CERVICAL DISC DEFORMATION DURING IN VIVO FUNCTIONAL MOVEMENT

Palmer, Mara; Anderst, William; Lee, Joon; Donaldson, William; Kang, James.
University of Pittsburgh, Pittsburgh, PA, USA

INTRODUCTION

The cervical spine is comprised of seven vertebrae (C1-C7) and the corresponding intervertebral discs (IVD) that exist between two vertebral bodies. IVD act as a cushion to prevent the collision of adjacent bones or the compression of critical spinal nerves. Each intervertebral disc consists of two regions: the nucleus pulposus and annulus fibrosus\(^1\). The nucleus is an incompressible, hydrostatic region in the center of each IVD. Surrounding the nucleus, the annulus, which consists of collagen fibers called lamellae, constrains the shape of the IVD under loaded conditions\(^2\). As an individual ages or the spine supports excessive loads, degenerative processes ensue due to abnormal forces experienced by the IVD and surrounding vertebral bodies. Stokes et al. confirmed that abnormal loading is one of the primary causes of disc degeneration\(^2\).

Disc degeneration is not a process that can be easily halted. The mechanism by which disc degeneration occurs is a compounding series of events that ultimately lead to deterioration. Degeneration begins in the nucleus, and the effects spread to the annulus of the disc. As a result of a conglomerate of factors, including age, abnormal or excessive loading, or injury, the nucleus begins to lose water content, rendering it incapable of supporting the loads that it once did. Therefore, additional forces are now spread to the annulus. The fibers of the annulus must compensate for the dysfunction of the nucleus. The additional forces in the annulus fibers can cause the disc to degenerate, resulting in collisions of two vertebrae or stress and compression of spinal nerves; both cause acute pain.

Individuals experiencing severe cervical disc degeneration undergo spinal fusion to alleviate pain. Spinal fusion consists of removing the IVD of the compromised motion segment, inserting a bone chip into the former IVD space, and fixing the vertebrae with a metal plate to facilitate the union of the two bones\(^3\). Disc degeneration is the primary reason individuals undergo spinal fusion\(^4\). Furthermore, a study completed in 2008 found that 413,171 individuals undergo spinal fusion annually, and of those cases, cervical disc degeneration was the second leading cause for surgery\(^4\).

Yet, with this high surgical rate, a method to detect in vivo disc degeneration using kinematic analysis does not exist. In vivo models of cervical IVD and the effects of dynamic motion on the disc are limited. Cadaveric studies compiled stress profiles of IVD in static flexed and extended positions under uniform loads\(^5\); however this is not representative of the angles and forces experienced within the disc during functional motion. Therefore, the study presented will use motion capture technology to analyze in vivo IVD deformation during functional motion, a parameter that cannot be measured from cadaveric studies.

OBJECTIVE

The objectives of this study are (1) to create an anatomically accurate computational model of cervical spine IVD, and (2) to characterize disc response and estimate in vivo disc deformation in four distinct regions of the disc (anterior, lateral, posterior, and posterior) in young, healthy individuals during the dynamic motions of flexion/extension, lateral bending, and rotation. The analyses made will ultimately consider percent deformation, identifying a change in disc fiber length throughout functional motion compared to a static neutral disc fiber length.

HYPOTHESIS

During functional, dynamic motion, the posterior region of the disc will experience the greatest percent deformation and the anterior region will experience the least percent deformation.

METHODS

Seven healthy, asymptomatic participants (26.7±5.5 yrs; 2 M, 5 F) provided informed consent to participate in the IRB-approved study. Kinematic data and subject-specific, CT-derived bone models from a previous study examining range of motion in young, healthy adults were used for this study. Kinematic data included the motion paths tracked by combining the CT-derived bone models, radiographs from a high-speed biplane X-ray system, which captures images at 30 frames/second for 3 seconds, and a volumetric model-based tracking program. The imaging techniques allow for continuous, three-dimensional motion to be analyzed, as opposed to similar studies that only examine static angles in two dimensions. The motions analyzed in both studies include flexion/extension, lateral bending, and rotation.

