**INTRODUCTION**

The meniscus plays an important mechanical role in stress transfer across the knee joint, and its structural compromise is associated with an elevated risk of arthritis [1]. The physical integrity of the meniscus is an indicator of joint health that is routinely assessed using MRI. Objective measures of that integrity have not been developed, however, leaving assessment in the realm of subjective visual observation.

Computational modeling of the knee provides an opportunity to analyze the mechanical factors that influence the development of arthritis. In previous work, discrete element analysis methods were used to provide estimates of contact stress,[2] but the meniscus was not included in those analyses, in part because of difficulties in extracting its geometry from noisy MR images.

The segmentation of the meniscus from MR images, for the purpose of assessing knee joint disease status and/or progression and to support computational modeling, is an area of active research. The development of a meniscus segmentation system that offers automation, robustness, accuracy, and speed is still an open problem.

A fully automated segmentation approach that provides quantitative analysis of meniscal volume and surface from OAI 3D sagittal DESS MR images is reported. We hypothesized that by extending our previously developed and validated automated knee bone/cartilage segmentation method, meniscus segmentation from 3D MR images could provide high volumetric accuracy and accurate meniscal surface positioning. The performance of the new approach has been evaluated in a large number of Osteoarthritis Initiative (OAI) database MR images against expert-traced analyses.

**METHODS**

A meniscal segmentation framework was developed, building on a previously reported method for automated simultaneous segmentation of all six bone and cartilage surfaces of the knee [3]. Once the knee joint bones and their cartilage surfaces were segmented in 3D, a candidate volumetric region of possible meniscal occurrence was automatically determined using a combination of computer-detected tibial and femoral cartilage surface boundaries, computer-identified region of tibia-femur contact, and a priori anatomical knowledge (Figure 1).

![Figure 1. The orange shading shows the volumetric region of possible meniscal occurrence that was searched.](image)

The lateral and medial menisci were identified within this region using a random forest classifier. The classifier was trained using 3T DESS MR image datasets from nine subjects randomly selected out of the OAI database. A trained expert observer manually traced the full 3D geometry of the menisci, providing expert-defined meniscal surfaces for volumetric evaluation of the method’s performance.

Meniscal segmentation accuracy was assessed using Dice Similarity Coefficient (DSC), sensitivity, and specificity analysis of the meniscal volume, performed in these nine knees using a leave-one-out training/testing approach. This evaluates the volumetric performance of the methods. Surface positioning errors of lateral and medial menisci were assessed in 60 additional OAI knees. The analyzed datasets included images both from the incidence and progression cohorts, to cover a range of OA severity (and presumed meniscal pathology). For performance assessment, the computer segmentation method was executed fully automatically, and no interactive editing was allowed.

**RESULTS**

Once bone and cartilage surfaces had been automatically segmented in 3D (a process which took roughly 20 minutes per dataset, on average), the meniscal segmentations took approximately 90 additional seconds per knee. The segmentations were performed using a standard desktop PC. A typical meniscal segmentation result is shown in Figure 2, clearly indicating the qualitative performance of the methods.

![Figure 2. (Top) Sample MR image slice from a 3D segmentation, with red indicating the meniscal result. (Bottom) The geometry of a typical meniscus segmentation result.](image)

Quantitatively, meniscal segmentation performance was very good, with DSC, sensitivity, and specificity values of $0.80±0.04$, $0.79±0.06$, and $1.00±0.00$, respectively. Mean signed and unsigned meniscal surface positioning errors were $0.65±0.20$ mm and $0.68±0.20$ mm, demonstrating a very good performance of the reported approach.

**DISCUSSION**

A fully automated, fast, and robust 3D meniscal segmentation approach was developed, starting from an automated bone and cartilage segmentation. The approach was able to automatically identify menisci, even in diseased knees of patients suffering from a range of pathological states, as included in the OAI incidence and progression cohorts. This suggests that the segmentation approach is well suited for objectively quantifying meniscal integrity.

The triangulated surfaces produced by the segmentation methods provide the geometry needed for characterizing meniscal integrity, or alternatively for subsequent computational modeling efforts. Since the methods are fully automated, large population-based studies may be undertaken.

While the methodology is general, its parameters are obtained via machine learning from sample MR images. Consequently, the parameters are MR-sequence specific and the system needs to be re-trained if new MR imaging sequences are used. In such a case, the shape information can be reused without changes but the image-appearance information must be re-learned from a new sequence-specific set of expert-traced image data. We are extending the functionality to other sequences as part of ongoing work.

**REFERENCES:**


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