) meniscal volumes for surgical and contralateral control knees using MR-based segmentation and water displacement. 565mm³ (range 325–1000mm³; water displacement-based) were removed from the medial meniscus of the surgical* knee. The mean surgical* pre-op water volume was 3020 ± 987mm³ (the sum of the post-op water volume and the volume of meniscus removed during meniscectomy). Pre-op water displacement volume equaled post-op water volume for medial control and all lateral menisci.

Table 1

The mean absolute errors between MR-based and water displacement volumes of the medial and lateral menisci Mean ($\pm$ 1 standard deviation) MR-based and water displacement volumes of one cadaver knee scanned 7 times (Aim 2). Water volume measurements were repeated 3 times.

Meniscus	Water Vol. Mean (mm ³ ; n=3)	MR-Based Mean (mm ³ ; n=7)	%Error
Medial	3041 ($\pm$ 43)	2927 ($\pm$ 118)	4.6
Lateral	3067 ($\pm$ 71)	2801 ($\pm$ 112)	7.9