Compressive Properties of Nucleus, Annulus, and Fibrous Repair Tissue

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INTRODUCTION
Wound healing is a process of filling a void or gap between tissue or implant edges. This fibrous repair tissue supports and load shares with implants including spinal intervertebral body cages or disc replacements under compression. Disc replacement implants in particular are in dynamic apposition to fibrous tissue which may experience substantial compressive stresses. Furthermore, fibrous tissue ingrowth about various types of implants and varying degrees of native disc resection place the fibrous tissue under various degrees of confined vs nonconfined compression. The dynamic implant/fibrous tissue environment may affect the mobility of the implant. Although there are studies describing the tensile properties of fibrous tissue, there is a scarcity of data in compression. The purpose of this study was to characterize the fibrous tissue under static and dynamic compressive loading conditions.

METHODS
Human lumbar discs and posterior deep spinal fibrous repair tissue obtained at revision spinal surgery (n=6 annulus; n=5 nucleus & fibrous tissue) were fresh frozen (-20°C at their native hydrated state) and cut into 12mm diameter x 6 mm high discs. Testing consisted of (i) 2 hr confined swelling in saline under 0.1 MPa which simulated in vivo static lumbar spine loads at rest; (ii) confined compression testing at 5%, 10% and 15% strain (2500, 4000, & 6000s dwell); unconfined compression testing from 5% to 15% strain at 2, 1, 0.5, 0.1, 0.01 and 0.001 Hz. Statistical analysis was performed using ANOVA.

RESULTS
There was no statistical difference between annuli and nuclei for increase in swelling height (p=0.93), but both were significantly greater than the fibrous tissue which had decreased height over time for all samples (p<0.001). In confined compression, equilibrium stress (σ) increased with increased strain and was greatest for annuli and least for the fibrous tissue (p<0.002, Fig. 1). There was no significant correlation of σ with age or degeneration for the sample size tested. Equilibrium modulus decreased with increased strain. Percent relaxation was similar for annuli and nuclei but greater for the fibrous tissue samples (Fig. 2). Unconfined dynamic testing found the storage modulus (G') was greater than the loss modulus (G'') for all tissues (Fig. 3). Annuli were found to have greater G' and G'' than nuclei, whereas values of G' and G'' were similar between annuli and fibrous tissue. Generally, there was an increase in both moduli values at greater frequencies for all tissues. Fibrous tissue had the lowest phase angle and was relatively stable across the various loading rates.

DISCUSSION
The results of the present study found numerous similarities to prior studies such as decreased compressive equilibrium modulus at increased strain and smaller values for nucleus relative to annulus (Heneghan 2008, Périé 2005). Prior reports used smaller and substantially thinner specimens as well as low preload conditions, whereas the present study was dimensionally appropriate to tissue about a nucleotomy or prosthetic spinal disc. Dynamic tests of human disc tissue were consistent with prior studies (Iatridis 1996, Leahy 2001). The relative values of the elastic component represented by G' relative to the viscous component G'' for the fibrous tissue as well as the low phase angle indicate a predominance of “solid elastic” behavior. The present study suggests that the mechanical properties of native disc tissues differ from fibrous repair tissue. The differences in mechanical properties probably reflect the difference in collagen structure and ground substance which reflects different osmotic tensions between the tissue types and therefore their hydration. This study suggests that fibrous tissue would not be a substitute for native tissue within the disc space but would still impart some degree of intersegmental stability when filling a void in the disc space. In reconstructive surgery, fibrous tissue should add to the stability to intradiscal implants particularly during acute loading conditions of a patient’s activities.

ACKNOWLEDGEMENTS
Funded by Synthes Spine, West Chester, PA and Midwest Spine Institute, Stillwater, MN.