Effect of Annulus Fibrosus Collagen Orientation on Intervertebral Disc Torsional Mechanical Behavior

Bo Yang and Grace D. O'Connell
University of California Berkeley, CA

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INTRODUCTION: The intervertebral disc experiences large complex deformations including compression, rotation, and bending under daily activity. For example, twisting while carrying a weight, loads the disc under axial compression and axial rotation. Previous work showed that the rate of degeneration and disc injury is higher for in workers that experience repetitive twisting and lifting [1]. Disc degeneration and injury alters fiber orientation, mechanical behavior (i.e. compressive and torsional stiffness), and load distribution between the disc and surrounding tissues [2]. Furthermore, axial rotation of individual disc joints has been shown to increase with degeneration [3]. Previous work in our laboratory demonstrated that torsional mechanics of healthy bovine discs are greatly dependent on axial compressive stress and the maximum rotation angle applied [4]. However, the effect of degeneration, injury and fiber orientation on compression-torsional mechanics is not well understood. A validated finite element model (FEM) can provide additional information about internal stress distributions that are difficult to measure experimentally. Therefore, the objective of this study is to develop and validate a FEM model of the disc joint under combined compression and torsion loading. Once the response was validated with experimental data, the model was used to determine the effect of AF fiber orientation on torsional mechanics. We hypothesize that the alternating orientation of collagen fibers through the AF plays an important role in stress distribution during axial rotation.

METHODS: *Geometry and mesh*: Previous experimental work on disc torsional mechanics has been performed in the laboratory using bovine caudal discs, which have relatively simple geometry compared to human discs [5]. Our model was built in FEBio [6] and consisted of cylindrical nucleus pulpous (NP), 8-layer tubular AF, a cartilaginous endplate covering the nucleus pulposus (NP) and half of the AF, and vertebral bone (hexahedral elements; 17270 nodes and 16128 elements). A representative sample from experimental work was used to calculate the NP and AF. *Constitutive models and material parameters*: A hyper-elastic model (Mooney-Rivlin) was chosen to describe the NP, endplate, and AF nonfibrillar matrix after considering the disc was subjected to large deformations. The Mooney-Rivlin material parameters included C_1, C_2, K (bulk modulus) and were: 0.05 MPa, 0.001 MPa, and 150 MPa, respectively, for the NP, 0.1 MPa, 0.001 MPa, and 9 MPa for the AF, and 0.5 MPa, 0.005 MPa, and 100 MPa for the endplate [7]. AF fibers were described using an exponential stress-strain relationship in the toe-region, followed by a linear function to describe the linear region behavior [6, 8]. Fibers were restricted to tension-only loading. The model parameters used to describe the fibers included C_3, C_5, C_6, and λ_m (transitional point of stretch from exponential to linear) and were set to 0.45 MPa, 45 (unitless), 93 MPa, and 1.035 (unitless), respectively. Fiber orientation was specified by the angle between fiber and the transverse plan, which decreased from 48° in the inner layer to 34° in the outer (2° decrease between layers) [9]. Vertebral bodies were modeled as Neo-Hookean material with Young's modulus (E) of 12000 MPa and Poisson's ratio (ν) of 0.3 [10], respectively. *Loading conditions*: To validate the model, axial compression was applied to 200 N followed by axial rotation to ± 5° or ±7° [4]. Axial displacement and torque were compared with experimental data. Then the fiber angle was reduced by 4° and 8° in each layer to represent fiber reorientation with degeneration or denucleation.

RESULTS: Torque and disc-height change induced by rotation agreed well with the experimental data for axial rotations of ±5° and ±7° rotations (Fig. 1A&B). The change in disc height during rotation was not symmetrical between +5° and -5°, resulting in small and larger peaks that were comparable to experimental observations (Fig 1B – circles vs. solid line). During axial rotation the disc height increased at a rate of 0.067 mm/°, resulting in decrease in disc radius at a rate of 0.112 mm/°. Circumferential stresses demonstrated significant differences in tensile stresses under axial rotation (Fig. 1C), with the outer AF experiencing more stress than the inner AF, as expected due to differences in radius. Decreasing the fiber orientation towards the transvers plane significantly increased the change in disc height (6.4% for -4° & 20% for -8°) during axial rotation (Fig. 1B).

DISCUSSION: Collagen fiber orientation with respect to the horizontal plane decreases from ±45° in the inner AF to ±28° in the outer AF [9]. Disc degeneration and nucleotomy decreases intradiscal pressure and increases the axial compressive stress applied directly to the AF [2]. These changes in stress distribution likely reorient collagen fibers towards the horizontal plane. In this study, we evaluated the effect of fiber orientation separate from changes in NP mechanics. As observed in both experimental results and simulation [4, 11], torsional loading resulted in dynamic changes in disc height. Decreasing collagen fiber orientation towards the horizontal plane increased the change in disc height under axial rotation. The AF experiences tensile stress in the circumferential direction under axial compression [12] and these stresses increase with axial rotation, thus hooping the NP and increasing disc height. The increase in disc height reduces disc radius, due to the Poisson's effect, and likely protects the AF from annular tears or microdamage by decreasing shear stress from axial rotation. Future work will focus on evaluating the effect of reduced NP pressure, due to degeneration or disc herniation, on AF stresses under axial rotation.

SIGNIFICANCE: A FEM model of the bovine intervertebral disc was developed and validated using experimental data of compress-torsional mechanical behavior. These findings demonstrate that AF collagen fiber orientation may act to protect the disc during rotation by increasing disc height, and, therefore, decreasing disc radius and maximum shear stress.

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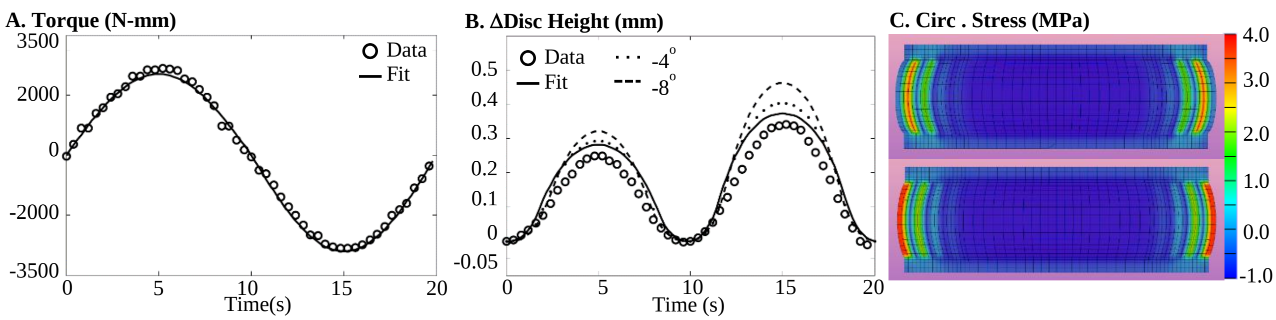

Fig.1 (A) Torque with ±5° axial rotation. (B) Change in disc height change (small peak for +5° and big peak for -5°) with rotation for data and FEM predictions (e.g., fiber angle rotation of 4° and 8° towards the horizontal plane). (C) Circumferential stress at +5° (top) and -5° (bottom).