Effect of Nucleus Pulposus Size and Location on Intervertebral Disc Mechanics

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Introduction

- The intervertebral disc is a complex structure, including the nucleus pulposus (NP) and the annulus fibrosus (AF), which act together to distribute large complex mechanical loads.
- The NP:Disc area ratio has been reported to be between 0.25 and 0.36, with the NP centroid located posteriorly of the disc centroid by up to 10% of the anterior-posterior width [1].
- The NP:Disc area ratio in computational and tissue engineering studies differs significantly from native tissues (0.1 - 0.60) [2-5].
- A recent study showed that the compressive stiffness of the disc decreased with an increase in NP area [6].
- The aim of this study was to ***evaluate the effect of NP size and position on disc joint mechanics under compression and bending, and rotation.***

METHODS

1. Geometry

- **Series I**: NP:Disc ratio was varied between 0.21 and 0.60 (Fig. 1 – 1st row). **Series II**: NP:Disc ratio = 0.28, NP centroid was offset anteriorly (**ASNP**) or posteriorly (**PSNP**) from the **Control** disc, which was 5% posterior to the disc centroid (Fig. 1 – 2nd row) [1].
- All seven models had the same overall disc geometry and the AF was divided into 20 layers [7, 8].
- Fibers were oriented at ±44° in the inner AF to ±28° in the outer AF [7]. The Nucleotomy model was generated by removing the NP.

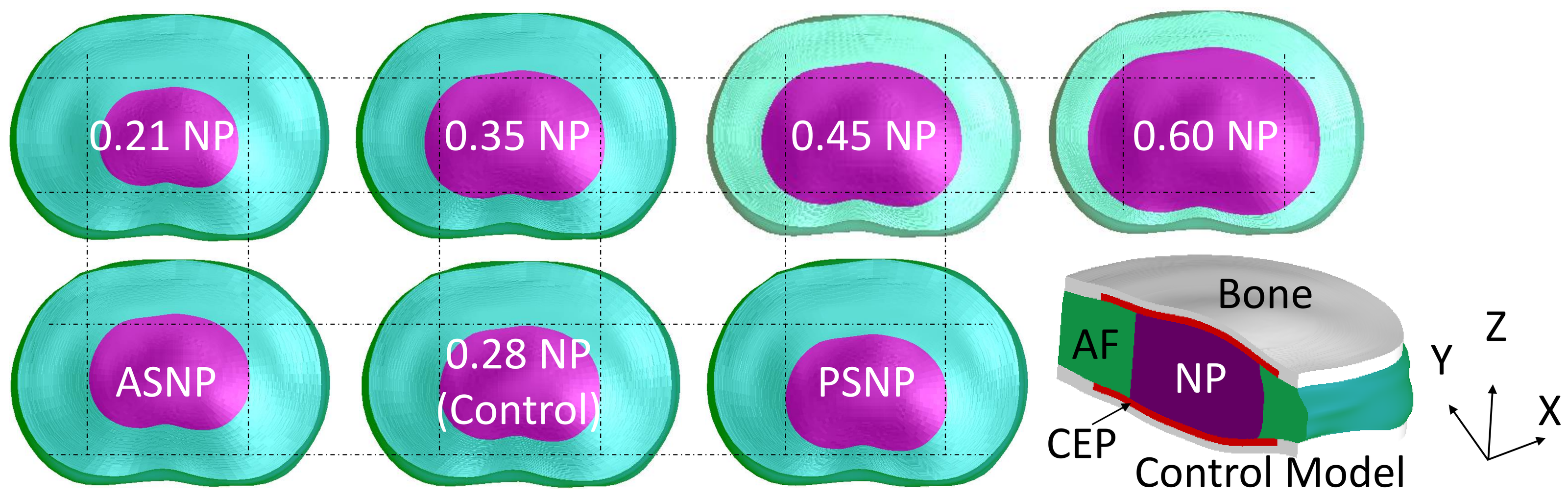

Fig. 1: Seven models with different geometric descriptions for the NP (purple) and AF (cyan).

