Disc Torsional Mechanics are Influenced by Axial Compression, Rotation Angle, and Disc Geometry

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INTRODUCTION: The intervertebral disc is a complex joint that is subjected to multidirectional loads, including combinations of compression, tension, bending and torsion. Disc mechanics under compression have been studied extensively but there is a lack of understanding of disc behavior under combined loading modalities. Furthermore, there is a high prevalence of lower back pain in people that experience large loads with twisting motions, including factory workers, athletes, and military service personnel [1-3]. Characterization of disc sub-failure mechanics under compression-torsion loads is important for understanding the mechanical behavior of healthy discs, developing physiotherapies, and designing repair strategies.

Direct comparison of torsional mechanics across studies has been difficult, due to variations in experimental protocols. The presence of compressive preloads increases torsional stiffness, and hysteresis energy [4]. Moreover, there are discrepancies between computational and experimental studies regarding the contribution of disc geometry on torsional mechanics [4-6]. Thus, the objective of this study was to evaluate torsional mechanical properties under a wide range of compressive preloads and rotation angles. The second objective was to normalize disc torsional mechanical properties with geometric parameters to provide a measure of torsional mechanics comparable across species using multiple regression analyses.

METHODS: Bovine tails were obtained from a local abattoir (17 spines, ~18 months) and bone-disc-bone motion segments were prepared by cutting through the vertebral bodies (n = 40 samples). Motion segments were potted in bone cement, and hydrated overnight in a 0.15 M saline bath to achieve steady-state hydration before testing. Samples were randomly assigned to a rotation group: ±2º, ±3º, ±4º, and ±5º. Each rotation group was tested at four compressive preloads applied in a random order: 150, 300, 600, and 900 N. Compression was held for 4 hours, followed by 10 cycles of axial rotation (0.5 deg/s to maximum rotation angle). Motion segments were rehydrated in PBS bath for 24 hours before retesting under a different compressive preload.

Following mechanical testing, discs were rehydrated and removed from vertebral bodies to measure disc geometry. The polar moment of inertia was calculated assuming the disc was a hollow ellipse [7]. The last cycle of torque-rotation data was used to compute torsional stiffness (K), hysteresis energy (E_H) and strain energy during loading (U). Torsional stiffness was normalized by disc height (h) and inertia (J) to compute apparent torsional modulus (G = Kh/J). A multiple linear regression model was used to characterize the relationship between torsional mechanics and independent variables (i.e., axial stress and rotation angle). In the regression model (Eqn. 1), y is the dependent variable, x is the independent variable (x_1= axial stress, x_2= rotation angle, x_1x_2 = interaction term), β is the regression parameter, and ε is the model error. Weighted least squares (WLS) approach was used to estimate the influence of each parameter in Eq. 1.

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1 x_2 + \varepsilon \quad (1)$$

To evaluate significant geometric parameters for each mechanical property, we conducted multiple regression analyses with an additional geometric term ($\beta_4 x_4$), where the candidate parameters were disc area, height, volume, and inertia. The geometric parameter was defined as an important influence on describing torsional mechanics if it reduced the root-mean-squared error (RMSE) and increased the adjusted R^2 of the model fit.

RESULTS: Torsional stiffness increased with an increase in compressive stress or a decrease in rotation angle (Fig. 1A). Inertia was the most significant geometric parameter that influenced the model fit, as expected [7]. Normalizing the torsional stiffness by disc geometry (i.e., apparent torsional modulus) improved the model fit (adj. R^2), and all β terms had significant influence on mechanics (Fig. 1B). Hysteresis and strain energy terms increased with axial compressive stress and maximum rotation angle (Fig. 1C, E). The rate of increase in energy parameters with axial compression was dependent on the maximum rotation angle. Including a model term that accounted for disc volume for describing energy terms had the strongest influence on the model fit (e.g., E_H: adj. R^2=0.88, RMSE =524 vs. adj. R^2=0.91, RMSE =423); therefore, hysteresis and strain energies were normalized by disc volume (Fig. 1D, F).

