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Finite element simulation of an artificial intervertebral disk using fiber reinforced laminated composite model

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ABSTRACT

Degeneration of intervertebral disk (IVD) has been increased in recent years. The lumbar herniation can be cured using conservative and surgical procedures. Surgery is considered after failure of conservative treatment. Partial discectomy, fusion, and total disk replacement (TDR) are also common surgical treatments for degenerative disk disease. However, due to limitations and disadvantages of the current treatments, many studies have been carried out to approach the best design of mimicking natural disk. Recently, a new method of TDRs has been introduced using nature deformation of IVD by reinforced fibers of annulus fibrosis. Nonetheless, owing to limitations of experimental works on the human body, numerical studies of IVD may help to understand load transfer and biomechanical properties within the disks with reinforced fibers. In this study, a three-dimensional (3D) finite element model of the L2-L3 disk vertebrae unit with 12 vertical fibers embedded into annulus fibrosis was constructed. The IVD was subjected to compressive force, bending moment, and axial torsion. The most important parameters of disk failures were compared to that of experimental data. The results showed that the addition of reinforced fibers into the disk invokes a significant decrease of stress in the nucleus and annulus. The findings of this study may have implications not only for developing IVDs with reinforced fibers but also for the application of fiber reinforced IVD in orthopedics surgeries as a suitable implant.

1. Introduction

The intervertebral disk (IVD) is the largest avascular tissue in the human body and provides the spine with flexibility and functional load support (Iatridis et al., 2013). The intervertebral disk consists of three components. The central region of a disk, the nucleus pulpous, is a hydrated gel. It contains water up to 85% which helps in spreading load on the vertebras. The essential component of the intervertebral disk is the annulus fibrous. It consists of 10–20 sheets of collagen named lamella (Castro et al., 2014). Adjacent lamellas are loosely bonded to each other by collagen and elastin fibers, and they are firmly embedded in the adjacent vertebra. Due to the hydrostatic fluid pressurization within the nucleus, the annulus fibrous tolerates frequently tensile loads, even under compressive loads. The other adjacent components of IVD are end plates (Sivan et al., 2013). These regions are plates of cartilage covering superior and inferior surfaces of disks. Degenerative disk disease can take place throughout the spine which can be painful and can greatly affect the quality of one's life (Holguin et al., 2013).

In the recent decade, intensive attention has been devoted to medical treatment of intervertebral disks degeneration. Previous reports have shown that on average, 450,000 spine fusion procedures are performed annually in the United States alone, of which 250,000 are for the lumbar region alone (Link et al., 2004; Singh et al., 2004). In addition, 70–80% of the population in industrialized society suffer from low back pain which mostly related to disk degeneration (Glover, 1976; Leavitt et al., 1971).

Two different approaches are commonly used for treatment of lumbar herniation, conservative and surgical. Surgery is considered after failure of conservative treatment. Partial discectomy, fusion, and total disk replacement (TDR) are also commonly surgical spine procedures for degenerative disk disease (Zhang and Teo, 2008). Patient satisfaction after a fusion operation is often low because of adjacent disk herniation in long term (Cauthen et al., 2006). This

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procedure restrains motion at the surgical level which results in high stress at the adjacent disk levels and accelerates degeneration in patients (Kuslich et al., 2000; Lee et al., 1991; Lehmann et al., 1987; Rahm and Hall, 1996).

Current TDRs are ball-and-socket and mobile core designs. Although they provide reasonable results in the short-term, concerns about changes in spinal motion remain such as overloading of the facet joints, adjacent segment disease, and wear. Recently, the other methods of TDRs have been introduced, which can overcome the concerns of sliding ball-and-socket using nature deformation of IVD that its concept is based on mimicking reinforced fibers of annulus fibrosis. Nonetheless, owing to limitations of experimental works on the human body, numerical studies of IVD may help to understand load transfer and biomechanical properties within the disks with reinforced fibers. Lee et al. (1991) suggested a deformable IVD by means of elastomeric materials. However, it was not able to mimic movement in axial compression and torsion, to improve that, they add a stiffer elastomer layer or fibers (Langrana et al., 1994; Vuono-Hawkins et al., 1995). Axial and torsional stiffness improved in both designs. Gloria et al. (2007, 2011) proposed HEMA–PMMA hydrogel disk reinforced with embedded PET fibers, and two hydroxyapatite reinforced polyethylene composites (HAPEXTM) endplates were added for fixation. PMMA was added to improve the strength. Static axial, shear and torsion stiffness were similar to IVD stiffness.

