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A SEMI-AUTOMATED APPROACH FOR CREATING A SUBJECT-SPECIFIC FINITE ELEMENT MODEL OF THE INTERVERTEBRAL DISC

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INTRODUCTION

Over one-third of the U.S. population suffers from lower back pain and a high proportion of these cases are associated with intervertebral disc malfunction [1]. Finite element modeling (FEM) is a powerful tool for understanding disc joint mechanics, providing detailed information of stress distribution within the disc and surrounding tissues. The accuracy of FEMs is dependent on the material properties used and the ability to accurately describe the disc's complex geometry and tissue architecture.

The disc is made of fibrocartilage tissue and consists of three distinct regions: nucleus pulposus (NP), annulus fibrosus (AF), and cartilage endplate (CEP). Many of the current disc models have been generated using mesh based on computer-aided design (CAD) [2, 3]. This approach first obtains 3D image data (computer tomography or magnetic resonance images (MRI)), and then surfaces are reconstructed through segmentation. Finally, elements are generated within the disc boundary. Without further processing, image data can only provide whole disc geometry, with NP segmentation from the AF set based on anatomical data in the literature. Generally, generating a CAD-based mesh is a time-consuming manual process, because the preferred hexahedral elements cannot be generated automatically like tetrahedral elements. Furthermore, the manual process can lead to user variability in tissue geometry and position.

In contrast, voxel meshing, or an image-based meshing, is an alternative technique to CAD-based meshing. This approach directly converts imaging data to brick elements and has been widely used in bone modeling [4, 5], but rarely for disc modeling. Therefore, to overcome aforementioned disadvantages in CAD-based meshing, the objective of this study was to develop algorithms to generate a voxel mesh of a bovine disc from MRI scans. MRI scans were turned into a sequence of images to create a 3D solid. Then, individual parts of the disc were identified, including the AF, NP, and vertebral bodies using custom algorithms in Matlab (Mathworks R2016b). The outputted mesh file is widely accepted by finite element programs (e.g., ABAQUS and FEBio).

METHODS

Bovine caudal spine sections were obtained from a local abattoir. Bone-disc-bone motion segments were prepared by removing surrounding musculature and cutting through the superior and inferior vertebrae (n = 11). Each sample was imaged using a 3D Fast Low Angle Shot (FLASH) sequence (7T, Bruker MRI machine; FOV = 5 X 5 X 2.5 mm, 128 slices, isotropic resolution = 0.195 mm/pixel). Then, the sample underwent a 16-slice 2D scan using a T2 RARE sequence (TR = 6 s, 5 echoes with TEs of 11 ms, 33 ms, 55 ms, 77 ms, and 99 ms, thickness = 0.585 mm, in-plane resolution = 0.195 mm/pixel). Compared to the 3D scan, the 2D T2 weighted image had a thicker slice to increase signal strength, resulting in the NP and AF being represented separate values on the grey scale.

Raw datum were imported into ImageJ to generate a 3D image stack (Fig. 1) [2]. First, image slices from the 3D scan were analyzed to generate the 3D disc boundary. Non-disc tissue surrounding the disc (*e.g.*, surrounding ligaments) had the same signal intensity as the disc, requiring manual selection of the disc boundary (Fig. 2A). Therefore, every 6th image slice (~25% of acquired slices) was used to select the disc boundary. Once the disc boundary was selected, a signed distance function (negative inside and positive outside) was used to determine the disc boundary between image slices through interpolation [6]. The output of this process was a 3D matrix of signed distance function.

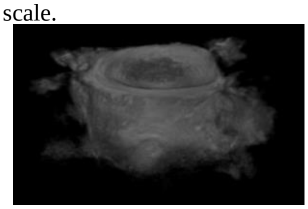

Fig. 1: 3D scan in ImageJ.

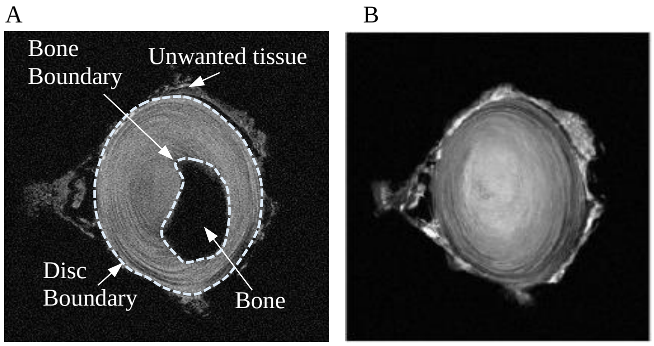

Fig. 2: (A) A 3D slice close to the bone. (B) A 2D T2 weighted image at the middle disc height.

