Voxel Meshing for Subject Specific Intervertebral Disc Finite Element Models

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Introduction

- Finite element models (FEM) are powerful tools that can be used to understand subject specific intradiscal stress-strain distributions with injury and degeneration.
- Most current disc models have been generated using mesh based on computer-aided design (CAD) [1, 2], which reconstructs smooth surface first then generates the mesh.
- Developing CAD-based meshing is time-consuming and full of manual variability in tissue geometry and position.
- Voxel meshing (image-based meshing) converts image data to brick elements, which is a ***automatic process*** generating ***geometry-close mesh***.
- Voxel meshing is widely used in bone modeling [3, 4], but rarely for disc modeling.
- Therefore, the objective of this study was to ***develop algorithms to produce a voxel mesh of a bovine disc***, a complex fibrocartilage structure that consists of nucleus pulposus (NP), annulus fibrosus (AF), and cartilage endplate (CEP).

Methods

1. Sample Preparation and MRI Scans

- Eleven bone-disc-bone motion segments were prepared.
- Specimens were imaged using a 3D Fast Low Angle Shot (FLASH) sequence and a 16-slice 2D scan using a T2 RARE sequence (7T Bruker scanner).

2. Disc Boundary Segmentation and Reconstruction

- ImageJ was used to visualize the scan as a 3D volume (Fig.2).
- A semi-automatic approach was used to segment the disc boundary every 6th image (25% of acquired slices; Fig. 3).
- A signed distance function was obtained for the disc boundary and interpolation was conducted on them resulting in a 3D matrix output of signed distance functions [5].

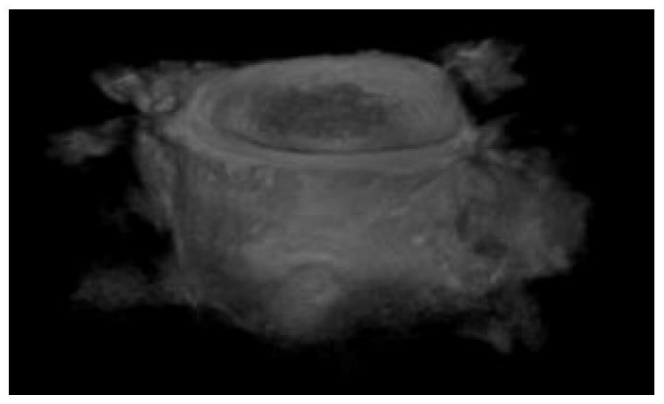

Fig 2: 3D Scan (Raw)

3.Boney Segmentation

- To separate the bone boundary, images were binarized with a set threshold (0.25).
- The bone boundary was detected using Sobel edge-detection method (Fig. 3) [6].
- The bone boundary curve was turned into a signed distance function used to interpolate between slices.
- Finally, the segmented vertebral bodies were subtracted, leaving a disc-only mesh.

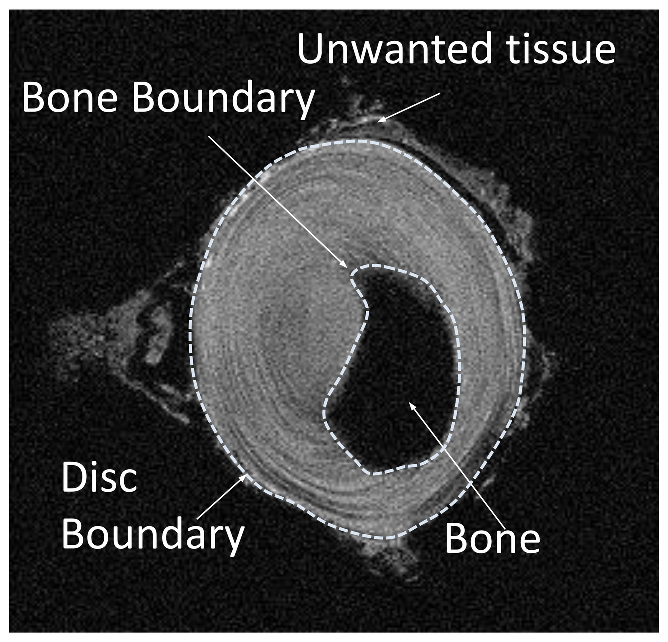

Fig 3: Selection of Two Boundaries

4. NP and AF Segmentation

- The boundary between NP and AF was determined automatically from T2-weighted images, where the NP signal intensity is greater than the AF (Fig. 4).
- Images were binarized with a threshold of 0.55.
- Unwanted regions were removed using a built in Matlab function (Matlab – bwareaopen).
- Again, the boundary was converted into a signed distance function and interpolated through the disc volume.

