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IN VIVO SUBJECT-SPECIFIC ESTIMATION OF CERVICAL SPINE DISCS MATERIAL PROPERTIES

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SUMMARY

A computational approach is presented and evaluated to estimate the *in vivo* elastic material properties of intervertebral disc of the cervical spine. In particular, this strategy utilizes an optimization to estimate elastic properties of both the annulus and nucleus based on *in vivo* data. Intervertebral motion data (flexion and extension) from multiple motion trials of a given subject, acquired with submillimeter accuracy using biplane radiography [1], were used to inversely estimate the disc material properties and then validate the spine mechanical model. The results showed that the proposed optimization approach can estimate the material properties to accurately reproduce the cervical spine motion.

Key words: *material characterization, optimization, intervertebral disc*

1 INTRODUCTION

Progressive deterioration of the intervertebral discs of the cervical spine is related to aging and a variety of mechanical factors. Spinal fusion is the most common surgical procedure to treat symptomatic disc degeneration. However, post-surgery, patients may experience degeneration of an adjacent disc, which has been linked to altered mechanical stresses within the cervical spine due to the fusion. Yet, the specific mechanisms behind this phenomenon remain unclear. In order to elucidate how mechanical stresses change after fusion surgery and their impact on individual intervertebral discs, it is important to establish an approach for subject-specific mechanical analysis of cervical spine mechanics. Previously developed spine models have typically assigned the same stiffness values to each disc based upon measurements obtained from cadaver tissue [2], [3]. However, this assumption neglects the heterogeneity among discs which may result in inaccurate predictions. To address this shortcoming, an optimization-based approach has been developed to estimate the material properties of each intervertebral disc based on *in vivo* motion data. The goal of this approach is to non-invasively estimate the subject-specific material properties for the annulus and nucleus of each disc within the cervical spine.

The current objective is to test the potential capability of the approach to estimate the subject-specific material properties of the annulus and nucleus of each intervertebral disc within the cervical spine. The approach is presented and evaluated with *in vivo* motion trials of a subject.

2 METHODOLOGY

2.1 Cervical spine finite element analysis approach

Computed tomography (CT) scans of the cervical spine with an average resolution of 0.30×0.30×1.0 mm were utilized, and 3D geometries of the vertebral bodies were extracted for the cervical spine (vertebrae C2 to C7). Then, intervertebral disc geometries, including annulus with embedded fibers and nucleus, were approximated based on the spacing between the vertebrae. Facet cartilage was also included to simulate the articulation between the posterior elements of adjacent vertebrae, as shown for an example vertebra in Fig. 1. The nucleus size was estimated so that it was between 40% to 50% of the total volume of the disc. The annulus fibers for each intervertebral disc were manually generated as a circumferentially oriented network embedded within the annulus matrix. The associated disc and facet cartilage were fully bonded to each vertebra. A surface-to-surface contact interaction was prescribed between facet cartilage of adjacent vertebrae with a friction coefficient of 0.1 [2]. For this preliminary study, each tissue component was assumed to be homogeneous with elastic and isotropic material properties, and initial material parameters were assigned to each component based on published values (Table 1). For all analyses the inferior endplate of C7 was fully constrained. The annulus and nucleus were assigned quadratic tetrahedral elements, and linear tetrahedral elements were used for the vertebrae and facet cartilage. Lastly, the annulus fibers were meshed as tension-only truss elements.

Table 1: Young's modulus (E) and Poisson's ratio (υ) of the spine model components [2]

Regions	Vertebrae	Annulus	Nucleus	Facet cartilage	Annulus fibers
E (MPa)	10,000	4.2	1	10.4	500
υ	0.3	0.45	0.49	0.4	0.3

The intervertebral disc geometry, including the annulus and nucleus as well as the facet cartilage were created using the commercial image processing software Simpleware. Simpleware was also applied to generate a tetrahedral mesh of tissue volumes. The annulus fibers were created and all finite element analysis was performed using the commercial finite element analysis software ABAQUS. Standard mesh convergence tests were used to ensure sufficient mesh refinement for all analyses. A total of 167,615 elements were deemed sufficient for the analysis of the subject considered.

