EFFECT OF ROTATION ANGLE ON DISC TORSIONAL MECHANICS

Semih E. Bezci and Grace D. O'Connell

Department of Mechanical Engineering, University of California, Berkeley
email:g.oconnell@berkeley.edu

INTRODUCTION

The primary function of the intervertebral disc is to absorb and distribute large complex loads placed on the spine, including combinations of compression, tension, bending, and torsion. While extensive research has been performed on compressive mechanics of the disc, there remains a lack of information about its torsional or axial-torsional properties.

Previous studies have indicated that combinations of torsion and compression can lead to disc degeneration, back pain, and disc injuries [1, 2]. The surrounding boney architecture of the disc joint, including the facets, may absorb part of the torsional loads placed on the spine. However, these loads may also result in rim lesions, which are tears between the disc and adjacent vertebral body, and result in neovascularization and nerve ingrowth [3]. Therefore, the disc's mechanical function under torsional loading is crucial for understanding the onset and progression of disc degeneration, back pain, and injury. The objective of this study was to evaluate the torsional properties of healthy intact bovine discs under various rotation angles.

METHODS

Caudal spine sections were acquired from skeletally mature bovines from the local abattoir (~18 months). The surrounding musculature and facet joints were removed and motion segments were prepared by making a parallel cut through the vertebrae and potted in bone cement (n = 10 samples). All samples were hydrated overnight in 0.15 M saline solution and allowed to equilibrate to room temperature prior to testing. Motion segments were attached to custom-designed fixtures with screws evenly spaced 60^o to ensure that samples did not slip during torsion. Samples were aligned with the center of the testing machine to ensure that the applied moment arm was similar for all samples. Then, samples were preloaded under axial compression (300 N) for 10 minutes, and 10 cycles of axial rotation was applied at 0.05 Hz to ± 1, 2, 3, 5 or 7^o. Maximum rotation angle was applied in a random order with full recovery between experiments. Axial force, axial displacement, torque, and rotation were recorded throughout the experiment.

Following mechanical testing, discs were removed from vertebral bodies using a scalpel. Disc geometry (i.e. disc height and cross sectional area) was measured using a custom-written algorithm in Matlab (Mathworks, Inc.) [4]. The disc's polar moment of inertia was calculated using Eqn. 1 [5]. Disc geometry and polar moment of inertia were used to normalize mechanical properties.

$$J = \frac{\pi(W_{AP}W_L^3 + W_{AP}^3 W_L - N_{AP}N_L^3 + N_{AP}^3 N_L)}{64} \qquad (1)$$

Torque-rotation data were analyzed using the last cycle of torsional loading. Axial displacement range (DR), torque range (TR), torsional stiffness (k_T), and energy loss (E_h) were computed. Torsional stiffness was defined as the slope of the most linear region of torque-rotation curve at rotation range of $0\text{-}1^o$. Energy loss was defined as the area between loading and unloading torque-rotation curve. DR was calculated by computing the difference between maximum and minimum axial displacement. Disc height (h) and the polar moment of inertia (J) were used to calculate the normalized torsional stiffness (MPa/deg), T, using Eqn. 2. Displacement range, torque range and energy dissipation were assumed to be zero under no rotation.

$$T = k_T * \frac{h}{J} \qquad (2)$$

One-way ANOVA with a Bonferroni post-hoc analysis was used to determine the effect of rotation angle on torsional mechanics. Significance was set at $p \leq 0.05$. A Pearson's correlation was performed between disc geometry and torsional mechanical properties. Correlation results that demonstrated $|r| \geq 0.7$ and $p \leq 0.05$ were considered to be strong and significant.

RESULTS AND DISCUSSION

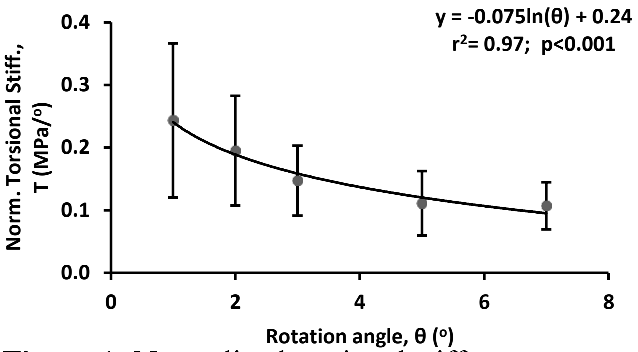

Figure 1: Normalized torsional stiffness.

