The Effect of Single-Level Disc Degeneration on Dynamic Response of the Whole Lumbar Spine to Vertical Vibration

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■ OBJECTIVE: **The objective of this study was to investigate the effect of single-level disc degeneration on dynamic response of the whole lumbar spine to vertical whole body vibration that is typically present when driving vehicles.**

■ METHODS: **Ligamentous finite element models of the lumbar L1-S1 motion segment in different grades of degeneration (healthy, mild, and moderate) at the L4-L5 level were developed with consideration of changing disc height and material properties of the nucleus pulpous. All models were loaded with a compressive follower preload of 400 N and a sinusoidal vertical vibration load of ±40 N. After transient dynamic analyses, computational results for the 3 models in terms of disc bulge, von-Mises stress in annulus ground substance, and nucleus pressure were plotted as a function of time and compared.**

■ RESULTS: **All the predicted results showed a cyclic response with time. At the degenerated L4-L5 disc level, as degeneration progressed, maximum value of the predicted response showed a decrease in disc bulge and von-Mises stress in annulus ground substance but a slight increase in nucleus pressure, and their vibration amplitudes were all decreased. At the adjacent levels of the degenerated disc, there was a slight decrease in maximum value and vibration amplitude of these predicted responses with the degeneration.**

■ CONCLUSIONS: **The results indicated that single-level disc degeneration can alter vibration characteristics of the whole lumbar spine especially for the degenerated disc level, and increasing the degeneration did not deteriorate the effect of vertical vibration on the spine.**

INTRODUCTION

Many cases of low back pain leading to work disability and reduced quality of life are attributed to disc degeneration,[1,2] which is related to aging, inadequate nutrition, genetic inheritance, and loading history.[3,4] In addition, neurologic degeneration, such as of the sinuvertebral nerve and basivertebral nerve, also affects disc degeneration. An early signal for disc degeneration is a reduction in water and proteoglycan content of the nucleus pulposus, which can decrease the swelling pressure and disc height.[5-7] With the progress of degeneration, increased collagen in the nucleus makes it more fibrotic and the nucleus tissue undergoes a process of stiffening.[8] The border between the nucleus and annulus gradually becomes diffuse.[9] In the degenerated disc, reduced intradiscal pressure caused by the loss of hydration also results in an abnormal stress distribution and large local stress peak in the annulus fibrosus.[10,11] These progressive changes of biochemistry and mechanics in the disc inevitably affect biomechanical behavior of the spine. Numerous experimental and numeric studies have been conducted to investigate the biomechanical alterations of lumbar spine with disc degeneration.

Experimental studies have shown that disc degeneration could affect multidirectional flexibilities of the lumbar spine. For example, an in vitro study by Kettler et al.[12] reported that range of motion (ROM) for the degenerated segment was decreased under flexion-extension and lateral bending but increased under axial

Key words
- Disc degeneration
- Dynamic response
- Finite element
- Follower preload
- Lumbar spine
- Whole body vibration

Abbreviations and Acronyms
FE: Finite element
ROM: Range of motion

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rotation in the early stage of lumbar disc degeneration. With increasing degeneration, the neutral zone ratio (i.e., neutral zone divided by ROM) showed an increase in all 3 loading directions, indicating greater joint laxity.[13] An in vivo study by Lee et al.[14] examined the effect of single-level and double-level disc degenerations on total lumbar ROM for flexion and extension postures. These investigators found that both degenerations resulted in a significant decrease in total ROM, and the upper lumbar had a larger ROM than the lower lumbar.