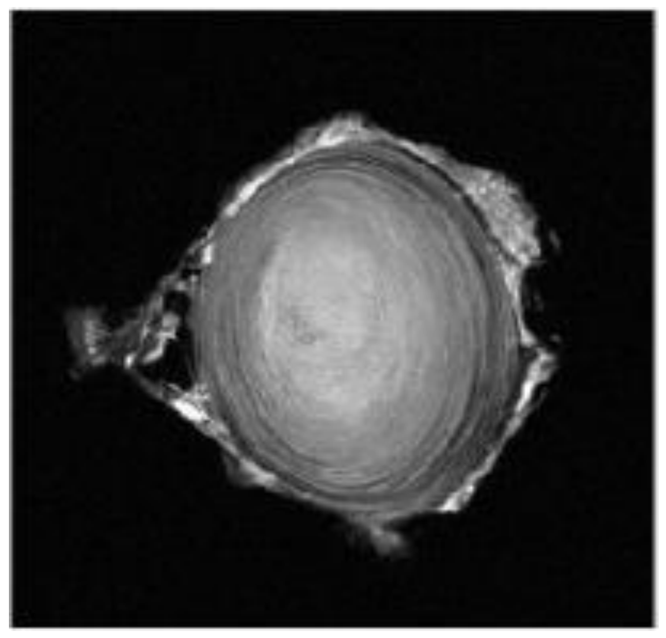

Fig 4: A 2D T2 weighted image at the middle disc height.

5. Meshing

- CEP (0.6 mm) and bony endplate (1.5mm) were added to the superior and inferior sections of the segmented disc using data reported in literature [7,8].
- Lastly, all geometries were written into an *.inp file, which can be imported into FEM software, including as FEBio and ABAQUS.

Results

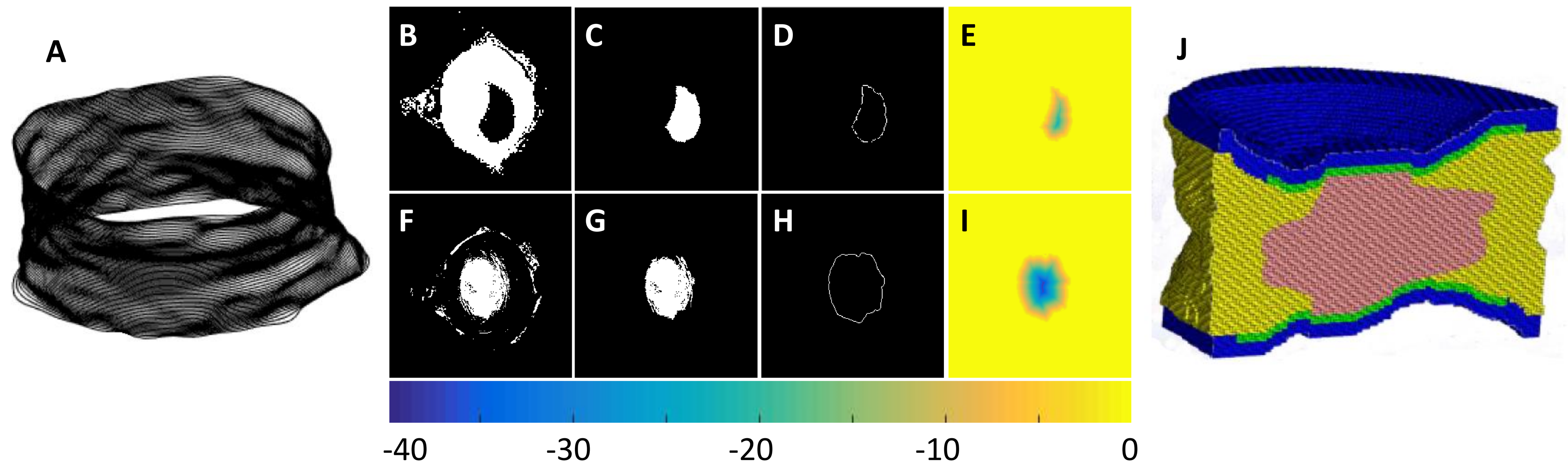

Fig. 5: (A-I) Images through each step of the mesh generation process. (J) Disc mesh shown in Preview (FEBio software).

- Fig. 5A: Disc boundary selection and interpolation through the disc thickness.
- Fig. 5B-E: Automated process for detecting the bone boundary and converting it into a signed disc function.
- Fig. 5F-I: Automated process for detecting NP boundary from the surrounding AF tissue using a similar approach that was employed for defining the bone boundary.
- Fig. 5J: Final voxel mesh, including the NP, AF, CEP, and bony endplate.

Discussion

- We developed a semi-automated approach for converting MR images of the intervertebral disc into a voxel-based mesh for finite element analyses.
- Voxel-based meshes for a single disc were generated within 15 minutes (not including scanning time), which is up to 20X faster than CAD-based approaches.
- *Importantly, this increases the feasibility of developing subject-specific models over representative models to investigate the effect of repair strategies.*
- We developed voxel mesh model for the intervertebral disc, but this method is also applicable to other soft tissue such as vessel, tendon and ligament modeling [9].
- Brick elements from voxel-based meshes have a higher quality than manually-generated hexahedral meshes, but have a larger number of elements that requires additional computational power finite element analysis [10].
- While we were able to visualize AF lamellae in the MRI the scan resolution was not sufficient to determine boundaries between lamellae.
- ***The semi-automated voxel-based mesh approach provided subject-specific disc geometry, and NP position and geometry.***
- Future work will employ the approaches described here on human discs to evaluate subject-specific stress distributions with injury and degeneration.

Acknowledgements

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References

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