Axial-torsion behavior of human lumbar intervertebral discs under physiological compressive loads

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INTRODUCTION: The primary function of the intervertebral disc is to support axial loads placed on the spinal column and to provide flexibility and mobility. During normal activities of daily living, the disc is subjected to combinations of compression, tension, bending and torsion. These complex loads result in a loss of disc height and changes in disc hydration, altering mechanical properties of the disc due to tissue compaction [1]. Previous studies have shown that torsion combined with axial compression can lead to disc degeneration and injury (e.g. disc prolapse and rim lesions), contributing to lower back pain [2-3]. Our preliminary work with bovine discs demonstrated that dynamic torsional mechanical properties were greatly dependent on maximum rotation angle and axial compressive stress [4]. There is limited data regarding the torsional mechanical behavior of human discs; however, work by Goel V.K. et al. demonstrated that 75% of axial rotation is absorbed by the disc [5]. Furthermore, the large variation of mechanical loading parameters across studies makes it difficult to compare their results. The effect of physiological changes, such as a change in intradiscal pressure due to degeneration, injury, or axial compressive loading, is important for understanding potential causes of annular injury or progression of the degenerative cascade. Therefore, the objective of this study was to determine the effect of axial compressive load on the torsional mechanical properties of human intervertebral discs.

METHODS: L3-L4 and L4-L5 discs (n = 9) were prepared from six human fresh-frozen cadavers (4 males & 2 females, age range 43-80). T2-weighted magnetic resonance images were obtained prior to sample preparation and discs were graded for degeneration using the Pfirrmann scale (grades I-III used) [6]. Three screws were inserted into superior and inferior vertebral bodies, and motion segments were potted in bone cement. Samples were hydrated overnight in 0.15 M saline and allowed to equilibrate to room temperature prior to testing. Potted segments were aligned and mounted in the material testing system (MTS, Bionix 858) and secured with evenly spaced screws that attached the grips to the bone cement (30^o spacing). Axial compression (300, 600, 900 and 1200 N) was applied and held for 2 hours. Compressive loads were selected to represent low to moderate physiological stresses. Following creep, samples were subjected to ten cycles of axial rotation (± 2^o, 0.05 Hz), based on *in vivo* measurements [7]. The testing order for each axial compression group was applied randomly with full recovery between tests. Axial force, axial displacement, rotation, and torque were recorded.

The last cycle was used to assess torsional mechanical properties, including torsional stiffness and energy loss. Energy loss was computed by calculating the area between the loading and unloading torque-rotation curve. Torsional stiffness was defined as the slope of the most linear region of torque-rotation curve at rotation range of 0-1^o. During axial rotation, the axial force and displacement were observed to follow a sinusoidal response with two distinct amplitudes. Displacement range was computed for both big (DR_B) and small peaks (DR_S; Fig. 1A). A mathematical model (Eq.1) was developed to describe the change in disc height during axial rotation (u_h), using a superposition of two Fourier series, where $b_n = \frac{4}{\pi}\frac{1}{(n-2)\cdot n\cdot(n+2)}$ for n ≥ 1 and n = odd and T is the time for half a cycle (i.e., 10 sec. for this study). One–way ANOVA was performed on mechanical properties with significance set at $p \leq 0.05$.

$$u_h = DR_B\left(\frac{1}{4}-\frac{1}{4}cos\left(\frac{2\pi t}{T}\right)+\sum_{n=1}^{\infty} b_{2n-1}\,sin\left(\frac{\pi t(2n-1)}{T}\right)\right)+DR_S\left(\frac{1}{4}-\frac{1}{4}cos\left(\frac{2\pi(t-T)}{T}\right)+\sum_{n=1}^{\infty} b_{2n-1}\,sin\left(\frac{\pi(t-T)(2n-1)}{T}\right)\right) \quad (1)$$

RESULTS: Creep displacement during the axial compressive preload agreed well with previously reported values at 1000 N (range 2.38-3.36 mm versus 2.14–3.53 mm reported in [8]). Similar to our findings with bovine caudal discs, torsional mechanical properties increased linearly with axial compressive load (Fig. 1). The constitutive relationship in Eq. 1 closely matched the change in disc height measured experimentally (R^2 = 0.98, Fig. 1A- red line). Axial displacement for both peaks decreased linearly with axial compressive load and the difference between the two peaks was consistent for all the axial compressive loading groups ($p < 0.001$; Fig. 1B). A similar trend was observed for axial load (data not shown). Torsional stiffness increased 1.8-fold from 2.98 N-m/^{o} in the low axial compressive group (300 N) to 5.39 N-m/^{o} in the high axial compressive group (1200 N; $p < 0.001$; Fig. 1C). Similarly, the energy loss during the last torsional cycle doubled from the low to the high axial compression group (~4.72 to 9.50 N-m-^{o}; $p < 0.001$; Fig. 1C).

