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Automated segmentation and analysis of normal and osteoarthritic knee menisci from magnetic resonance images – data from the Osteoarthritis Initiative

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SUMMARY

Objective: To validate an automatic scheme for the segmentation and quantitative analysis of the medial meniscus (MM) and lateral meniscus (LM) in magnetic resonance (MR) images of the knee.
Method: We analysed sagittal water-excited double-echo steady-state MR images of the knee from a subset of the Osteoarthritis Initiative (OAI) cohort. The MM and LM were automatically segmented in the MR images based on a deformable model approach. Quantitative parameters including volume, subluxation and tibial-coverage were automatically calculated for comparison (Wilcoxon tests) between knees with variable radiographic osteoarthritis (rOA), medial and lateral joint space narrowing (mJSN, lJSN) and pain. Automatic segmentations and estimated parameters were evaluated for accuracy using manual delineations of the menisci in 88 pathological knee MR examinations at baseline and 12 months time-points.
Results: The median (95% confidence-interval (CI)) Dice similarity index (DSI) ($2*|Auto \cap Manual|/(|Auto| + |Manual|)*100$) between manual and automated segmentations for the MM and LM volumes were 78.3% (75.0–78.7), 83.9% (82.1–83.9) at baseline and 75.3% (72.8–76.9), 83.0% (81.6–83.5) at 12 months. Pearson coefficients between automatic and manual segmentation parameters ranged from $r = 0.70$ to $r = 0.92$. MM in rOA/mJSN knees had significantly greater subluxation and smaller tibial-coverage than no-rOA/no-mJSN knees. LM in rOA knees had significantly greater volumes and tibial-coverage than no-rOA knees.
Conclusion: Our automated method successfully segmented the menisci in normal and osteoarthritic knee MR images and detected meaningful morphological differences with respect to rOA and joint space narrowing (JSN). Our approach will facilitate analyses of the menisci in prospective MR cohorts such as the OAI for investigations into pathophysiological changes occurring in early osteoarthritis (OA) development.

Introduction

Quantitative analyses of the medial meniscus (MM) and lateral meniscus (LM) from three-dimensional (3D) magnetic resonance (MR) imaging offer opportunities to better understand the pathophysiological processes involved in the structural and functional degeneration of the menisci associated with osteoarthritis (OA)[1–3]. Recent semi[4–11] and fully-quantitative[8–15] MR studies have reported significant differences in the volume, tibial-coverage and subluxation of the menisci between knees with distinctive radiographic osteoarthritis (rOA), medial and lateral joint space narrowing (mJSN, lJSN) or pain scores. While MR scoring methods provide good reproducibility and reliability for clinical evaluation of the menisci[4–6], acquisition of detailed quantitative data on these structures through MR segmentation offers increased measurement precision for investigating the *in vivo* 3D morphological and biochemical characteristics of these fibro-cartilaginous discs (e.g., T_2, $T_{1\rho}$ imaging[16–19], analysis of volume changes with OA or post surgery[20,21]).