Finite element (FE) analysis is often used to quantify the effect of disc degeneration on stress and strain responses in the spinal components under physiologic loading conditions.[15-19] For example, Kim et al.[15] found that with degeneration, disc bulge and maximum strain in annulus fibers for axial compressive loading decreased at the degenerated disc but increased at the adjacent disc. Rohlmann et al.[16] showed that for the degenerated disc, increasing the disc degeneration increased maximum von-Mises stress in annulus ground substance for flexion, extension, lateral bending, and axial rotation. Ruberte et al.[17] investigated the effect of single-level disc degeneration on its adjacent segments and found that with progressive degeneration, maximum von-Mises and shear stresses at the levels above and below the degenerated one increased for flexion, extension, lateral bending, and axial rotation. However, these previous FE studies mainly focused on determining the effect of disc degeneration on spine biomechanical responses to static loading. Very few have dealt with the condition of whole body vibration, which is typically present when driving vehicles.[20-22]

Therefore, this study aimed to provide a quantitative investigation of the effect of single-level disc degeneration on dynamic response of the whole lumbar spine to vertical vibration using a developed and validated three-dimensional ligamentous FE model of the lumbar L1-S1 motion segment, allowing simulation of the different grades of degeneration.

METHODS

FE Modeling

A healthy FE model of the L1-S1 motion segment (Figure 1) was constructed based on computed tomography scans (0.6 mm thick) of a female volunteer without bone diseases and spinal abnormalities. The vertebral body consists of cancellous bone and cortical shell (including end plate) measuring 0.7 mm.[23] The intervertebral disc consists of the nucleus pulposus and annulus ground substance comprising 6 fiber layers with a crosswise pattern at ±30° from the horizontal.[24] The fluidlike behavior of both the nucleus and the annulus ground substance was simulated with the Mooney-Rivlin hyperelastic material law. The contact between the facet joints was approximated by frictionless surface-to-surface contact. The major spinal ligaments and the annulus fibers were modeled as tension-only truss elements.

FE models of the lumbar spine representing different grades of disc degeneration (mild and moderate) were generated by decreasing disc height and changing the material property of the nucleus at the L4-L5 level of the healthy model. Based on the disc degeneration grading system of Wilke et al.,[25] disc height was assumed to be decreased by 16.5% and 33%, respectively, for mild and moderate degeneration. The reduction in disc height caused a buckle in the fibers and in all the ligaments other than interspinous and supraspinous ligaments that were prestressed. Similar to an FE study by Rohlmann et al.,[16] these changes were simulated by offsetting their stress-strain curves. With degeneration, material values of the nucleus approaches that of the annulus ground substance, and the values for mild and moderate degeneration were taken from a study by Schmidt et al.[18]

Material properties used in the developed FE models were obtained from the published studies[18,26-29] and are summarized in Table 1. Validation of the present models was conducted by comparing their predictions with corresponding experimental results in the literature.[13,30,31]

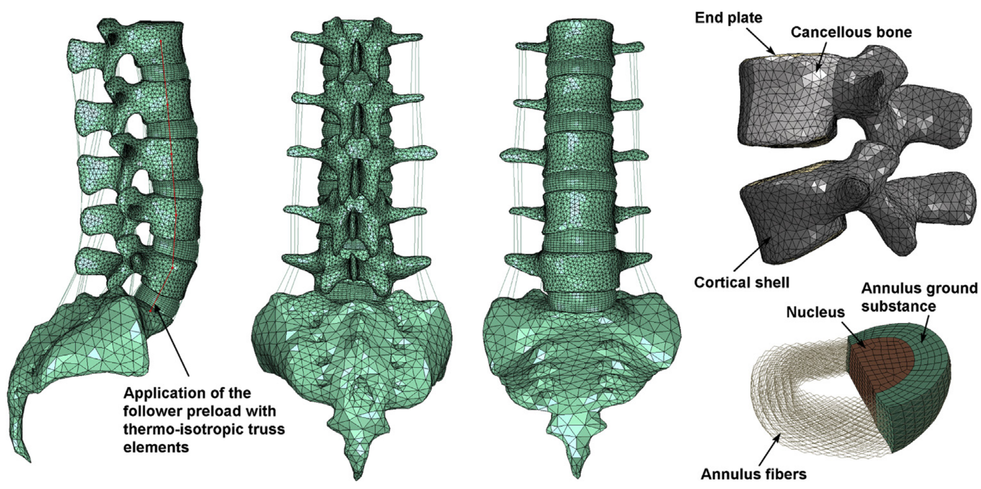

Figure 1. A finite element model of the whole lumbar spine L1-S1.