Residual Stress and Pressure Formation due to Swelling of Tissues within the Intervertebral Disc

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INTRODUCTION: The nucleus pulposus (NP) and the annulus fibrosus (AF) of the intervertebral disc have an excellent capacity to absorb water (up to 70% increase in volume) [1, 2]. The increase in volume after removal from the disc suggests that the tissues are not able to fully swell under *in situ* boundary conditions. Interactions between NP, AF, cartilage endplate (CEP), and bony endplate (BEP) during swelling and rehydration are not well understood. Experimental and computational studies have shown that AF swelling results in formation of region-dependent residual stresses, such that the inner AF experiences compressive stresses while the outer AF experiences tensile stresses [3-5]. Residual stress throughout the AF is thought to be important for maintaining uniform stress distribution under physiological loading, where internal pressure from the NP results in radial pressure on the AF [3-5]. However, previous studies have been limited to AF rings, without inclusion of the NP, CEP, or BEP, which will alter boundary conditions during tissue swelling. Therefore, the objective of this study was to develop a finite element model to evaluate swelling behavior of the disc joint and its sub-components [6].

METHODS: Five models were developed: Disc (>193k elements), NP + AF (>123k elements), NP explant ($1 \times 1 \times 1$ mm^3, 1000 elements), AF Ring (20 layers, >109k elements), and CEP explant ($1 \times 1 \times 0.5$ mm^3, 1000 elements; Fig. 1A). The Disc model, including separate material descriptions for the NP, AF, CEP, and BEP, and the geometry was based on L3L4 human lumbar disc (Fig. 1A - inset) [7]. NP, CEP, BEP, and AF extrafibrillar matrix were described as a triphasic material, where fixed charge density (FCD) represented the glycosaminoglycan content. FCD in the NP, CEP, and BEP was -400, -312, and 0 mmol/L, respectively, while the AF FCD decreased linearly from -300 mmol/L in the inner AF to -100 mmol/L in the outer AF [8-10]. AF collagen fibers were defined using a non-linear stress-strain relationship and material parameters were calibrated using data from single-lamellae tensile tests [11, 12], with fibers orientated at ±43° in the inner AF and ±28° in the outer AF [13]. Other material coefficients were chosen from [10]. Steady-state swelling was simulated by increasing the FCD from zero to the specified value and keeping the surrounding environment constant (0.15M saline). Swelling ratio was calculated as the volume in the deformed condition divided by the volume in the reference configuration. A normalized swelling ratio was calculated for each subcomponent as the swelling ratio in tissue-explant models divided by the swelling ratio for the tissue in the Disc model. Pressure, stress, and strain distributions were evaluated and weighted-averages were calculated for each layer.

RESULTS: ***Swelling ratio***: Normalized swelling ratio for the NP was 1.69, which was comparable to values reported for the bovine disc and represents a ~70% increase in volume when NP explants are removed from the disc [1, 2]. Similarly, the normalized swelling ratio was 1.37 for the AF and 1.45 for the CEP. Tissue swelling capacity of the NP and AF increased with each reduction in boundary constraints. That is, the NP swelling ratio increased from 1.39 in the full Disc model to 2.11 in the NP+AF model and 2.35 in the NP explant model (Fig. 1A). Removing the vertebral bodies and endplates (*i.e.,* NP + AF model) caused the NP to swell outward in the axial direction, as observed by experimentalists, and for the inner AF to swell inward in the radial direction (Fig. 1A). In the full Disc model, AF swelling was relatively uniform (1.07-1.15) across in inner-mid AF, but increased rapidly at the outer AF (Fig. 1B-1st row, black line). Swelling behavior throughout the AF was affected by endplates, such that layer-averaged swelling decreased linearly from the inner AF to the outer AF in the NP+AF and annular ring models (Fig. 1B - 1st row, black vs. grey or orange lines). ***Residual pressure & stress***: In the Disc model, intradiscal pressure was 0.22 MPa, decreasing to 0.03 MPa with the removal of adjacent endplates. The AF in the Disc model and the AF ring model developed large compressive stresses in the circumferential direction of the inner AF and tensile stresses in the outer AF, with peak tensile stresses occurring in the outer posterior AF (Figs. 1B - 2nd row, black line & 1C). However, the magnitude of tensile stress in the NP+AF model was lower than the Disc model (Fig. 1C – top vs. bottom). Residual stresses in the inner AF in the NP+AF model shifted from compressive to tensile (Figs. 1B - 2nd row, grey line & 1C).