2. Material Properties

- The NP, cartilage endplate, and bony endplate were described as isotropic hyperelastic materials, while the AF was described with nonlinear fibers in an extrafibrillar matrix.
- Fiber properties were calibrated using experimental data from the literature [7, 8], and other properties were selected from [2].

3. Model Validation and data analyses

- The Control model was validated by comparing experimental responses for single loading modalities, such as axial compression, axial rotation, and bending [9-14].
- Then, we evaluated the response of each models under duel loading conditions: 936 N (0.48 MPa) of compression before rotation (6.5° flexion, 4° extension, 5° lateral bending, and 4° axial rotation; n = 28 simulations).
- Pressure and 1st principal strain of each element was averaged in the NP and AF. For Series I, mechanical properties were curve-fit to a linear regression equation.

RESULTS

- The model was considered valid, because the response under compression (Fig. 2A) and bending (Fig. 2B & 2C) agreed well with published data.

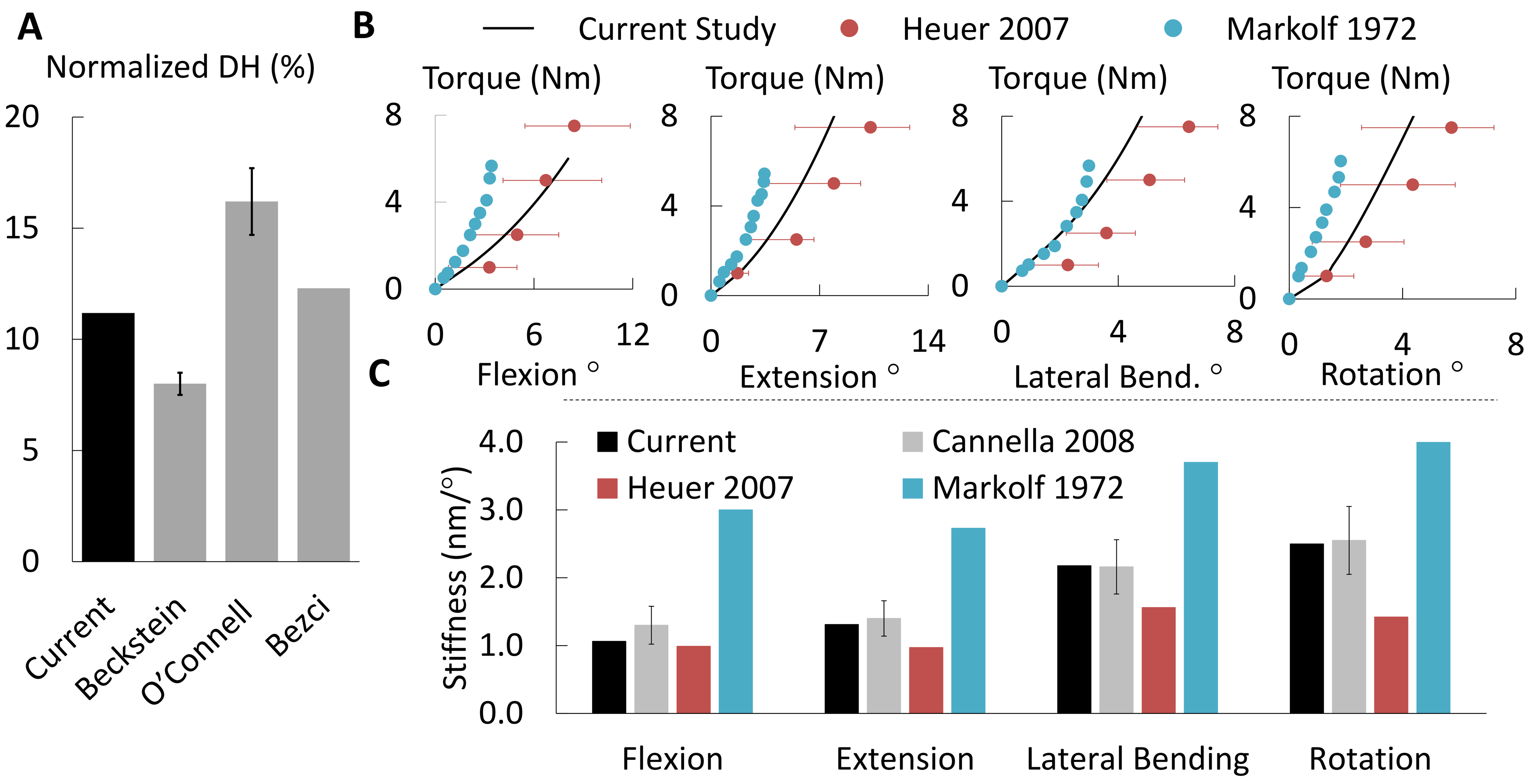

Fig. 2: Model validation results. (A) Normalized change in disc height under compression and (B) torque-rotation curves agreed well with previous studies. (C) Toe- and linear-region stiffness for bending and axial rotation compared well to data in the literature. Error bars in A and C represents one standard deviation, while bars in B represent min-max range.

- Normalized compressive stiffness increased linearly with NP:Disc area ratio (Fig. 3).

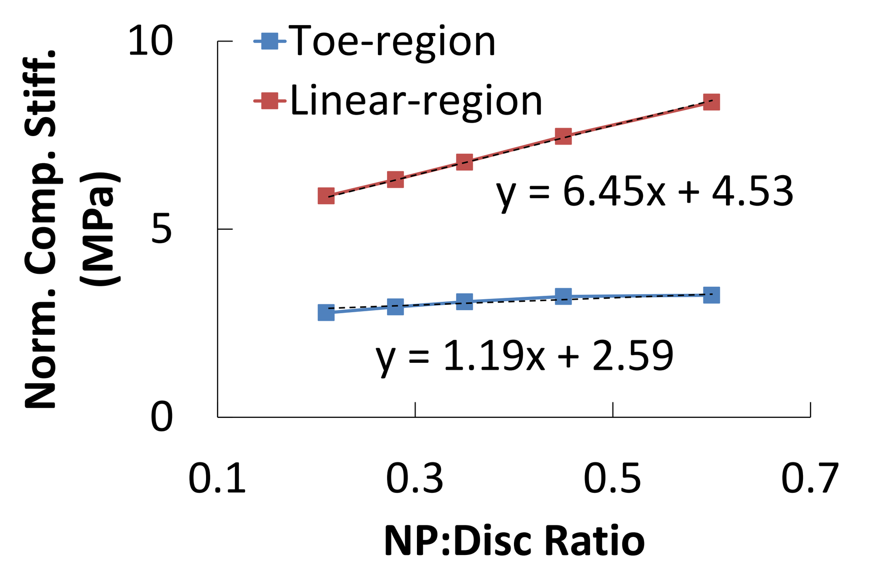

Fig. 3: Normalized compressive stiffness of toe and linear-region versus NP:Disc area ratio.

- ASNP and PSNP developed high-pressures at the interface between the NP and AF under flexion and extension, respectively (Fig. 4).

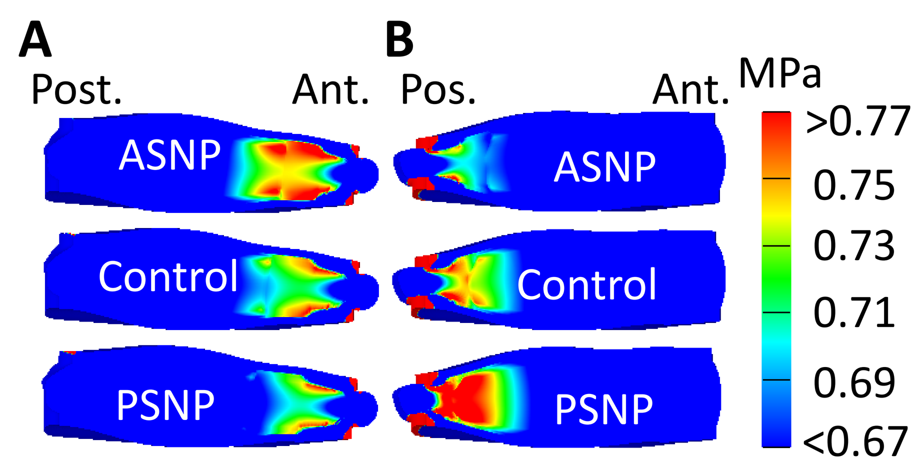

Fig. 4: Pressure distribution at the mid-sagittal plane for models loaded under compression with A) flexion or B) extension.