Using a software program, IVD boundaries were defined on five vertebrae (C3-C7) for each participant. A total of 20 location markers were placed on the superior endplate of each subject-specific CT-derived bone model, four for anatomical reference (anterior, posterior, right and left) and 16 for IVD boundary definition. In total, 18 markers were placed on the inferior endplate of each vertebral body; four for anatomical reference and 14 for IVD boundary definition. Boundary markers were distributed based on curvature of the endplate; the superior endplate has more curvature in its morphology due to the uncovertebral joint. Therefore, it received more markers. The markers used for IVD creation were placed in general regions common to all vertebrae to accommodate for differences in size and shape of the bones.

IVD anatomy was based on previous studies and was pivotal for accurate in vivo analysis. The anatomical aspects of the disc considered were annulus geometry, fiber orientation, and fiber spacing. The crescent shape of the cervical IVD and fiber angle orientation were provided by Mercer et al’s study\(^1\). The crescent geometry means the anterior region has a greater number of fibers that decrease in amount as the annulus spreads to the posterior region\(^1\). The anterior portion of the IVD contains fibers oriented at small, acute angles which gradually becomes less severe as the fibers continue to the posterior region\(^1\). Fibers in the posterior region approach a vertical orientation\(^1\). Cervical IVD morphology data is limited; hence, lumbar disc fiber spacing was adapted from a study completed by Marchand et al\(^6\).

Four IVD were created for each spine (C3-C4 through C6-C7). An existing in-house program coupled the kinematic motion
data with the defined IVD boundaries to create a computational IVD model and calculate percent deformation of the disc fibers across the dynamic movements. Fiber lengths of the modeled cervical IVD were measured in a static neutral position. Disc fiber length was subsequently measured throughout each motion, and the change in fiber length was divided by the static neutral fiber length to calculate percent deformation across each motion for each IVD in the spine.

The data collected was statistically analyzed using a 3-way repeated analysis of variance test (3x4x4) in SPSS Statistics. Tests were performed on the maximum of the average percent deformation in each of the four regions of the disc, across the three motions performed, and the four IVD analyzed (C3-C4 through C6-C7). The alpha value was set at 0.05, and Bonferroni correction was applied to account for multiple comparisons. Each direct comparison of disc regions showed a significant difference (p < 0.05).

RESULTS
The study yielded both qualitative and quantitative results. Qualitatively, the program produced a computational IVD model (Figure 1). The fibers in each region were color-coded for visual distinction. Both the complete cervical spine and a single-level IVD can be visualized. The model illustrates correct anatomical morphology, as defined by the literature. The disc model includes 20 fiber rings anteriorly, and 6 posteriorly. The number of fibers per ring ranges from 20, for the small rings close to the nucleus, to 60, for the large rings farthest from the nucleus.

Figure 1: Computational Model of Cervical IVD. The above picture depicts a completed model of the cervical spine (C3-C7), left, and a single level IVD, right. Yellow represents anterior fibers; blue, lateral fibers; green, posterior-lateral fibers; and red, posterior fibers.

(Figure 2). The posterior region exhibited an average percent deformation of 34.2±3.9%; the posterior-lateral region, 28.9±2.7%; the lateral region, 21.2±4.0%; and the anterior region, 13.0±3.8%. The posterior region experienced a significantly greater percent deformation than the anterior region (p ≤ 0.001).

DISCUSSION
The results of the study support the hypothesis. An explanation of this finding is that the fibers in the posterior region have shorter lengths when in a static neutral position; therefore, any change in fiber length will have a greater impact on the percent deformation. Additionally, both objectives of the study were met. An anatomically correct computational model of the cervical IVD was successfully created, and the deformation of the disc in the defined regions during functional motion was recorded.

Results of the experiment support clinical observations. Physicians noted that a majority of patients complain of pain in the posterior region of the spine, which is the location where the greatest percent deformation occurs.

With a comparative model available, the IVD percent deformation of a patient experiencing acute, severe pain can be calculated using the method above and the results compared to the control group created through this study. From the comparison, clinicians can alter the patient’s daily movement and set limitations to prevent excessive or abnormal loading of the IVD, and consequently prevent the progression of disc degeneration and delay the need for surgical procedures.

Limitations of this study include the analysis of only young, healthy individuals and adaptation of lumbar disc fiber spacing to the cervical disc model. Future directions include analyzing fusion patients to compare the fusion-affected IVD percent deformation to the control group.

ACKNOWLEDGMENTS
I would like to thank Scott Tashman, Ph.D., James Kang, M.D., Maya McKeown, Yashar Assi, and Tyler West for their help with the project, as well as Synthes Spine for funding the project.

REFERENCES