DISCUSSION: In this study, finite element modeling was used to quantify the impact of adjacent tissues on swelling behavior and residual stress formation. As expected, the endplates restricted axial-direction deformations, increasing NP pressure and the magnitude of circumferential direction residual stress in the AF. Findings from this study suggest that NP and AF do not experience full hydration *in situ*, causing large increases in tissue volume when explants are removed for *ex situ* experiments [1, 2]. Moreover, residual stress formation in the inner AF was greatly dependent on the surrounding tissues, suggests that AF residual strains measured by cutting the tissue are not solely due to relaxation or expansion of collagen fibers [4]. Interestingly, the wedge shape of the disc resulted in peak tensile stresses to form in the posterior region of the outer AF, which is the most common location for full thickness annular tears and the resulting disc herniation [14]. These findings suggest that differences in tissue swelling capacity, due to differences in glycosaminoglycan content from the inner AF to the outer AF, may act maintain swelling homeostasis throughout the AF (Fig. 1B). Lastly, the magnitude of circumferential direction stress was relatively low in the inner AF, with a rapid transition at the mid-AF, which was likely an artifact of the CEP covering only the inner 10 layers of the AF (Fig. 1A - inset). Future work will explore the role of tissue remodeling on disc swelling behavior and residual stress formation [8, 9].

SIGNIFICANCE: Finite element models were developed to study joint- and tissue-level swelling behavior of the intervertebral disc. Models were validated using experimental data in the literature. Findings from this study highlight interactions between disc subcomponents during hydration and demonstrated the importance of swelling capacity of disc tissues for maintaining intradiscal pressure and residual stress.

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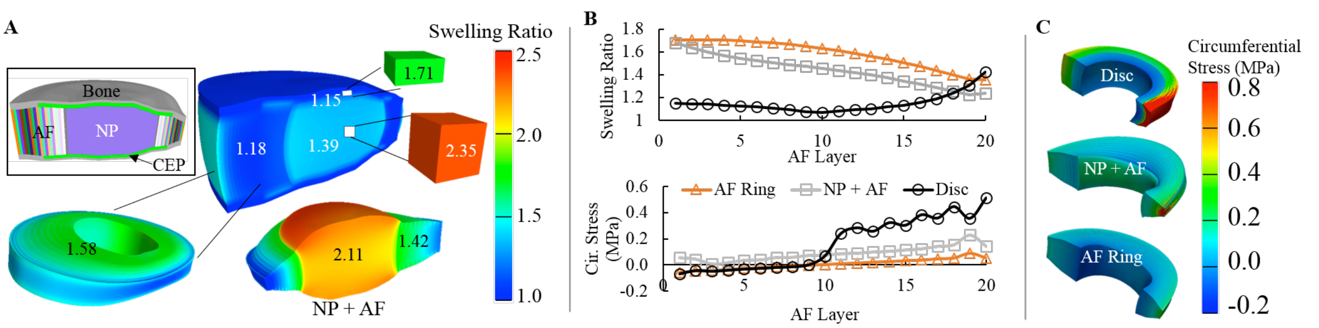

Fig. 1 (A) Swelling results for the Disc, NP + AF, AF Ring, and tissue explant (NP & CEP) models. ***Inset:*** mid-sagittal view of Disc model. Values represent tissue-swelling ratios. (B) Layer-averaged swelling ratio (1st row) and circumferential direction stress (2nd row). (C) Distribution of AF circumferential direction stress. ***Note:*** The NP was included in the simulation for Disc and NP+AF models but is not shown here.