There was a nonlinear decrease in the normalized torsional stiffness with rotation angle (Fig. 1). Normalized torsional stiffness appeared to plateau at approximately 0.1 MPa/^{o} for healthy discs. In contrast, there was a nonlinear increase in hysteresis, or energy loss during torsion, with rotation angle (Fig. 2). Normalizing energy loss (N-mm) by the displacement range (DR, mm) demonstrated a constant value of 28 kN for all rotations greater than 2^o. The direction of rotation (i.e. + or – rotation) did not show any difference in mechanical properties, as previously reported [5].

Torsional stiffness, a solid-like property of the disc was strongly correlated with disc height, while the energy loss, a fluid-like property of the disc, was strongly correlated with disc cross-sectional area and the polar moment of inertia (Fig. 3). However, torsional stiffness was only strongly correlated with disc height at high angles of rotation. The correlation between torsional stiffness and disc height increased with rotation angle ($|r|$= 0.09, 0.39, 0.44, 0.73 and 0.71 at ± 1, 2, 3, 5 and 7^o, respectively), which may suggest separate mechanisms absorbing torsional loads at very low angles versus higher angles. That is, as the disc experiences higher torsional loads, the collagen fibers become more engaged and have been shown to contribute to the highly nonlinear behavior of the disc under compression.

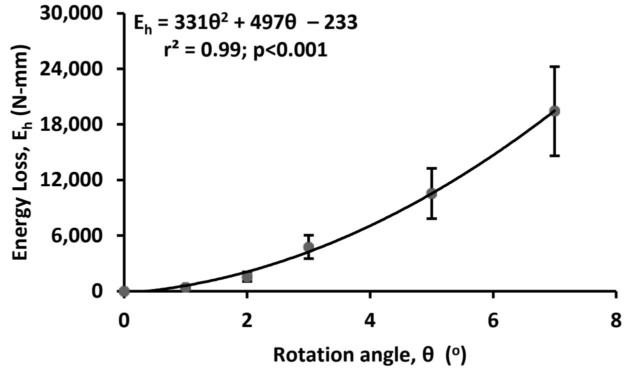

Figure 2: Energy loss with rotation angle.

The findings of this study demonstrate a functional difference between the elastic solid-like properties and fluid-like properties of the disc in axial rotation. The data in this study will be valuable in accurately describing the viscoelastic function of healthy discs. Further studies will examine the effect of torsional loading on healthy, degenerated, and injured human discs.

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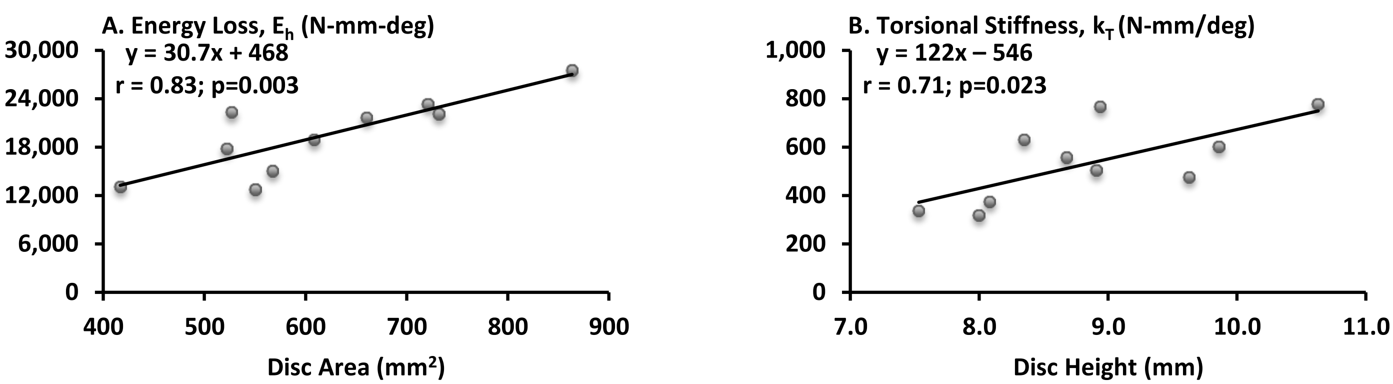

Figure 3: A) Energy loss with respect to disc area at 7^o B) torsional stiffness with respect to disc height at 7^o