Material property sensitivity of disc mechanics under physiological loading: A nonlinear finite element approach

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INTRODUCTION: Finite element analysis (FEA) is valuable to simulate the effects of degeneration or therapeutic intervention on disc and motion segment mechanics. While several spine FEA have been developed with a range of material models and material properties, and many have addressed aging and degeneration, the material property choices are not always justified and it is unknown how changes in the tissue-level material properties impact the overall motion segment's mechanical behavior. With a view toward future subject-specific models, the objective of this study was to conduct a parametric sensitivity analysis of a disc FEA model exploring how the range of physiological nucleus pulposus (NP) and annulus fibrosus (AF) material properties most impact motion segment behaviors in torsion, bending, flexion and axial creep.

METHODS: We used a non-degenerated intervertebral disc geometry [4] and baseline material properties that were validated against experimental motion segment mechanics [1,2]. We modeled the inner AF, outer AF, and NP as nonlinear, biphasic materials. The material model included: a Holmes-Mow elastic solid with strain-dependent permeability, Donnan equilibrium osmotic swelling, and in the AF only, non-linear fibers to provide anisotropy [3,4] with baseline material properties obtained from prior experiments. The FEA model was radially segregated into four distinct regions (NP, inner AF, outer AF and a transition region between them, each having different material properties. Properties in transition regions were interpolated so they would vary smoothly, based on our prior work [3,4,5]. Among the 11 parameters in each tissue region (7 matrix and 4 fiber) arising from these material models, we performed a one-parameter-at-a-time sensitivity analysis of the NP and AF properties, where the range of material properties are intended to represent both population variability and changes that occur with age, degeneration, or tissue damage. In the first case, we simulated the effect of degeneration on the NP, where each of the 7 matrix parameters in the NP region was altered, keeping the three AF regions at baseline (Table 1). Next, to explore the impact of the AF tensile material properties, each of the 4 AF fiber properties were varied (for inner and outer AF together), keeping NP and AF matrix properties unaltered (Table 2). Material property ranges were taken from tissue experiments when available or otherwise fitted to prior experimental data to extract the relevant parameters [6,7]. The FEA study design simulated four motion segment loading conditions (torsion, lateral bending, flexion, and axial creep) that were previously used to validate the baseline model [3,4].

RESULTS: In **axial torsion**, NP fixed charge density (FCD), AF fiber modulus, and AF fiber power law exponent had the largest impact on the motion segment response, while the non-fibrillar matrix had minimal effect (Fig 1A,B). In lateral **bending** (Fig 1C,D) and **flexion** (Fig 1E,F) the motion segment response was primarily governed by the NP matrix modulus and AF fiber modulus, with FCD (not shown) also exerting a significant influence during bending. In **axial creep**, the response was primarily governed by NP matrix hydraulic permeability, along with the AF fiber angle (Fig 1G,H). For each of the two cases (NP and AF) we have only highlighted the parameter with the highest sensitivity during the analysis.

DISCUSSION: This study showed that NP matrix properties of FCD and permeability predominantly governed torsional and creep behavior, whereas AF properties of fiber modulus and fiber angle, were most influential in bending, flexion, and torsion. For the NP, FCD governed torsional response, with higher values increasing swelling pressure and disc stiffness, while NP permeability strongly influenced creep, with higher permeability accelerating fluid exudation and deformation. These directions align with disc degeneration, where decrease in FCD and increase in permeability reduce the disc's ability to maintain hydration and resist sustained compression. For the AF, increased fiber stiffness increased resistance to torsion, bending and flexion whereas reduced stiffness, indicating fiber damage or degeneration diminished load bearing capacity. Overall, disc mechanics were largely governed by a small set of parameters while most had minimal impact. Moreover, different parameters have varying influence within the same disc model under various loading conditions. Variability in material properties can reflect either the state of a disc along the spectrum from healthy to degenerated or the natural variation observed within a population. These are needed to create models that replicate various stages of degeneration and, ultimately, to establish patient-specific disc models based on a reduced set of the most influential material properties. It is also important to note that the FE analyses here used non-degenerate geometries. Structural changes associated with degeneration, such as altered shape or loss of height, could influence disc mechanics in ways beyond the effects captured by changes in material properties alone.

SIGNIFICANCE/CLINICAL RELEVANCE: Since *in vivo* investigation of disc mechanics is challenging, computational approaches along with sensitivity analysis aid in investigating disc mechanics while incorporating inter-individual variability relevant towards subject-specific modeling.

REFERENCES: [1] Cortes et al. J Biomech, 2014. [2] DeLucca et al. J Biomech, 2016. [3] Newman et al. JOR Spine, 2021. [4] Fleps et al. J Orthop Res, 2024. [5] Jacobs et al. J Biomech, 2014. [6] DeLucca et al. JOR Spine 2019. [7] O'Connell et al. J Mech Behav Biomed Mater, 2011.

Table 1: NP matrix parameters and their variations

Parameters	Base	Minimum	Maximum
Modulus (MPa)	0.06	0.02	0.65
Poisson's Ratio	0.24	0.10	0.35
Exp Stiff Coefficient	0.95	0.09	6.00
Hyd Permeability (mm^4/Ns)	0.0005	0.0001	0.0060
Exp Strain Dependency	1.92	0.40	4.00
Fixed Charge Density (mM)	230	180	320
Water Content (%)	79	60	90

Table 2: AF fiber parameters and their variations

	Parameters	Base	Minimum	Maximum
Outer	Modulus (MPa)	15.6	8.0	145
	Exp Coefficient	4.0	2.0	153
	Transition Stretch Ratio	1.03	1.01	1.07
	Fiber Angles (deg)	31	27	35
Inner	Modulus (MPa)	6.92	2	135
	Exp Coefficient	4.0	2.0	153
	Transition Stretch Ratio	1.07	1.05	1.10
	Fiber Angles (deg)	42	37	50

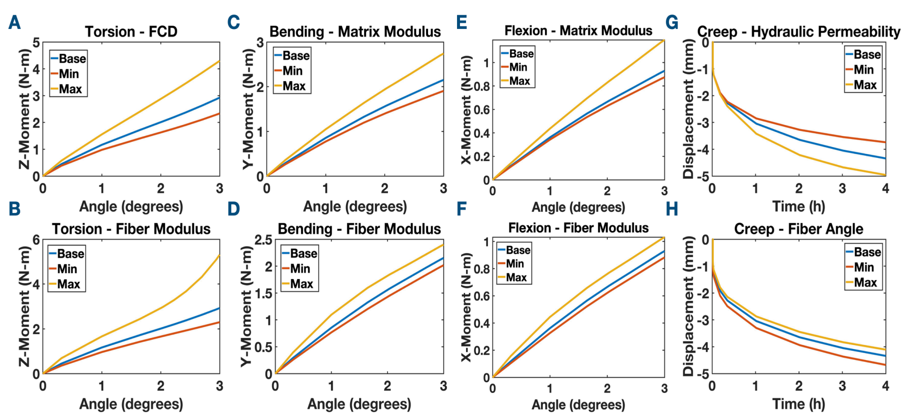

Figure 1: Variation in motion segment response for variation in NP matrix properties (TOP) and AF fiber properties (BOTTOM) during (A-B) Torsion, (C-D) Bending, (E-F) Flexion and (G-H) Axial Creep. These parameters emerged as most sensitive to these loading conditions.