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Journal of Biomechanics 39 (2006) 2484–2490

JOURNAL OF BIOMECHANICS

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Analysis of the influence of disc degeneration on the mechanical behaviour of a lumbar motion segment using the finite element method

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Accepted 18 July 2005

Abstract

Compared to a healthy intervertebral disc, the geometry and the material properties of the involved tissues are altered in a degenerated disc. It is not completely understood how this affects the mechanical behaviour of a motion segment. In order to study the influence of disc degeneration on motion segment mechanics a three-dimensional, nonlinear finite element model of the L3/L4 functional unit was used. Different grades of disc degeneration were simulated by varying disc height and bulk modulus of the nucleus pulposus. The model was loaded with pure moments of 10 N m in the three main anatomic planes. The finite element model predicted the same trends for intersegmental rotation and intradiscal pressure as described in the literature for in vitro studies. A comparison between calculated intersegmental rotation and experimental data showed a mean difference of 1.9° while the mean standard deviation was 2.5°. A mildly degenerated disc increases intersegmental rotation for all loading cases. With further increasing disc degeneration intersegmental rotation is decreased. For axial rotation the decrease takes place in the final stage. Intradiscal pressure is lower while facet joint force and maximum von Mises stress in the annulus are higher in a degenerated compared to a healthy disc.

Keywords: Finite element method; Lumbar spine; Disc degeneration

1. Introduction

Intervertebral discs provide flexibility of the spine and transmit and distribute large loads. To carry out these tasks the intervertebral discs consist of a gelatinous nucleus pulposus and the annulus fibrosus. The latter consists of a fibrous collagen matrix embedded within an aqueous gel of proteoglycans, water and other proteins (Iatridis et al., 1998). The structure of the annulus is highly layered and oriented. The orientation of the fibres changes between successive layers, alternating at ~30° and 150° to the transverse plane of the intervertebral disc (Galante, 1967).

Most humans aged 30 and more show degenerative changes in the intervertebral discs (Miller et al., 1988). These changes affect the material properties of the disc tissues and thereby both their individual behaviour and the overall function of a disc. Degeneration is a deterioration of the tissue or the replacement of healthy by inferior tissue. Degenerated discs have a decreased height due to the reduced hydration capacity and the more fibrotic appearance of the nucleus pulposus (Gunzburg et al., 1992). The cross-sectional area of the adjacent vertebral endplates is increased because of the

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0021-9290/$ - see front matter
doi:10.1016/j.jbiomech.2005.07.026

presence of vertebral osteophytes. In degenerated soft tissue there is a loss of swelling pressure and an increase in matrix deformation (Iatridis et al., 1998; Urban and McMullin, 1988). The water content in degenerated discs is reduced, the number of fibres in the nucleus pulposus and the stiffness of the height reduced annulus are increased, leading to a lower intradiscal pressure in degenerated than in healthy discs (Adams et al., 2002; McNally and Adams, 1992). While a healthy nucleus pulposus shows a hydrostatic pressure, the pressure distribution in a degenerated disc is nonuniform and direction dependent (McNally and Adams, 1992). With increasing degeneration the border between nucleus and annulus becomes diffuse (Adams et al., 2002). In a strongly degenerated disc, inner lamellae of the annulus are buckled inwards thus reducing the space for the nucleus (Adams et al., 2002). Poisson's ratio, tensile failure stress and strain energy density of the annulus fibrosus decrease with degeneration (Acaroglu et al., 1995). Ligaments and annular fibres show a nonlinear stress–strain behaviour. In the process of degeneration the region of low ligament and annular fibre stiffness increases (Mimura et al., 1994). For degenerated discs, the range of motion in flexion/extension and lateral bending is reduced but increased for axial rotation. Whereas the quotient of the neutral zone and the range of motion is increased for all loading directions (Mimura et al., 1994). Disc degeneration is often accompanied by arthritic changes in the facet joints (Butler et al., 1990). The reduced thickness of the articular cartilage could be one reason for the increased range of axial rotation.

In finite element models disc degeneration was mostly simulated just by removing the incompressibility of the nucleus without changing disc height and material properties of the annulus fibrosus. Kurowski and Kubo (1986) studied the influence of disc degeneration on the mechanism of load transfer through the lumbar vertebral body. They predicted the highest stresses in the centre of bony end-plates for healthy discs, in contrast to the degenerated discs where the highest stresses were calculated in the lateral aspects of the end-plates, in the cortical wall, and in the vertebral body rims. Kim et al. (1991) investigated the effects of disc degeneration on the biomechanical behaviour of the adjacent motion segment with finite element models consisting of two motion segments. Disc degeneration was simulated by solely removing the hydrostatic capabilities of the nucleus and increasing disc stiffness. The influence of disc degeneration on the mechanism of burst fractures was studied by Shirado et al. (1992). They found in specimens with a severely degenerated disc very low stresses at the end plate under the nucleus. Goto et al. (2002) created a finite element model of the 4th and 5th lumbar vertebrae and established a degenerated model without intradiscal pressure for standing.

Kumaresan et al. (2001) used a finite element model of the C4–C6 cervical spine to simulate progressive disc degeneration at the C5–C6 level. In their study, severe degeneration included a decrease in the intervertebral disc height with altered material properties of the nucleus pulposus and the annulus fibrosus. They calculated an increased segmental stiffness at the degenerated level.

A realistic finite element model of a degenerated disc is required to get a more sophisticated view of the effect of disc degeneration on the mechanical behaviour of the lumbar spine. After integrating it in a multisegmental finite element model of the lumbar spine it will enable extensive studies, for example, about the effect of disc degeneration on adjacent segments and on facet joint loading.

The aims of the present study were to develop a finite element model of a lumbar motion segment which allows the simulation of different grades of disc degeneration and to investigate the influence of disc degeneration on the biomechanical behaviour of a motion segment.

2. Methods

A three-dimensional, nonlinear finite element model of the functional spinal unit L3/L4 was created (Fig. 1). The geometry of the vertebrae was transferred from our former model (Zander et al., 2001) whose data were taken from CTs and the literature. The model consists of 11,368 volume elements, about 450 hydrostatic fluid elements and 105 spring elements and has nearly 75,000 degrees of freedom. Volume elements were used for the vertebrae and fluid elements for the nucleus pulposus. The curved facet joints had a gap of 0.5 mm and could transmit only compressive forces. Facet joint cartilage was simulated by the contact stiffness, which is a nonlinear function of the strains experienced by the cartilage. It was modelled as described by Sharma et al. (1995). The orientation and curvature of the facet joints were chosen according to the literature (Panjabi et al.,

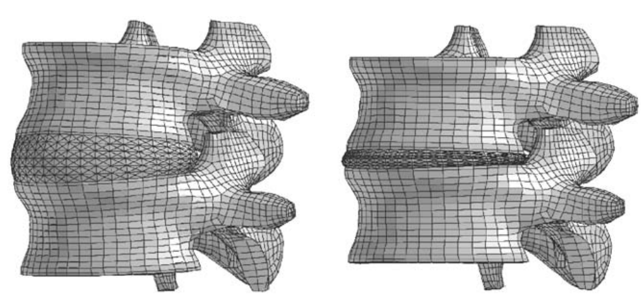

Fig. 1. Element meshes of the motion segment L3/L4 with a healthy (left) and a severely degenerated (right) disc.