A Computational Model of Annulus Fiber Deformation in Cervical Discs During In Vivo Dynamic Flexion\Extension, Rotation and Lateral Bending

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Introduction: Abnormal mechanical loading is believed to be one of the primary factors driving intervertebral disc degeneration[1]. Abnormal loading can be identified by computational models that estimate stress and strain within the tissues of the intervertebral disc. In order for a computational model to accurately reflect in vivo mechanics, the morphology and material properties of the tissues included in the model must accurately depict the in vivo condition. Because the overall disc response to load is affected in large part by the behavior of the annulus, the morphology and material properties of the annulus have been meticulously evaluated[2,3,4]. Anatomic studies of cervical discs have demonstrated that the structure of adult cervical discs is very different from lumbar discs[4,5]. In particular, the annulus in the adult cervical disc is crescent-shaped, being thick anteriorly but tapering laterally as it approaches the uncovertebral region[4]. These morphologic details are important to include in any computational model of the cervical disc because the mechanical behavior of the entire annulus fibrosus is determined essentially by annulus fiber bundles[2]. The objective of this study was to estimate in vivo fiber strain within the annulus of the lower cervical spine (C3-C7) during flexion\extension, rotation and lateral bending. It was hypothesized that strain would be significantly higher during the flexion\extension movement than during either the rotation or lateral bending movements. The second hypothesis was that fiber strain would be significantly different among vertebral motion segments (highest in the C34 disc, progressing to lowest in the C67 disc). The final hypothesis was that annulus fiber strain would vary significantly among regions of the disc (highest in the posterior, lowest in the anterior).

Methods: Seven healthy adults (26.7±5.5 yrs., 2 M, 5 F) provided informed consent to participate in this IRB-approved study. Participants performed full range of motion flexion/extension, axial rotation, and lateral bending movements of their head and neck while seated within a biplane X-Ray system. Three-dimensional vertebral motion was tracked using a volumetric model-based tracking technique that matched subject-specific bone models (obtained from CT) to the biplane radiographs collected at 30 frames/second. This model-based tracking technique has been validated in vivo to have an accuracy of 0.2 mm or better[6]. Morphology of the annulus[4] and geometry of the fiber bundles[3] were modeled according to the literature. Annulus fibers were arranged in rings forming a crescent-shape, with fiber orientation alternating between adjacent rings, and becoming more vertical from the anterior (30°) to the posterior (60°) annulus. Fibers rings were spaced approximately every 0.2 mm apart in the radial direction on adjacent endplates. Fiber bundles originated every 0.75 mm along each fiber ring. The annulus was modeled with three superior-inferior layers that provided attachment sites for circumferentially curved fibers that could bulge outward in response to disc compression[7]. Fiber strain was calculated from the length of each fiber in the static neutral position and the length of each fiber in each frame of the dynamic movement trial: strain = (L_{dynamic} - L_{static})/L_{static}. Thus, continuous curves of
fiber strain versus intervertebral angle were available for each of the three dynamic movements. To facilitate statistical analysis, fiber strains were averaged within four annulus regions each frame of the dynamic movements (Figure 1).

Statistical tests were performed on the maximum of the average strains within each annulus region over the entire range of motion for each of the three movements. A 3-way repeated measures analysis of variance test (3 x 4 x 4) was performed to identify differences in maximum average fiber strain among the three movements, the four motion segments (C3-C4 to C6-C7), and the four disc regions (posterior, posterior-lateral, lateral, and anterior). Significance was set at p < .05, with the Bonferroni correction applied to account for multiple comparisons.

**Results:** Peak fiber strains during the rotation (26.9±3.5%) and bending (26.5±3.5%) movements were significantly greater than during the flexion/extension movement (19.5±3.7%) (Figure 2).
Peak fiber strain consistently decreased from superior to inferior: C34 disc (29.5±7.6%), C45 disc (24.0±4.8%), C56 disc (23.8±6.1%), C67 disc (19.8±3.4%). However, these differences were not statistically significant (all p > 0.310). Peak fiber strains in the posterior (34.2%±3.9%) and posterior-lateral (28.9%±2.7%) regions were significantly greater than in the lateral (21.2%±4.0%) and anterior (13.0%±3.8%) annulus regions, and peak fiber strains in the lateral region were significantly greater than in the anterior region (Figure 3).

*Figure 2: Average peak fiber strain in the annulus during flexion/extension, rotation and bend movements, averaged over all discs and all disc regions (±95% confidence interval).*
Discussion: A computational model of annulus fiber deformation during in vivo flexion-extension, axial rotation and lateral bending was developed. This model incorporated morphology unique to the cervical discs and it accounted for disc bulging that occurs with compression. Contrary to our hypothesis, peak fiber strains were larger during the rotation and bending movements in comparison to the flexion-extension movement. Although the majority of computational models of the spine focus on the flexion-extension movement, the results of the present study suggest that rotation and bending movements may yield valuable information regarding peak disc loading during in vivo movement.

Although peak fiber strain progressively decreased from the C34 disc to the C67 disc, this difference was not statistically significant, and thus the hypothesis that fiber strain changes significantly across discs could not be supported. Finally, annulus fiber strain was significantly greater in the posterior and posterior-lateral annulus than in the lateral and anterior annulus, supporting the hypothesis that annulus strains vary among disc regions. This finding is in agreement with the clinical experience that cervical discogenic pain is most often related to damage to the posterior and posterior-lateral regions of the annulus.

The peak strain in the annulus fibers estimated by the current model (between 13% in the anterior annulus and 34% in the posterior annulus) are within the range of maximal fiber strain values reported previously (between 4% to 50%) [2,8]. A limitation of this study is that fiber spacing and orientation values were adapted from reports on lumbar annulus morphology.

These disc fiber strain values may be used as a guide to develop in vitro loading regimens that assess the biochemical response of the disc to load. Additionally, the fiber deformation values determined by the model can be combined with stress-strain parameters specific to the annulus fibers to estimate fiber stress during dynamic functional motion.
**Significance:** The results suggest that it may be more valuable to study rotation and bending movements, rather than flexion\extension, when estimating peak cervical disc loads. Larger fiber strains identified in the posterior and posterior-lateral annulus are in agreement with clinical experience indicating that these are the most common sites for disc abnormalities in symptomatic patients.

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