Effects of Intervertebral Disc Degeneration on Biomechanical Behavior of the L4-L5 Lumbar Functional Spinal Unit

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Abstract. The consideration of biomechanical alterations due to intervertebral disc (IVD) degeneration is crucial for the accurate analysis of spine biomechanics. In this study, finite element (FE) models of the L4-L5 functional spinal unit with full coverage of the degeneration grades from healthy IVD to severe degeneration were developed. The effects of IVD degeneration on spine biomechanics were analyzed under physiological loading conditions using compressive forces and bending moments. Severe IVD degeneration showed lower inter-segmental rotations in flexion-extension and lateral bending, lower intradiscal pressure in all motions and higher facet joint forces in lateral bending and axial rotation in all motions versus the healthy IVD. These findings could provide fundamental information for understanding the characteristics of the biomechanical behavior of the degenerated lumbar spine.

Keywords: Lumbar Spine, Biomechanics, Finite Element Analysis, Intervertebral Disc Degeneration

1 Introduction

Intervertebral disc (IVD) degeneration is caused by geometric change of the IVD and a reduction in water content [1, 2]. It is known that greater than 90% of people over 60 years of age have experienced low back pain related to degeneration. Therefore, studies of spine degeneration are very critical for understanding the basic principles of spine biomechanics and the mechanism underlying pain in IVD degeneration, selecting optimal clinical treatment techniques, or developing new surgical devices.

In this study, we developed finite element (FE) models of L4-L5 functional spinal unit (FSU) with full coverage of the degeneration grades (grade 0: healthy, grade 1: mild degeneration, grade 2: moderate degeneration, grade 3: severe degeneration). The physiological loading condition based on the follower load path was applied to analyze the effect of degeneration grades and types on the spine biomechanics of a FSU.

2 Materials and Methods

A three-dimensional FE model of L4-L5 FSU, which is symmetric across the mid-sagittal plane, was generated based on the CT images. Two vertebrae bones, facet joints and soft tissues such as the nucleus pulposus, annulus ground substance, annulus fibrosus, ligaments and articular cartilages were modeled based on the literatures [3-5]. FE models for mild (grade 1), moderate (grade 2), and severe (grade 3) degenerations were generated from the healthy FSU (grade 0). The disc height decreased (grade 0: 0%, grade 1: 20%, grade 3: 50% and grade 3: 80%), compressibility of the nucleus pulposus increased, ligaments and annulus fibrosis were buckled or pre-stressed by decrease of IVD height [2-5].
Developed FE model of the healthy L4-L5 FSU was validated under a compressive load of 4,000 N and bending moment of 10 Nm with a compressive load of 100 N on the aspects of compressive stiffness and intersegmental rotation, respectively. After validation, effects of various grades of IVD degeneration on intersegmental rotations, facet joint forces and intradiscal pressure (IDP) under physiological loading conditions which are bending moments of 10 Nm simulating with a compressive load of 500 N. The FE models were generated using a commercial pre- and postprocessor, FEMap10.1.1 (MSC.Software Co., Santa Ana, CA, USA) and analyzed using ABAQUS Standard/6.10 (Simulia, Providence, RI, USA).

3 Results

The developed FE model of a healthy L4-L5 FSU was validated on the aspects of compressive stiffness and intersegmental rotation by comparing to in vitro experimental data (Fig. 1) [6, 7]. The predicted axial displacements using the FE model were 1.07 mm and 1.52 mm for compressive loads of 2,000 N and 4,000 N, respectively. The inter-segmental rotations of the L4-L5 FSU were calculated as 8.3° for flexion, 3.6° for extension, 5.4° for left lateral bending, and 2.5° for left axial rotation under 10 Nm moments with a compressive load of 100 N.

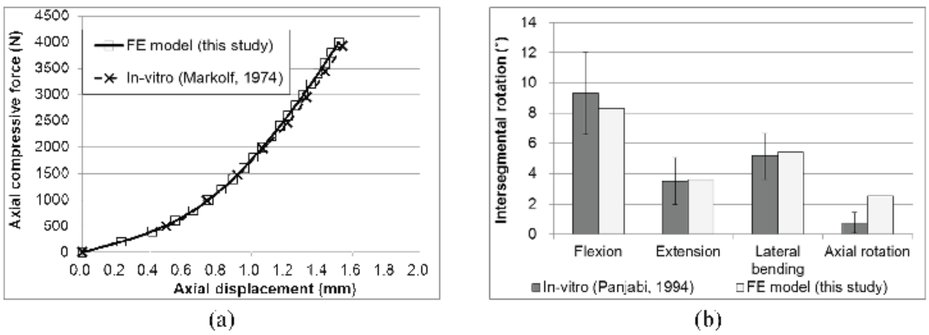

Fig. 1. Comparison of predicted (a) compressive stiffness in the compressive load of 4,000 N and (b) intersegmental rotation in the bending moments of 10 Nm with a compressive force of 100 N to the results from in-vitro tests