In this study, a three-dimensional (3D) finite element (FE) model of the L2-L3 disk vertebrae unit with 12 vertical fibers embedded into annulus fibrosis was constructed. Important biomechanical parameters considered in artificial disk with 12 reinforced fibers. A three-dimensional finite element model of the L2-L3 disk vertebrae unit was constructed. The most important parameters of disk failures are stress concentration and deformation. The FE model was subjected to compressive force, bending moment, and axial torsion. Axial compression, torsional rotation in the sagittal plane and the lateral bending were considered and the main factors such as vertical displacement, radial outward bulge, axial rotation, and endplate tilt were compared with that of experimental results.

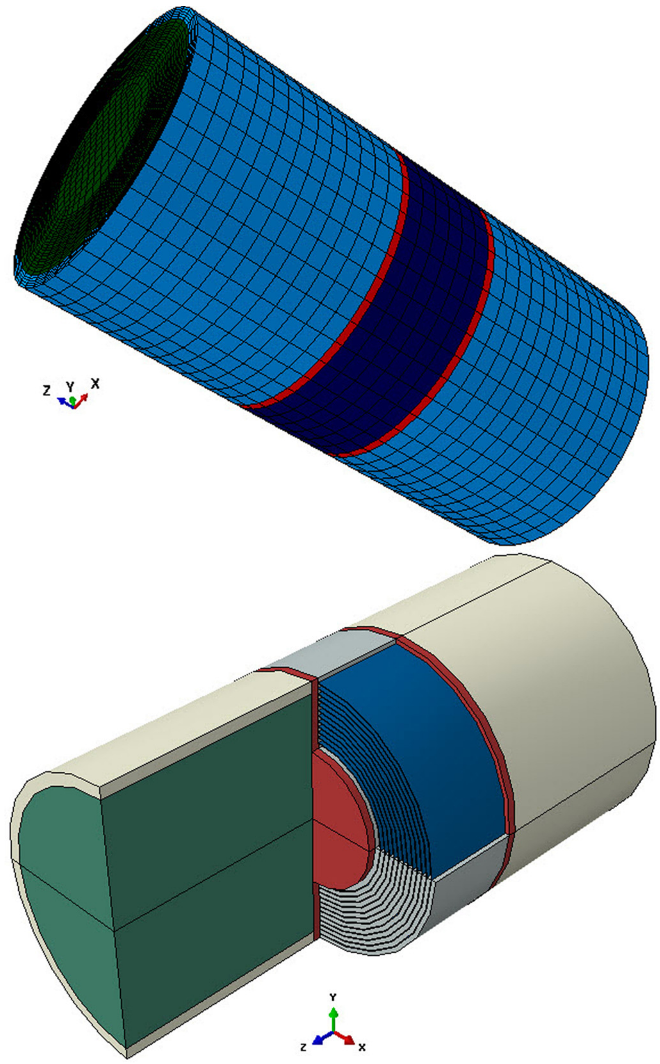

Fig. 1. Three-dimensional finite element model of L2-L3 segment and disk with reinforced fibers.

2. Materials and methods

2.1. Finite element model

The simulation model of the L2-L3 motion segment was made based on anthropometric data. Since most disk degeneration is occurred in this area, L2-L3 was chosen to be modeled. The FE model was consisted of vertebrae (cortical and cancellous bones), disk (annulus, nucleus, and fiber reinforcement), and end plates. Twelve vertical fibers were used in different parts of annulus with equal spacing in the radial direction and embedded into annulus fibrosis (Kumaresan et al., 1999; Nissan and Gilad, 1984; Panjabi et al., 1991, 2001; Skrzypiec et al., 2007; Vasavada et al., 2008). Due to the complexity of vertebrae, a simplified model for decreasing the solution time is recommended. The FE model is presented in Fig. 1. The simulation was executed using ABAQUS 6.10 (SIMULIA Corporation, Providence, RI, United States). Reinforced fibers were modeled using truss elements and the rest were built of solid elements. The details of element types and volumes are listed in Table 1. The material properties are also presented in Table 2. The IVD was considered to be homogeneous and nearly incompressible (Poisson's ratio of 0.5). These properties have been proven to be well addressed the mechanical behavior of the disk under various loading conditions (Kasra et al., 1992).

2.2. Boundary conditions and loading

Under normal conditions, human's spine applies compression, bending, and torsion to the vertebrates. Therefore, these three types of loading were considered with the magnitudes of 400 N, 5 N m

Table 1
The number of elements and nodes in different parts of the model.

Part	No. of nodes	No. of elements[a]
Disk with fibers	8253	6948
Vertebrae	17,685	16,212
End plate	2358	1158

[a] Linear hexahedral of type C3D8R.

Table 2
Material properties of the different parts of intervertebral disk.

Material	Modulus of elasticity (MPa)	Poisson's ratio
Nucleus	1	0.5
Cortical bone	12,000	0.3
Cancellous bone	10	0.2
End plate	24	0.4
Annulus fiber	450	0.3
Annulus ground substance	4	0.4