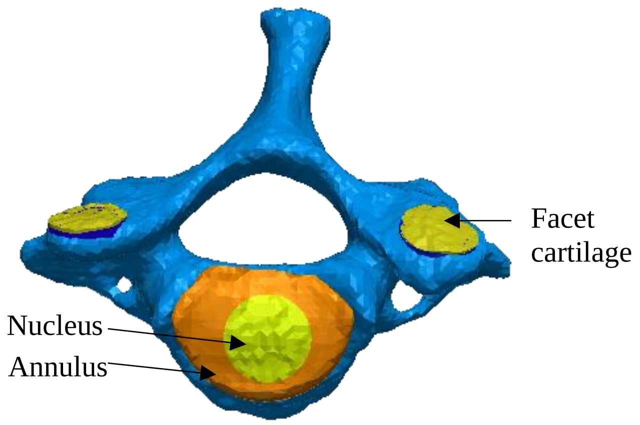

Fig.1 Three-dimensional geometry of the vertebra with intervertebral disc and facet cartilage

2.1.1 Assessment of model suitability

To first assess the suitability of the assumptions used for this subject-specific spine modeling approach, a force-deformation response from this approach with the initial material parameters was compared with *in vitro* experimental data from the literature. A moment of $1\,N \cdot m$ simulating flexion/extension was applied on the superior plane of C2 and the relative rotation of each segment (i.e., C2-C3, C3-C4, …, C6-C7) was estimated.

The estimated rotation of each segment with respect to applied moment from the finite element analysis compared with the corresponding experimental values from the literature are presented in

Fig. 2. The estimated rotations for each segment are within the range of *in vitro* experimental values reported in the literature. Thus, the finite element modeling approach presented was considered sufficiently consistent with prior similar work and suitable for further analysis.

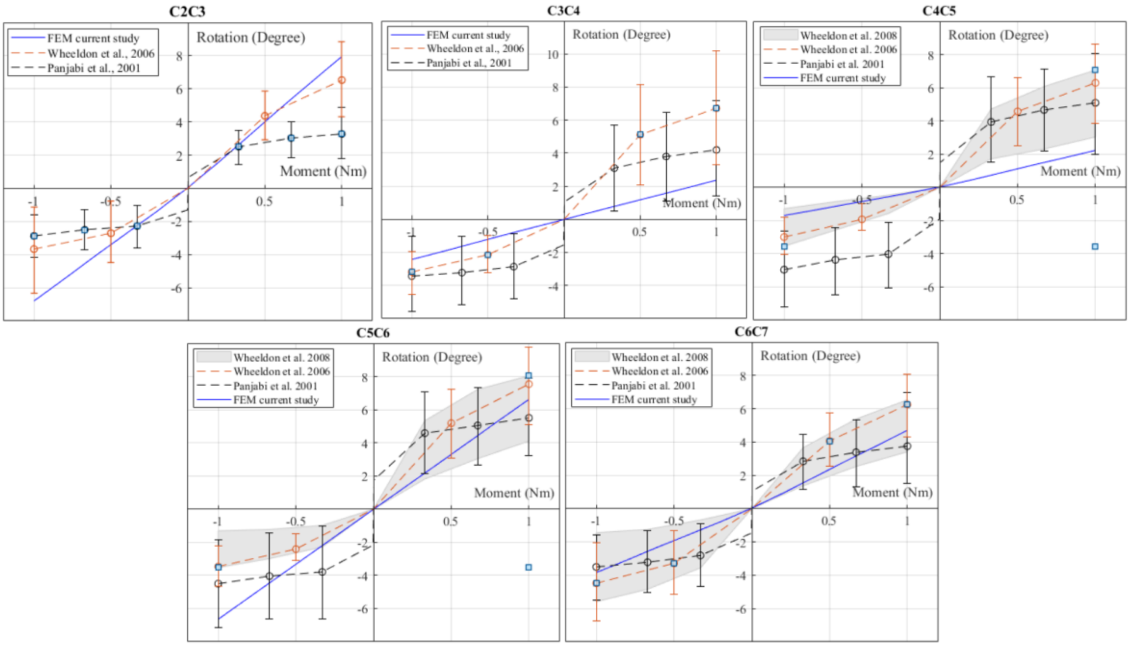

Fig.2: Validation of the developed computational spine model with literature

2.3. Calibration and validation

The calibration of the material properties of the annulus and nucleus was carried out using data from a flexion and extension trial. More specifically, kinematic data (rotation and translation) were extracted from the measured *in vivo* flexion and extension data and were applied on C2 while fully fixing the inferior endplate of C7. The calibration process was based on the displacement of two nodes (anterior and posterior) in each vertebra at the points of maximum flexion and extension. Both nodes were used to compare their simulated distance between the unloaded and loaded configuration (flexion/extension) with the measured distances for the chosen subject. As such, the calibration process sought to minimize an objective function of the following form:

$$\sum_{j}\sum_{i}\left\|\boldsymbol{U}_{Rj}^{i}-\boldsymbol{U}_{Ej}^{i}\right\|$$

where $\boldsymbol{U}_{Rj}^{i}$ is the measured (i.e., real) displacement vector of the ith node in the jth motion direction (i.e., flexion or extension) for the subject, $\boldsymbol{U}_{Ej}^{i}$ is the corresponding displacement estimated using the subject-specific spine model, and $\|\cdot\|$ is the standard L2 metric norm.