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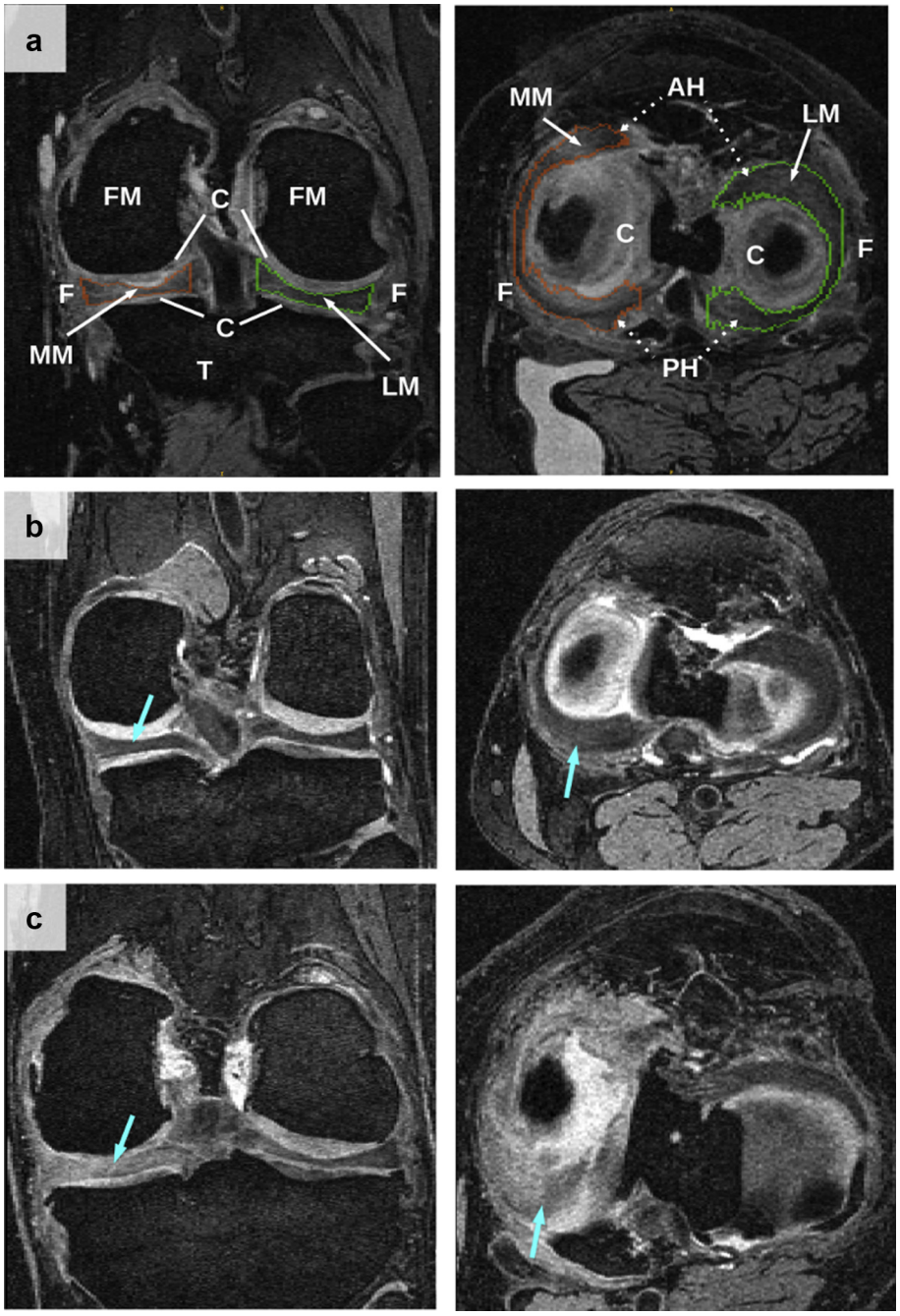

Fig. 1. (a) Manual segmentation of the menisci in a 3D weDESS MR image acquired in the sagittal plane (patient 9,056,363, female, age 57, height 168.5 cm, body mass index (BMI) 31.8 kg/m^2, rOA grade III). *(left)* Coronal view, MM = medial meniscus, LM = lateral meniscus, FM = femur, T = tibia, C = cartilage, F = fat. *(Right)* Axial view, AH = anterior horn, PH = posterior horn. (b) A 3D sagittal weDESS MR image of healthy menisci demonstrating high tissue intensity homogeneity and clear demarcation between the surrounding cartilage and fat tissues in *(left)* coronal and *(right)* axial views (patient 9,323,403, male, age 51, height 161.8 cm, BMI 27.4, rOA grade 0). (c) The menisci in a patient with moderate/severe rOA of the knee joint demonstrating "lesions" in the menisci in *(left)* coronal and *(right)* axial views (patient 9,800,677, male, age 65, 184.7 cm, BMI 31.1 kg/m^2, rOA grade III).

Manual segmentation of the menisci from 3D MR images is a time- and expertise-intensive process (35 min reported for segmentation of a single coronal water-excited double-echo steady-state (weDESS) MR[9]). Specifically, it requires numerous subjective interpretations for separating adjacent structures with comparable signal contrasts which predispose to low intra-rater reproducibility and high inter-rater variability[12]. A desirable direction is the automation of the MR segmentation and analysis.

Several semi-automatic methods for the 3D segmentation of the menisci have been developed to reduce both analysis time and rater biases[19,20]. However these still require expert training and varying levels of manual intervention. In terms of fully automated segmentation approaches[22–25], good accuracy, as measured with the Dice similarity index (DSI)[26], has been achieved for the MM (75 ± 10%) and LM volumes (77 ± 10%)[24] and a total meniscal volume (81 ± 3%)[25] although these methods were only validated on healthy menisci.

To the best of our knowledge, results and validation of fully automatic segmentations of the menisci from MR images of individuals with knee rOA have not been published. There are