Intersegmental rotation of FE models with different degeneration grades were predicted under bending moments of 10 Nm in various directions with a compressive load of 500 N (Fig. 2). The rotation angles were decreased with IVD degeneration in flexion and lateral bending (from 8.1° to 2.1° in flexion, from 4.7° to 1.3° in lateral bending, respectively), while the rotation angles in extension and axial rotation slightly changed (from 3.4° to 3.2° in extension, from 2.1° to 2.3° in axial rotation, respectively) with IVD degeneration. IVD degeneration led decrease of IDP in all loading conditions (from 0.52MPa to 0.08MPa in flexion, from 0.26MPa to 0.23MPa in extension, from 0.38MPa to 0.20MPa in lateral bending, and from 0.43MPa to 0.23MPa in axial rotation, respectively). The predicted contact forces in the facet joint for grade 0 were 52 N, 3 N, and 101 N in extension, lateral bending, and axial rotation, respectively (Table 1). The forces were increased with increasing IVD degeneration in lateral bending and axial rotation, while the forces were decreased in extension. Thus, the maximum contact force (151 N) was shown in axial rotation for grade 3.

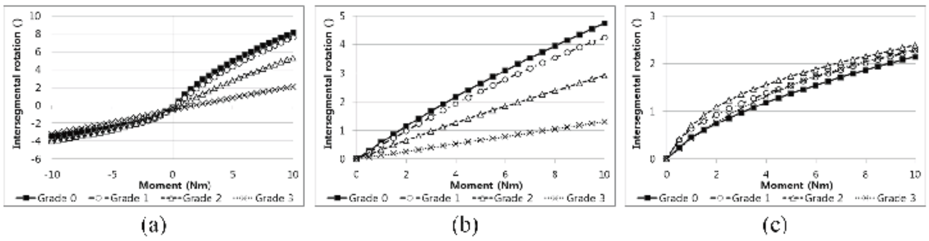

Fig. 2. Moment-rotation curves for (a) flexion-extension, (b) lateral bending, and (c) axial rotation from FE models of grades 0, 1, 2, and 3 under bending moments of 10 Nm with a compressive load of 500 N.

Table 1. Predicted IDP and facet joint force in flexion, extension, left lateral bending, and left axial rotation for different grades of IVD degeneration under 10 Nm moments with a compressive load of 500 N

		Grade 0	Grade 1	Grade 2	Grade 3
Intradiscal pressure (MPa)	Flexion	0.52	0.37	0.23	0.08
	Extension	0.26	0.15	0.16	0.23
	Lateral bending	0.38	0.26	0.21	0.20
	Axial rotation	0.43	0.37	0.30	0.23
Facet joint force (N)	Extension	52	51	43	23
	Lateral bending	3	6	11	13
	Axial rotation	101	112	123	151

4 Discussion

In this study, we developed the FE models of L4-L5 FSU with full grades of IVD degeneration. Developed FE model of the L4-L5 healthy FSU was compared to in-vitro experimental results on the various aspects, compressive stiffness and intersegmental rotation, for accurate validation. The predicted compressive stiffness and intersegmental rotation from developed FE model of the healthy L4-L5 FSU showed good agreements to the results from previously published in-vitro studies.

The results of this study showed that IVD degeneration led increase of stiffness in flexion and lateral bending, while IVD degeneration didn't significantly affected stiffness changes in extension and axial rotation. IVD degeneration also led decrease of IDP. Decrease of stiffness in FSU causes instability of the lumbar spine. And high IDP is associated with IVD disease such as IVD herniation. Thus IVD degeneration led decrease of risks of IVD disease in the degenerative FSU. However, high facet joint forces in degenerative FSU may cause facet joint arthrosis. The findings of this study could provide fundamental information for understanding the characteristics of the biomechanical behavior of the degenerative lumbar spine.

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