The objective function was minimized using gradient based optimization, where the gradient of the objective function was computed using finite difference for simplicity. The previously defined initial material parameter values (see Table 1) were the initial guess for the optimization process. The stopping criteria for the optimization was when the relative change in the objective function between iterations was less than 10^{-6} or the norm of the change in the Young's moduli estimations was less than 10^{-6} in subsequent iterations.

To validate the results, the subject-specific finite element model with the material parameters estimated by the calibration process was then used to estimate displacements at intermediate points (not used for the calibration) in the flexion and extension motions and again compared with the corresponding *in vivo* subject data. For this validation, the same nodes along each vertebra as used in the calibration process were used for the comparison.

3 RESULTS AND DISCUSSION

The calibration process was performed for a female subject, 47 years of age, who was scheduled to undergo a C5-C6 anterior cervical discectomy and fusion surgery. The estimated Young's moduli for each disc's annulus and nucleus for the subject are presented in Table 2.

Table 2: The calibrated material properties for the annulus and nucleus

	C2C3	C3C4	C4C5	C5C6	C6C7
$E_{Annulus}$ (kPa)	4626.0	3990.4	4425.0	6287.6	4643.3
$E_{Nucleus}$ (kPa)	241.7	247.6	783.9	3340.3	903.0

An example flexion and extension trial for validation is shown in Figure 3, which shows the position of the two nodes on each vertebra of the calibrated subject-specific finite element model compared to the *in vivo* kinematic data for the subject.

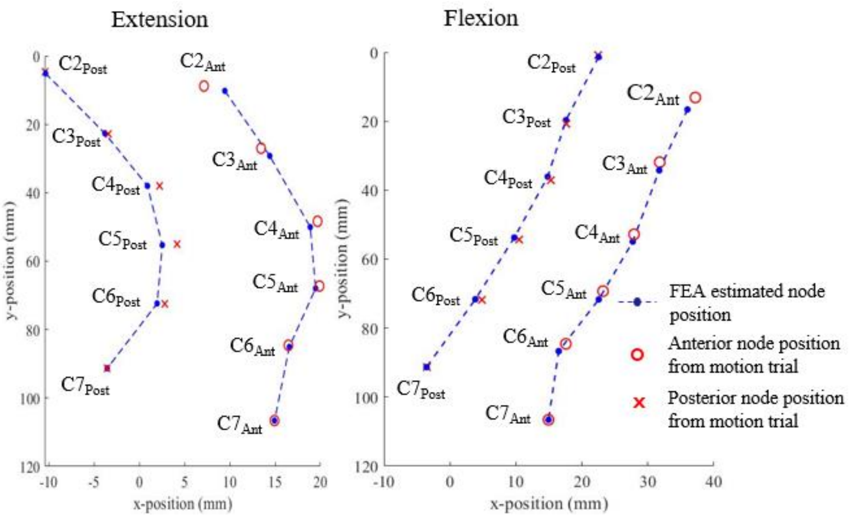

Fig. 3: The unloaded and loaded position of the nodes predicted by the spine model compared with real data.

The validation results had a mean absolute error of 0.99 mm and 2.4 mm for the displacement of the posterior and anterior nodes, respectively, for 61 frames of movement during flexion and extension. The relative accuracy of these results suggest it may be possible to estimate subject-specific material properties of the intervertebral discs non-invasively using an optimization-based approach with *in vivo* kinematic data and subject-specific finite element analysis.

Unlike traditional invasive methods, this preliminary study uses a non-invasive approach to estimate the discs material properties based on *in vivo* motion data. This method has the potential to enhance the accuracy and subject-specificity of spine mechanical models. Furthermore, incorporating heterogeneous subject-specific material properties also potentially allows for identifying discs that are more susceptible to degeneration. Future work includes expanding the cohort examined and adding potentially important biological details to the finite element analysis, such as ligaments and/or within-disc heterogeneity of each annulus (e.g., anterior, posterior, and lateral variations in properties).

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