- Average NP and AF pressure decreased and average 1st principal strain increased with NP size (Fig. 5).

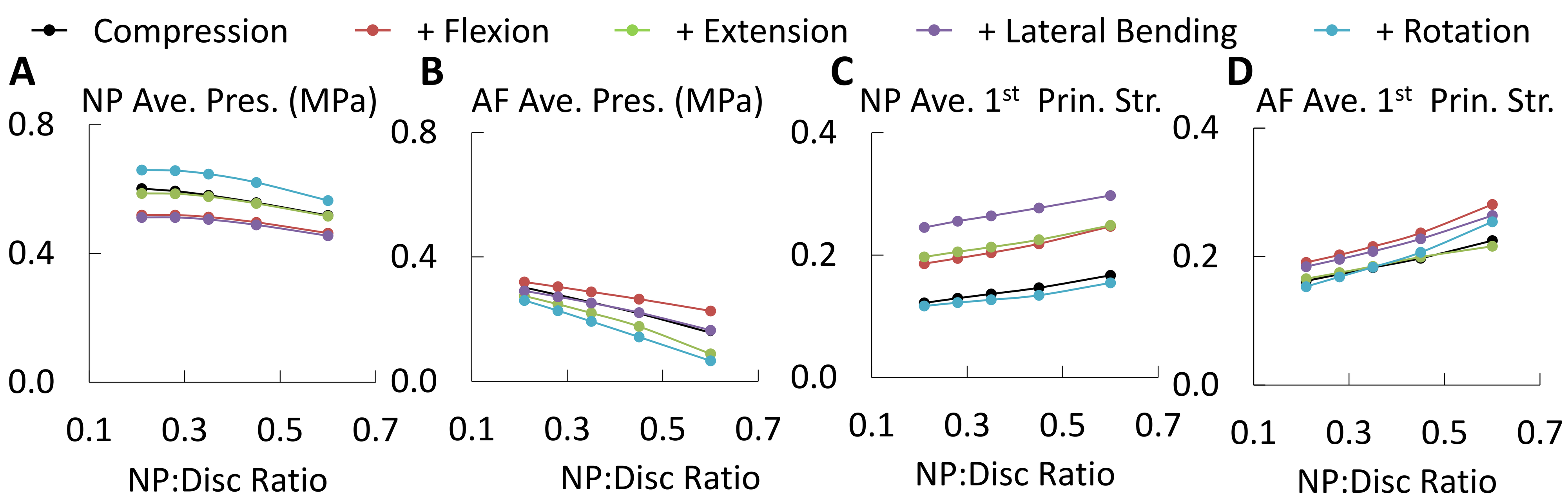

Fig. 5: Average pressure in the A) NP and B) AF under compression, bending or rotation with respect to NP:Disc area ratio. C & D) Average 1st principal strain for the NP and AF.

DISCUSSION

- Decreasing the relative NP area, decreased disc compressive stiffness, which may partially explain the loss in compressive stiffness with age [13].
- The NP area of engineered discs (NP:disc ratio = 0.1- 0.2) are often much lower than native discs, which may contribute to relatively low disc-joint stiffness [4, 5].
- The findings from this study suggests that there may exist an optimal relative NP area that maintains a homeostatic balance between pressure and principal strain (between 0.25 and 0.40).
- Although there were no differences observed in joint-level mechanics for ASNP and PSNP models, there were large differences in peak pressure distributions, highlighting the importance of quantifying intradiscal and joint-level behavior.
- A recent study showed that compressive stiffness increased with NP area [6]. The discrepancy with our findings may be due to differences in disc geometry (cylinder *vs* kidney-bean shape), differences in lamellae structure (1 *vs* 20 layers), or differences in collagen fiber orientation (±20° vs ±43° in inner AF).
- ***In conclusion, the relative NP area is important for disc joint stiffness and strain distribution in compression, while the NP centroid location is important for pressure distributions during flexion and extension.***

REFERENCES

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