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Biomechanical investigation on the influence of the regional material degeneration of an intervertebral disc in a lower lumbar spinal unit: A finite element study

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ABSTRACT

Intervertebral disc degeneration involves changes in its material properties that affect the mechanical functions of the spinal system. However, the alteration of the biomechanics of a spinal segment through specific material degradation in a specific region is poorly understood. In this study, the influence of the constitutive material degeneration of disc tissues on the mechanics of a lower lumbar spinal unit was examined using a three-dimensional nonlinear finite element model of the L4-L5 functional spinal unit. Different grades of disc degeneration were simulated by introducing a degeneration factor to the corresponding material properties to represent fibrous nucleus, increased fibre and ground substance laxity, increased fibre stiffness and total annular fracture along posterior and posterolateral regions. The model was loaded with an axial compression of 500 N and pure moments of up to 10 Nm to simulate extension, flexion, lateral bending and axial rotation. To validate the model, the spinal motion and intradiscal pressure of healthy and degenerated discs with existing in vitro data were compared. The disc with a fibrous nucleus and the presence of intradiscal pressure increase the spinal instability during flexion and axial rotation, and the absence of intradiscal pressure increases the spinal instability in all directions. Bulging displacement and shear strains in the disc with total fracture and ground substance laxity are high in all of the loading cases. Our study could provide useful information to enhance our understanding of the influence of each constitutive component of the intervertebral disc on the mechanics of the spinal segment.

1. Introduction

Intervertebral discs (IVDs) are composites of fibrous tissues that interconnect the vertebrae along the spinal column. Structurally, IVDs are composed of multiple layers of firm annulus embedded with layers of alternating fibres. Fibre orientations vary radially (outer to inner layer) and circumferentially (posterior to anterior region), thereby influencing spinal stiffness during tension loading [1–3]. Annular layers encapsulate the gelatinous nucleus pulposus, which consists of a loose network of collagen fibres suspended in a base of water. Upon applied loading, the nucleus with intradiscal pressure (IDP) vertically and laterally acts on endplates and annular layers, respectively, thereby providing flexibility to the spinal system by absorbing shock and pressure during various postural states.

Morphological changes of IVDs, including variations in structural or material properties, likely influence the biomechanics of IVD tissues and the overall mechanics of the spinal system. Discs subjected to repetitive cyclic loading were found to be more susceptible to gradual prolapse [4, 5], herniation initiation and progression [6], annular delamination [4] and direction of nucleus deformation depending on the loading condition [7]. Repetitive cyclic loading affects the changes in material properties, thereby causing the gradual degeneration of annular layers. Such degeneration may affect either the fibre matrix or the ground substance element. A vibration experiment performed on a porcine spinal unit subjected to 5 Hz cyclic compressive loading resulted in an increase of stress-stretch ratio in the excised annular lamellae, especially in the toe region [8], which may suggest that IVD tissues undergo loss of elasticity prior to total fracture, particularly in the region frequently subjected to high tension during repetitive flexing posture. In another experiment, a degenerated IVD specimen showed a significant increase in the stiffness of annulus fibre materials and a slight decrease in the stiffness of its ground substance compared with a healthy disc [9]. The defected region

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is susceptible to total annular fracture, thereby expediting nucleus migration through the fractured opening and compromising the dural sac and the intervertebral foramen space [10]. Consequently, the risk of IVD interrupting an adjacent nerve root tissue increases, and pain is stimulated. IVD degeneration is also characterised by a progressive decrease in water content in the nucleus pulposus as a result of the natural dehydration process of an aging disc [11]. A significant loss of intradiscal pressure in the nucleus may also be contributed by vertebral endplate fracture which promotes the extrusion of the nucleus material into the vertebral marrow [5]. An imaging study on human cadaveric spine has shown that at a certain degenerative grade, the annulus-to-nucleus boundary became indistinguishable [12]. Such finding may be influenced by the loss of osmotic pressure within the nucleus, which leads to a more fibrotic nucleus and mitigates annular layer delamination.

The influence of degenerated IVDs on the mechanics of the spinal system is commonly identified as increased spinal instability with an increased spinal motion. However, the consequential effect of IVD degeneration on spinal instability varies among studies. For example, results of an experimental study performed on cadaver lumbar spine with different grades of degeneration based on the Pfirrmann grading system showed that the spinal motion of a degenerated IVD with increased fibre stiffness and decreased ground substance stiffness was unstable only in axial rotation, and its range of motion during flexion and extension loading was similar to that of a healthy disc [9]. In another study based on Thompson's grading system, an IVD with apparent fibrous characteristics experiences spinal instability during lateral bending and axial rotation, whereas a high degeneration grade with the focal disruption of annulus layers causes a decreased spinal motion [12]. In accordance with the Pfirrmann-based degeneration grade, the disc with Thompson's degeneration grade also showed no significant changes during extension and flexion. By contrast, another study applied moment loading to a dissected IVD that is categorised as highly degenerated based on the Pfirrmann grading system; results showed a low range of motion during flexion–extension and lateral bending [13]. Disparities in the kinematic responses of the spinal system may be contributed by a specific degeneration mode involving either single or multiple constitutive IVD tissues.

