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Damage accumulation location under cyclic loading in the lumbar disc shifts from inner annulus lamellae to peripheral annulus with increasing disc degeneration

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ABSTRACT

It is difficult to study the breakdown of lumbar disc tissue over several years of exposure to bending and lifting by experimental methods. In our earlier published study we have shown how a finite element model of a healthy lumbar motion segment was used to predict the damage accumulation location and number of cyclic to failure under different loading conditions. The aim of the current study was to extend the continuum damage mechanics formulation to the degenerated discs and investigate the initiation and progression of mechanical damage. Healthy disc model was modified to represent degenerative discs (Thompson grade III and IV) by incorporating both geometrical and biochemical changes due to degeneration. Analyses predicted decrease in the number of cycles to failure with increasing severity of disc degeneration. The study showed that the damage initiated at the posterior inner annulus adjacent to the endplates and propagated outwards towards its periphery in healthy and grade III degenerated discs. The damage accumulated preferentially in the posterior region of the annulus. However in grade IV degenerated disc damage initiated at the posterior outer periphery of the annulus and propagated circumferentially. The finite element model predictions were consistent with the infrequent occurrence of rim lesions at early age but a much higher incidence in severely degenerated discs.

1. Introduction

Low back pain is a major health condition affecting every population worldwide (Andersson, 1999). It can lead to decreased quality of life, diminished physical activity and psychological distress (Deyo and Tsui-Wu, 1987; Deyo et al., 2011). Intervertebral disc degeneration is associated with low back pain (Cheung et al., 2009; Luoma et al., 2000; Samartzis et al., 2011; Savage et al., 1997). Epidemiological studies have identified frequent bending and lifting as a major risk for disc prolapse (Kelsey et al., 1984; Kumar, 1990). Damage to disc structure has been reported in response to cyclic loading of the motion segment by a number of studies involving human cadavers and animal models (Adams and Hutton, 1983, 1985; Adams et al., 2000; Goel et al., 1988a, 1988b; Hansson et al., 1987; Liu et al., 1983; Liu et al., 1985; Yoganandan et al., 1994). Yu et al. (2003) reported penetration of nucleus pulposus into the endplate and annulus fibrosus in the healthy porcine lumbar discs in response to compressive cyclic loading. Radial rupture of the central posterior annulus adjacent to the endplates was observed in healthy ovine discs subjected to nucleus pressurization in the flexed position (Veres et al., 2009). Parkinson and Callaghan (2009) reported herniation in the posterior annulus of the healthy porcine motion segments subjected to dynamic compression and flexion. Posterior tracking of nucleus into the annulus was introduced in healthy porcine discs subjected to cyclic flexion and axial rotation (Marshall and McGill, 2010). Experimental studies involving healthy animal specimens have successfully introduced radial fissures under different cyclic loading conditions. However, postmortem human cadaveric studies have reported occurrence of different types of annular lesions in discs of different grades of degeneration. Haefeli et al. (2006) examined 41 cadaveric human lumbar spines aged 7 months to 88 years. Radial tears were observed in 5% of specimens until the age of 20 years however its occurrence increased to 25% by the third decade and to 60% by the sixth decade. Peripheral rim lesions were reported in 22% of specimens older than 50 years. Vernon-Roberts et al. (2007) examined 70 cadaveric human L4/L5 discs aged between 13 and 79 years for structural failures. Radial tears were reported in 68% of discs aged between 10 and 30 years and increased to 90% in age group 51–80 years. Rim lesions were infrequent in early age with only 20% of discs in age group 10–30

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years but increasing to 40% in age group 31–50 years and 90% in age group 51–80 years. Gordon et al. (1991) reported disc herniation in cadaveric lumbar motion segments subjected to combination of flexion, axial rotation and compression for an average duration of 36,750 cycles. Nucleus extrusion into the inner annulus layers was observed in mildly degenerated discs while separation of peripheral annulus layers was found in severely degenerated discs. In case of the human cadaver studies, the discs had already degenerated with pre-existing annular disruptions. With current imaging techniques it is not possible to identify the location and extent of damage during different stages of testing without interruptions. It is difficult if not impossible to apply complex loadings that are representative of daily life activities in the cadaver testing setup. These limitations make it hard to track the initiation and progression of structural damage in the intervertebral disc under complex loading conditions in the experimental setup.

Finite element (FE) modeling has been used extensively to analyze the spine biomechanics. However most of the FE models of the spine are employed to elucidate the spine kinematics under single load cycle (Goel et al., 1995; Argoubi and Shirazi-Adl, 1996; Rohlmann et al., 2006; Little et al., 2007; Schmidt et al., 2007; Galbusera et al., 2011). Influence of disc degeneration on spinal kinematics had been studied using FE models but there is no FE study for lumbar spine that investigates the damage accumulation in the degenerated discs due to cyclic loading to the best of the authors' knowledge (Shirazi-Adl, 1989; Natarajan et al., 1994; Schmidt et al., 2009). Authors have already studied with the help of FE analyses of lumbar motion segment the initiation and progression of damage in a healthy disc under different loading conditions (Qasim et al., 2012). The purpose of the current study was to extend the continuum damage mechanics methodology to predict damage initiation and progression in a degenerated disc under cyclic loading. The healthy disc model was modified to represent Thompson grade III and IV disc degeneration by incorporating morphological and biochemical changes. It was hypothesized that the (a) number of load cycles to disc failure will decrease as the severity of disc degeneration increases and (b) damage accumulation location will shift from inner annulus lamellae in the healthy disc to the peripheral annulus as the disc degenerates.