At the superior and inferior ends of the disc, vertebral bodies were observed in MRI scans as a dark region (Fig. 2A). To obtain a disc-only mesh geometry for finite element modeling, this region was subtracted. To detect the bony region, 3D slices were binarized with a low threshold (0.25) making the bone area in the middle black and the surrounding disc tissue gray (Fig. 2A). The bone boundary was detected using the Sobel edge-detection method [7], which resulted in two regions being selected (Fig. 2A – dashed line). The outer edge selection was removed, leaving the bone boundary (Boolean operation). To enable interpolation, the boundary curve was turned into signed distance function.

In the third step, the boundary between NP and AF was extracted automatically from 2D T2 weighted scans, where the signal intensity in the NP is greater than AF due to a higher water content (Fig. 2B). The image was binarized and a threshold of 0.55 was selected for robust and repeatable results, based on preliminary experiments. Unwanted tissue surrounding the disc was as bright as NP, and, thus, remained in the binarized image. Therefore, unconnected regions of white pixels were removed using a built-in Matlab function (Matlab – bwareaopen). Finally, then NP boundary was converted into a signed distance function and interpolated for all heights throughout the disc's cross-sectional area.

CEP and bony endplate were automatically added to the superior and inferior sections of the segmented disc and was based on anatomy reported in the literature. CEP had a thickness of 0.6 mm, covering the entire NP and inner AF, while the bony endplate had a thickness of 1.5 mm [8, 9]. The last step was to write NP, AF, CEP, and bony endplate geometries into an Abaqus mesh file (.inp), which could then be imported into FEM software, such as FEBio. Finally, a Matlab GUI was developed to conduct all processes described above.

RESULTS

The disc boundary edge was obtained following boundary selection and interpolation (Fig. 3A). Fig, 4 A-D show binarization, cleaning, and edge detection of a vertebral body. Once separated, the bone was subtracted to obtain disc-only tissue at the superior and inferior ends of the disc. Fig. 4 E-D show the automated process for detecting the NP boundary from the surrounding AF tissue. The final voxel mesh contained four parts, including the NP, AF, CEP, and bony endplate (Fig. 3B).

DISCUSSION

We developed algorithms to create a semi-automated approach for converting MRI scans of the intervertebral disc into a voxel mesh for finite element analysis. While the process to determine the disc boundary required manual selection, detection of the vertebral body and NP boundaries were automated with pre-defined thresholds. Furthermore, disc segmentation and mesh generation processes were automated. In general, generation of a voxel mesh for a single disc was generated within 15 minutes (MRI scan time not included), which is much lower than the commonly used CAD-based approach (a couple of ***days***).

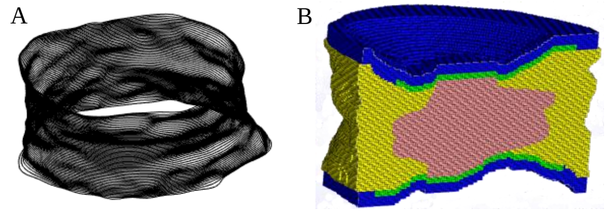

Fig. 3: (A) Disc boundary. (B) Disc meshes shown in Preview.

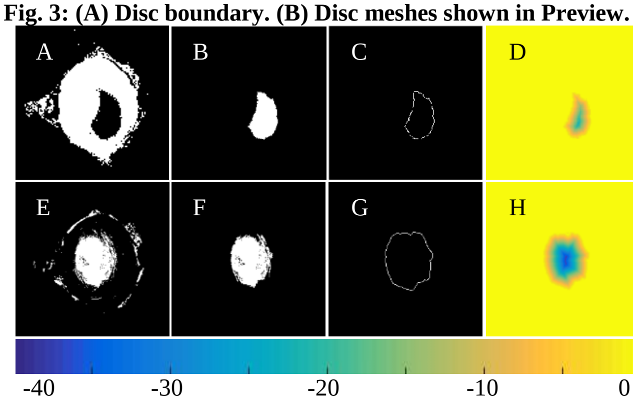

Fig. 4: (A-D) shows the process of binarization, cleaning, edge detection, and obtaining signed distance function for bone bound, original figure is Fig. 2 (A). (E-D) shows the process of detecting NP boundary, original figure is Fig. 3 (B).

Brick elements from the voxel mesh approach have higher quality than manually generated hexahedral meshing [10]. However, a disadvantage of the voxel mesh approach is the large number of elements that are generated, requiring more computational power for finite element analysis. For example, the bovine intervertebral disc model contained ~1×10^6 elements, while a CAD-based mesh approach would result in less than 10,000 elements. Therefore, voxel-mesh models require a super computer for analysis.

Auto-segmentation provided subject-specific disc geometry, and NP position and geometry (Fig. 3B). We were able to visualize AF lamellae in MRI scans (lamellae thickness ~0.3-0.7 mm; Fig. 2B) [11]; however, the scan resolution was not sufficient to determine boundaries between lamellae. In conclusion, the semi-automated voxel mesh approach presented here allowed us to create subject-specific models, with the NP, AF and vertebral bodies defined as separate tissues. The methods described here will be valuable for developing patient-specific models of human discs that can be used for diagnosis, surgical planning, or treatment evaluation.

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