In finite element (FE) studies, IVD degeneration is usually modelled by altering the nucleus properties and the magnitude of intradiscal pressure [14,15]. A degenerated IVD model with a stiff nucleus material reveals lower facet joints with increased intradiscal pressure and exacerbated disc bulging and stress on the annular ground substance, especially in posterior and lateral regions [14]. Alternatively, the absence of intradiscal pressure does not cause changes in stress on vertebral endplates [15]. Alteration to the material properties of the nucleus and the annulus in combination with changes in the geometric parameters of IVD represents a higher degeneration grade [16–18]. In the cervical model developed by Kumerasan et al. [16], material properties of nucleus and annulus showed changes that represent dehydration and disintegrated fibres respectively, whereas higher degeneration state additionally incorporates decrease in IVD height. Such degeneration state shows reduced disc bulge and annulus stress and strain, whereas the spinal stiffness increases at the degenerated level. A similar modelling strategy established by Ruberté et al. [17] was applied to the lower lumbar unit; results suggested that except for extension-flexion, degeneration decreased spinal motion for the other bending moment. Interestingly, extension-flexion motion increased for mild degeneration, whereas further degeneration decreased its motion. The study also highlighted that spinal segment adjacent to degenerated unit are exposed to increased risk of injury based on the computed changes in motion, as well as the rapid increase on maximum Von Mises stress and maximum shear stress. A degenerated IVD model for the lower lumbar spine was developed by Rohlmann et al. [18]; this model considered the increase in the compressibility of the nucleus and the decrease in IVD height, thereby demonstrating an increase in spinal motion during mild degeneration and a decrease in motion during high degeneration. Another degenerated IVD model in the lower lumbar spine considers the combined alteration in geometric features and nucleus, annulus fibre and ligament properties and shows a decrease in spinal motion, especially during flexion–extension and lateral bending [19]. Changes in IDP and facet joints depend on spinal level. A comprehensive model incorporates geometric alteration and osteophyte formation parallel to the alteration of the nucleus, annulus fibre and ligaments [20]. In this model, spinal motion increases in axial rotation, flexion, and extension during mild degeneration, whereas spinal motion decreases in all directions in severely degenerated IVDs. Another FE model incorporated viscoelastic properties for the annulus fibres and ligaments; this model suggested that initiation and progression of annulus fracture was affected by axial compressive load, angular moment and disc saturation [21]. With the incorporated viscoelastic parameters, maximum tensile stress is predicted in the fibres at the inner-posterior annulus. Furthermore, several poroelastic models have also been developed and have been partially validated, thereby supporting the significance of fluid transport in the mechanics of the spinal segment in the case of degenerated IVD [22–24]. A poroelastic creep model developed by Argoubi & Shirazi-Adl [22] investigated the creep response of the lumbar segment subjected to constant axial force ranging from 400 N to 2000 N for 2 h. The model predicted that nonlinear permeability increased the spinal segment stiffness through resistance of fluid flow caused by compaction of the solid material under a larger amount of strain. Furthermore, a poroelastic model developed by Malandrino et al. [23] varied cartilaginous endplate permeability and determined its significance during compression, vertical displacement, torsional motion and the nucleus pore pressure. Another poroelastic model by Williams et al. [24] investigated the dynamic loading of lower lumbar spinal unit by applying short term creep and cyclic loading. The study supported the inclusion of regional elastic and poroelastic material properties towards agreeable prediction of spinal behaviour. However, variability on the degenerated IVD mechanics complicates the comparison with experimental data especially when liquid phase is involved.

Variations in the kinematic response of the spinal system remain unclear because biomechanical responses may be contributed by the specific degeneration of single or multiple constitutive IVD tissues. Therefore, this study aimed to examine the effect of the specific material degradation of IVD tissues, including the nucleus, annulus ground substance and annulus fibres, on the biomechanical behaviour of the spinal segment with retained geometrical characteristics. In this study, three-dimensional nonlinear FE models of a lumbar spinal unit were developed and validated for a healthy and degenerated IVDs. The simulation of the degenerated state was considered for fibrous nucleus in the presence and absence of intradiscal pressure, increased fibre and ground substance laxity, increased fibre stiffness and total annular fracture, particularly along posterior and posterolateral regions. In this study, material laxity referred to the loss of stiffness of IVD tissues.

2. Materials and methods

2.1. FE model of healthy spinal unit

A three-dimensional nonlinear FE model of the L4-L5 functional spinal unit was developed (Fig. 1a), and the FE program FEBio was used [25]. The geometric characteristics of the vertebrae were defined on the basis of our former model [26] which was segmented from an adult male cadaver's CT images of the Visible Human Project©. The IVD was modelled by interpolating the mesh between the superior and inferior nodes of adjacent vertebral endplates with a 1 mm preliminary bulge profile. This IVD was composed of eight annular layers with 66% volume relative to the total IVD volume, and the remaining volume was allocated for the nucleus pulposus [27]. The IVD model consisting of 10,336 elements with 12,024 nodes was discretised by a set of 8-node second-order hexahedral elements. Each annular layer was reinforced with collagen fibres oriented in a crosswise arrangement (Fig. 1a). Six spinal ligaments, namely, anterior longitudinal ligaments (ALL), posterior longitudinal ligaments (PLL), facet capsular ligaments (FC), flavum ligaments (FL),