DISCUSSION: This study determined the effect of axial compressive load on torsional mechanical properties of human lumbar discs. Torsional properties increased at a rate that was half the rate of the increase in axial compression under physiological levels of loading. That is, increasing axial compressive load by 4-fold resulted in a 2-fold increase in torsional mechanics, including stiffness and energy loss. A lack of torsional data in the literature and differences in testing parameters make it difficult to directly compare previously reported values; however, an increase in torsional stiffness due to axial compression was comparable to observations in rat discs [9]. Tensile mechanical behavior of the AF is highly nonlinear. AF fibers experience tensile stresses in the circumferential direction under axial compression, and these stresses increase under axial rotation. The linear response between physiological levels of axial compression and torsional mechanics indicates that AF fibers are loaded within the linear region of the stress-strain response during axial rotation. The change in disc height during axial rotation suggests a decrease in disc radius due to the Poisson's ratio of the disc subcomponents. These changes in disc height and radius may act to protect the outer AF from high stresses in during rotation (i.e., location of peak shear stress in torsion). In short, the complex architecture of the intervertebral disc is well suited for absorbing loads during axial rotation. This data demonstrates the importance of compressive-torsion relationship in disc torsional mechanics. Future work will focus on understanding the effect of degeneration and surrounding tissues (e.g., facet joints) on compression-torsion mechanics of the disc joint.

SIGNIFICANCE: The coupled effect of torsion and axial compression on disc mechanics is not well understood. In this study, we observed a linear increase in human lumbar disc torsional mechanics with axial compression.

REFERENCES: [1] Bezci S.E. + J Biomech Eng, (*In Press*); [2] Marras W.S. + Spine: 18(5): 617-28, 1993; [3] Hadjipavlou A.G. + Am J Orthop: 28:561-71,1999; [4] Bezci S.E. + Proc of SB3C, Utah, 2015; [5] Goel V.K. + Spine: 23(6): 684-91,1998; [6] Pfirrman C.W.A + Spine: 26(17):1873-78, 2001; [7] Haughton V.M. + Am J Neuroradiol: 23(7):1110-6, 2002; [8] O'Connell G.D. + J Mech Behav Biomed Mater: 4:933-42, 2011; [9] Showalter B.L.+ Spine: 37(15):E900-7, 2012

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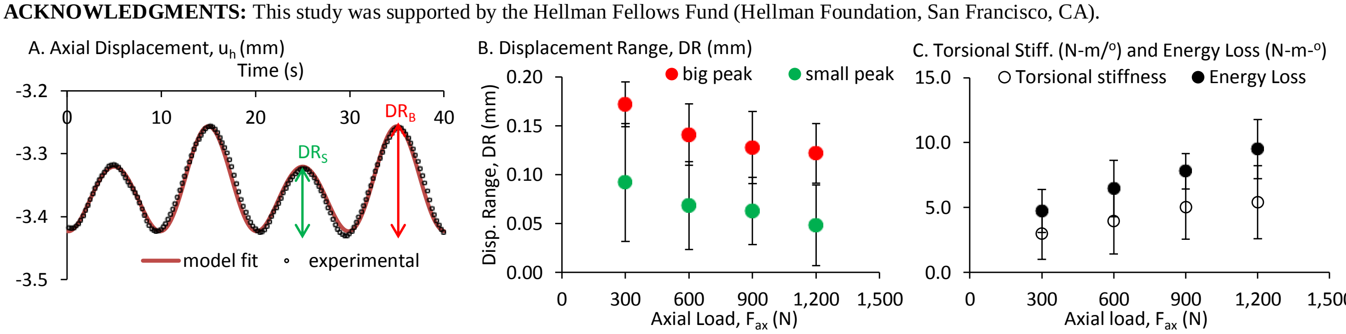

Fig 1. A) Axial displacement during torsional loading, B) Displacement range for both peaks and C) Torsional stiffness and energy loss ($p < 0.001$ for all).