Automated segmentation of knee MR images for biomechanical modeling of the knee joint

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I. Introduction

Subject-specific finite element (FE) modeling has provided insight into the cartilage mechanics of normal and pathological knees. Subject-specific FE modeling may someday be used as a diagnostic tool to customize care and enhance therapeutic interventions, but it is currently a time-consuming process, owing in large part to the segmentation of geometry from biomedical imaging.

Here, we propose an automated segmentation method for FE model geometry, where a 3D U-Net convolutional neural network (CNN) and a statistical shape model (SSM) are combined to extract the distal femur and proximal tibia from MR images of the Osteoarthritis Initiative (OAI) database (https://nda.nih.gov/oai/). The validity of the automated approach was verified by comparing FE-predicted maximum principal stress between manual and automated segmentations.

II. Method

First, the femur and tibia were segmented using a 3D U-Net. The outcome was adjusted for improved segmentation using a SSM that included translation, rotation, and scaling [1]. The cartilages were segmented using a 3D U-Net only. The neural network has a 5-level architecture with 16, 32, 64, 128, and 256 (bottleneck) channels respectively at each level. In total, the network has 23 convolutional layers. We used the dice loss as the loss function, i.e., 1 - dice score, and the dice score as the metric for validation. A total of 507 MR images (61.87±9.33 years; 29.27±4.52 BMI [kg/m^2]; 0.36×0.36×0.7 image resolution [mm]) from the OAI database with publicly available masks[2] were used for training, validation and test sets (365, 92 and 50 MR images, respectively). Articular cartilage was extruded from the bone surface using the cartilage thickness from the 3D U-Net. The resulted geometry was meshed using hexahedral elements. Articular cartilage was described using a biphasic constitutive model consisting of an incompressible fluid phase and a fibril-reinforced solid/matrix phase. Bones were considered isotropic homogeneous elastic. A compressive force was applied to the femur, while the tibia was held fixed. The FE-predicted maximum principal stress in the cartilage between the two segmentation methods was compared.

III. Results

The Dice similarity index for femur and tibia were 98±0.3% and for the cartilages was 88±3%. The manual construction of bones and cartilage for each subject took 8 h, as opposed to 10 min using the automated segmentation. The time history of the maximum principal stress from the two FE models developed using either the manual or automated segmentation were compared. The stress magnitude and distribution were very close and statistically insignificant ($p > 0.05$). Previous FE studies of the knee joint using automated segmentation methods examined only cartilage and ignored bones, while our method considered both bone and cartilage. Previous automated segmentation methods for creating biomechanical modeling of the knee joint were image intensity dependent, while our method eliminated this dependency by using a SSM for geometry adjustment in case of intensity artifacts in an MR image.

IV. Conclusion

The combination of CNN and SSM is a novel method for automated segmentation and geometry development of patient-specific FE models of the knee joint. This method relies on both intensity (CNN) and coordinate (SSM) data of the region of interest, resulting in stress distributions from FE analysis comparable to the model from the manual segmentation.

References

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