2. Materials and method

2.1. 3D poro-elastic finite element model of healthy L4/L5 lumbar motion segment

A previously validated (Natarajan et al., 2006, 2008; Williams et al., 2007) three dimensional non-linear poro-elastic FE model of a healthy lumbar L4–L5 motion segment was modified for the current study. It included parameters such as porosity, osmotic pressure and the strain dependent permeability. Element and material model information for the FE model are listed in the Table 1 and detailed information is included in the Appendix A. FE analyses were carried out using a commercially available software package ADINA (ADINA R&D Inc., Watertown, Massachusetts).

2.2. Degenerated lumbar disc models

The healthy disc model was modified to represent Thompson grade III and IV disc degeneration. Biochemical changes in the disc due to disc degeneration were simulated by altering the drained elastic material properties and the poro-elastic properties of the annulus and the nucleus (Table 2). Disc height was reduced by 15% and 33% as compared to the healthy disc height to represent grade III and IV disc degeneration respectively. Nucleus area for the grade III degeneration model was kept the same as healthy disc model, but it was reduced by 67% to represent grade IV disc degeneration. Morphological and biochemical changes introduced in degenerated disc models were adapted from the available literature (Urban et al., 2003, 1981, 1988; Iatridis et al., 1998, 1997; Ebara et al., 1996; Best et al., 1994; Gu et al., 1999; Elliott and Setton, 2001; Umehara et al., 1996).

2.3. Continuum damage methodology application to lumbar spine FE model

Kachanov (1999) introduced a concept of damage being continuously distributed throughout the solid and proposed a damage variable as an internal state variable describing the state of degradation of the material. A computational formulation for the prediction of degradation of annulus under cyclic loading based on Kachanov's concept was employed in the current study and is described again here briefly (Qasim et al., 2012).

In the FE model, annulus was divided into a large number of finite elements. Element properties were calculated at eight integration points distributed within the element. At the beginning of the analysis each integration point in the elements representing annulus was assigned a value of zero for the damage variable d representing its healthy state (Fig. 1). The loading was applied to the FE model in incremental steps. At the maximum load step, principal tensile stress was calculated at each integration point in the annulus elements. The number of load cycles to failure (N) was calculated at each integration point in the annulus using a Stress–Failure (S–N) curve. The lowest number of cycles to failure (N_{min}) corresponded to the integration point with the highest tensile stress value. Damage d at each integration point was incremented following the Miner's rule. When damage d for an integration point reached a value of 0.9, the corresponding integration point in the element was assumed unable to share any load. The elastic modulus at the damaged integration points was reduced by one hundredth of its original value, introducing the degradation of the material at that location in the annulus. The number of load cycles required to cause the given damage in the annulus was equal to $N_{min.}$ The stiffness matrix was then updated. The same loading was again applied to the motion segment and damage was incremented for each integration point following the above procedure. The damage initiation and progression was tracked by recording the damaged integration points. The S–N curve for the annulus (Fig. 2) was developed by using the data from a cyclic cadaver study carried out by Green et al. (1993) and was described in detail previously (Qasim et al., 2012).

2.4. Validation of grade III and IV degenerated disc FE models

Degenerated disc FE models were validated by comparing the angular rotation predictions with the cadaveric human lumbar motion segment experimental studies (Fujiwara et al., 2000; Tanaka et al., 2001). Fujiwara et al. (2000) tested 110 cadaveric lumbar motion segments under pure bending moments of 6.6 Nm in the three principal directions. The ROM results were classified based on the Thompson scheme for disc degeneration grading. Tanaka et al. (2001) tested 114 cadaveric lumbar motion segments under pure bending moments of 5.7 Nm in the three principal directions. They grouped the ROM results according to disc degeneration grades based on morphological and magnetic resonance imaging assessment.

Table 1
Element and material model information for L4–L5 finite element model (Ebara et al., 1996; Elliott and Setton, 2001; Goel et al., 1988a, 1988b; Gu et al., 1999; Koeller et al., 1986; Panjabi et al., 1984; Sanjeevi et al., 1982; Sharma et al., 1995).

Structure	Drained elastic modulus	Poisson's ratio	Type of element	No. of elements	Material model
Cortical bone	12 GPa	0.30	3-D Solid (8 node)	1759	Linear Elastic
Cancellous bone	100 MPa	0.20	3-D Solid (8 node)	3112	Linear Elastic
Posterior elements	3.5 GPa	0.25	3-D Solid (8 node)	2112	Linear Elastic
Endplate	20 MPa	0.40	3-D Solid (8 node)	264	Linear Elastic
Nucleus	1.0 MPa	0.40	3-D Solid (8 node)	720	Linear Elastic
Annulus	4.2 MPa	0.10	3-D Solid (8 node)	1920	Linear Elastic
Annular fibers	–	–	Rebar Elements	1760	Non-linear Elastic
Ligaments	–	–	Truss	32	Non-linear Elastic
Facet cartilage	11 MPa	0.4	3-D Solid (8 node)	192	Linear Elastic
Facet contacts	–	–	Contact	24	–