

Auto-segmentation of Meniscus from MRI via a Bilateral Connectivity-based Deep Learning Network

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INTRODUCTION: MR imaging has been a valuable tool in reconstructing meniscus morphology and biomechanical changes with loading in vivo [1, 2]. Nonetheless, the manual segmentation process has remained a labor-intensive task. Hence, an algorithm that automatically produces repeatable segmentations will be beneficial to accurately assess the morphology and mechanics of menisci. Machine learning has demonstrated its potential to reliably automate the segmentation process, with the UNet, a convolutional neural network, exhibiting promising outcomes in medical image segmentation [3]. However, the UNet is a pixel-wise classification architecture, so predicted segmentations are often limited by outlier prediction and disconnected regions. On the other hand, a novel deep learning network, the bilateral connectivity-based UNet (Bicon-UNet), accounts for inter-pixel relationships, and has outperformed classic pixel-wise classification neural networks in salient object detection and medical image segmentation [4, 5]. Therefore, the objective of this study was to employ the Bicon-UNet to train and validate an algorithm to automatically and consistently segment the meniscus in knee MR images. Our hypotheses are that the Bicon-UNet algorithm will produce accurate and repeatable segmentations and will outperform the UNet algorithm.

METHODS:

Data acquisition: 10 participants without a history of lower limb injury were recruited to participate in this IRB approved study. Participants underwent MR imaging of their right knee using a 3.0T MR scanner (TrioTim; Siemens Medical Solutions) with an 8-channel knee coil while supine. Each subject contributed two scans at different times of day, with each scan consisting of 120-150 slices of sagittal plane images acquired using a double-echo steady state (DESS) sequence (field of view: 16 cm x 16 cm, matrix size: 512 x 512 pixels, slice thickness: 1 mm, flip angle: 25°, repetition time: 17 ms, echo time: 6 ms) [6]. Ground truth labels were manually segmented by a single rater and reviewed by a musculoskeletal radiologist with 30 years of experience.

Training: Our model utilized the BiconNet architecture, with a UNet as a backbone (Bicon-UNet) (Figure 1). Within this architecture, the binary ground truth label is converted into an 8-channel connectivity mask, which describes each pixel's connectivity to its 8 surrounding pixels. The bilateral-voting (BV) module enhances the output of the connectivity map, which then feeds into the region-guided channel aggregation (RCA) module to allow edge specific feature enhancement [5]. A separate UNet was trained as a baseline comparison. Models were trained for 80 epochs with a batch size of 8, Adam as the optimizer, and an initial learning rate of 0.0006 for Bicon-UNet and 0.01 for UNet. A k-fold leave-one-out cross-validation was conducted for both models.

Evaluation: Both trained algorithms were evaluated with two metrics: mean dice score coefficient (mDSC) and precision.

Repeatability: A separate dataset comprised of sagittal DESS knee scans from 8 participants, acquired from two separate visits, was used to assess the repeatability of both algorithms [7]. Segmentations from the top performing models from both algorithms were obtained and multiplied by the slice thickness to estimate the meniscus volume for each subject. A two-way random-effects Intraclass Correlation Coefficient (ICC) was used to quantify the repeatability of the model.

RESULTS: The Bicon-UNet yielded an mDSC of 0.904 and a precision of 0.933 (Figure 2), whereas the UNet baseline produced 0.831 and 0.892 for the same metrics. The Bicon-UNet yielded more repeatable results with an ICC of 0.967, compared to 0.927 from the UNet baseline. 3D point cloud reconstructions of the medial meniscus of the same subject from two morning visits are shown in Figure 3.

DISCUSSION: In this study, we used the Bicon-UNet, a novel machine learning architecture, to develop an algorithm to automate the process of producing repeatable segmentations of the meniscus from DESS knee MR scans. Preliminary results showed that the BiconNet achieved a better overall performance compared to the UNet baseline, with higher mDSC and precision. The repeatability of both models was quantified using a two-way random-effects ICC. The resultant ICC indicated excellent repeatability, with the Bicon-UNet outperforming the UNet baseline. Results from this study further signified the benefit of utilizing inter-pixel relationship in segmentation task performance. The BiconNet demonstrated its effectiveness in generating accurate and repeatable results, which reduces data variability in investigating meniscus mechanics and increasing research throughput by greatly decreasing analysis time (manual: 6hrs vs. automated: 7.5s per volume). Further work may improve the algorithm by incorporating additional and more diverse training data, such as including MR scans from those who have MRI proven meniscus tears or degeneration.

SIGNIFICANCE: This preliminary work demonstrates the ability of a novel connectivity-based architecture to automate the labor-intensive segmentation task of segmenting the meniscus. These automated 3D reconstructions of menisci can accurately and repeatably quantify meniscus morphology, thereby aiding in the study of meniscal mechanics.

REFERENCES: 1) MacLeod 2015, 2) Kawahara 2017, 3) Ronneberger 2015, 4) Yang 2021, 5) Yang 2022, 6) Coleman 2013, 7) Heckelman 2022

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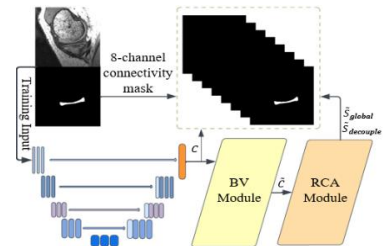


Figure 1: Bicon-UNet schematic. The Bicon-UNet contains UNet as backbone, as well as the BV and RCA module. Binary label is converted into an 8-channel connectivity mask.

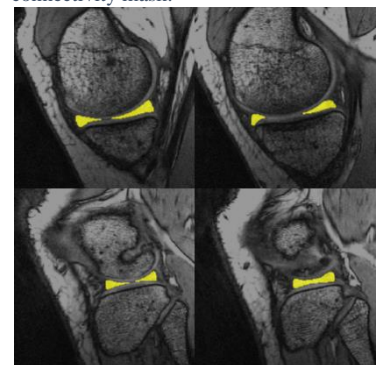


Figure 2: Overlaid predicted masks from best model of Bicon-UNet. Yellow denotes the predicted meniscus region.

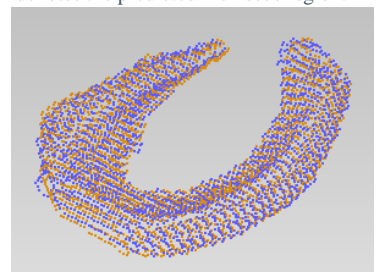


Figure 3: Overlaid 3D point cloud reconstructions of the medial meniscus of the same participant from MR scans acquired on two different mornings. The averaged estimation of the entire meniscus volume from the Bicon-UNet was about 4500 mm³, with a mean percent change of -1.27% for the two respective mornings, which achieved an ICC of 0.967.