DISCUSSION: In this study, we investigated disc torsional mechanics of healthy bovine discs under a wide range of axial compressive stresses and rotation angles. Disc torsional mechanics were dependent on compressive stress, maximum rotation angle, and the interaction of the variables, emphasizing the need to study disc mechanics under combined loading modalities that better mimic physiological motions. The apparent torsional modulus (0.03-0.22 MPa/ deg) was within the range of previously reported values for human, bovine, rat, mouse, baboon, goat and rabbit (0.02-0.28 MPa/ deg) [7,8]. The multiple linear regression model, developed based on bovine experimental data, accurately predicted normalized hysteresis energy for human discs (0.10 N-deg/mm^2), agreeing with the previously reported values for healthy human lumbar discs (0.13 ± 0.07 N-deg/mm^2 at ±2º rotation) [9]. Similarly, the model accurately predicted the hysteresis energy of rat caudal discs under 10º of rotation ($E_{H,\ predicted}$ = 1.08 N-deg/mm^2 vs. $E_{H,\ measured}$ = 1.07 N-deg/mm^2) [10]. Future work will evaluate the relationship between axial compression and rotation angle on torsional mechanical properties of healthy and degenerate human lumbar discs. In conclusion, the comparable findings between our study and previous studies suggest that the relationships defined in this study are valuable for making predictions and comparing torsional mechanical properties across studies with different loading protocols and species.

SIGNIFICANCE: Multiple linear regression models developed in this study will allow researcher to compare disc torsional mechanics across various protocols found in the literature (e.g., different loading conditions and species).

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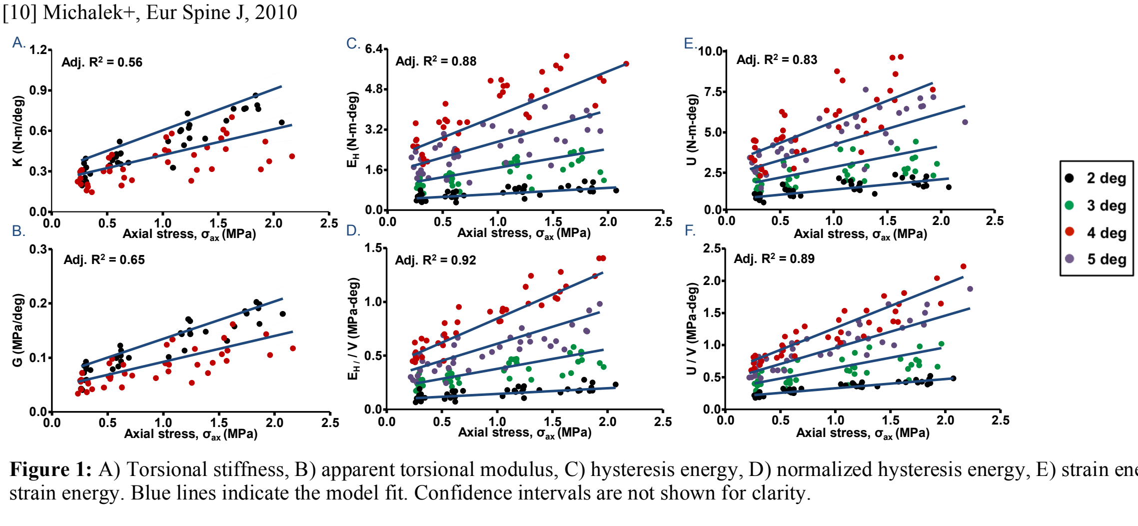

Figure 1: A) Torsional stiffness, B) apparent torsional modulus, C) hysteresis energy, D) normalized hysteresis energy, E) strain energy, and F) normalized strain energy. Blue lines indicate the model fit. Confidence intervals are not shown for clarity.