Multigenerational Growth Approach to Incorporate Residual Stress in an Intervertebral Disc Finite Element Model with Validation in Multi-Axial Loading

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Disclosures: None to report.

INTRODUCTION: Residual stresses and strains arise in the disc from both osmotic swelling and growth & remodeling processes, and they contribute to disc mechanical behavior. For example, the "unloaded" disc has significant internal pressure and annulus fibrosus fiber tension [1]. While swelling-induced residual stresses are well described in disc finite element models (FEM), no FEMs of the disc include residual stresses in the AF fiber material properties, even though these residuals are very large. Indeed, when AF material properties are measured, the AF is cut from the disc, releasing its residual stresses, therefore, they are not incorporated into the constitutive models used in the disc FEM. We hypothesize that incorporating material models that include residual stresses are essential for disc FEM to simulate the mechanical response in all physiologically relevant loading directions. Therefore the objective of this study was to apply a multigenerational growth approach to incorporate residual stresses arising from both swelling and fiber tension in a disc FEM and to validate the model using experimental disc segment testing in all six degrees of freedom.

METHODS: FEBio was used to develop two FE models: one only included residual stress due to swelling and the other included residual stress due to both swelling and growth. Residual stresses from swelling were modeled using Donnan osmotic swelling pressure via fixed charge density [3]. Residual stresses from growth were modeled using a multigeneration approach [4] applied to the AF fibers. This approach allows for fiber populations to be added as 'generations' that are in a different reference state, enabling greater tensile stresses in the AF. To achieve this, the first fiber family (generation) was deposited with the disc rotated $+\alpha°$ in torsion, the second fiber family was deposited at $-\alpha°$, and then the disc was returned to the 0**°** position, resulting in AF fibers that are residually stressed. In addition, the disc model was given an initial outward bulge (*b*, mm) to represent the effects of internal pressure in the unloaded state and counteract the tendency for the disc to deform inward as the fiber tension increases. A parametric study on these two multigenerational parameters (α and *b*) was performed using simulated swelling under 50 N axial compression and 0.2 MPa overnight compressive creep, and the parameter values that resulted in bulge and creep displacement closest to experimental data [5] were selected. Model simulations: Using the selected α and *b*, both FE models were run to simulate disc loading and compared to experimental measures via the following protocol. Experimental protocol: Moderately degenerated (grade 2-3) cadaveric human lower lumber discs (n=6) that were preloaded to 0.2 MPa NP pressure overnight and tested in 6 degree of freedom: lateral shear, anterior-posterior (A-P) shear, torsion, lateral bending, flexion-extension and compression with a 30 min recovery between each sequence. The nonlinear load-displacement means and ± 95% confidence intervals of the responses and the stiffness at 70-90% of the peak load were calculated and compared to the FEM.

RESULTS: From the parametric study a combination of *b*=1.8 mm and α=4**°** rotation matched experimental disc bulge and creep displacement (Fig. 1A). The model that included both osmotic and growth residual stresses matched the experimental nonlinear loading response curves and the stiffness better than osmotic swelling alone for all loading directions (Fig 1B). Indeed, when both osmotic and growth residual stresses were included, the FEM predicted 4 of 6 loading directions within the 95% CI of experimental data. When only osmotic loading residual stresses were included, the model predicted stiffnesses within the 95% CI of the mean for only 2 of the 6 directions (Fig 1B).

DISCUSSION: This study demonstrated that including residual stresses arising from both osmotic loading and fiber tension are needed to model the multi-axial loading encountered by the disc. Moreover, for the first time, multigenerational approach of growth & remodeling achieved these residual stresses based on experimental data to achieve the desired constitutive properties of the disc tissues. By including AF fibers at different reference states, the AF residual stresses can be increased from those derived from swelling-only. This approach improves model predictions of multiaxial mechanics. Inclusion of only swelling-induced residual stress is sufficient to predict the disc's response to compression, as is common in the literature, but these results show the disc's response to other motions requires additional consideration of AF fiber residual stress.

SIGNIFICANCE: The disc experiences large multidirectional loading under daily activity and simulating the disc's mechanical response to these loadings is vital to the design and evaluation of implants and therapies. This study provides a methodology to apply multigenerational growth & modeling to achieve physiological residual stresses and improve the predictive capabilities of disc FEM.

REFERENCES: [1] Michalek et al. 2012 *J Biomech*, [2] Wile et al. 1999 *Spine*, [3] Jacobs et al. 2014, *J Biomech*, [4] Ateshian and Ricken 2010, *Biomech Model Mechanobiol*, [5] Showalter et al. 2016 *J Ortho Res*

ACKNOWLEDGEMENTS: NIH R01AR050052 and a Whitaker International Summer Fellowship.

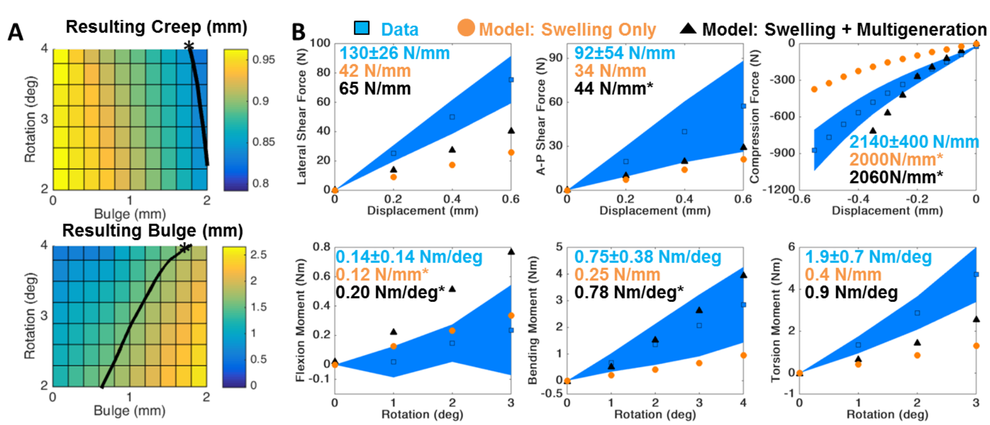

Figure 1: (A) Results of parametric study on α and *b*. Black lines show combinations of α and *b* which match experimental data. (*) denote where lines intersect. (B) Comparisons between 6DOF response for experimental data, swelling-only model, and swelling/growth model. (*) denote within 95% CI.