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Initiation and progression of mechanical damage in the intervertebral disc under cyclic loading using continuum damage mechanics methodology: A finite element study

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ABSTRACT

It is difficult to study the breakdown of disc tissue over several years of exposure to bending and lifting by experimental methods. There is also no finite element model that elucidates the failure mechanism due to repetitive loading of the lumbar motion segment. The aim of this study was to refine an already validated poro-elastic finite element model of lumbar motion segment to investigate the initiation and progression of mechanical damage in the disc under simple and complex cyclic loading conditions. Continuum damage mechanics methodology was incorporated into the finite element model to track the damage accumulation in the annulus in response to the repetitive loading. The analyses showed that the damage initiated at the posterior inner annulus adjacent to the endplates and propagated outwards towards its periphery under all loading conditions simulated. The damage accumulated preferentially in the posterior region of the annulus. The analyses also showed that the disc failure is unlikely to happen with repetitive bending in the absence of compressive load. Compressive cyclic loading with low peak load magnitude also did not create the failure of the disc. The finite element model results were consistent with the experimental and clinical observations in terms of the region of failure, magnitude of applied loads and the number of load cycles survived.

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). Appearance of annular lesions has been suggested (Osti et al., 1992; Sharma et al., 2009a, 2009b; Vernon-Roberts et al., 2007a, b) as the first sign of the disc degeneration process. 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; Adams and Hutton, 1985; Adams et al., 2000; Goel et al., 1988a, b; Hansson et al., 1987; Liu et al., 1983; Liu et al., 1985; Yoganandan et al., 1994). Yu et al. (2003) reported presence of irregular fibres, buckling and bleeding in the porcine annulus in response to compressive cyclic loading. Gordon et al. (1991) reported disc herniation in 14 cadaveric lumbar motion segments, subjected to combination of flexion, axial rotation and compression for an average duration of 36,750 cycles. Liu et al. (1983) subjected cadaveric lumbar motion segments to cyclic axial loads ranging from 37%–80% of their failure load limit for up to 10,000 cycles. Disc injury was reported in 2 of 11 specimens while all the specimens experienced endplate or vertebral bone cracking. Parkinson and Callaghan (2009) conducted a series of in-vitro fatigue testing on porcine motion segments to understand the failure mechanism. They concluded that cyclic flexion/extension bending results in the failure of the disc while large cyclic compressive loading fractures the vertebral body. Average numbers of load cycles for disc injury were reported to be 9000 as compared to 930 for vertebral bone fracture. Marshall and McGill (2010) showed that cyclic flexion/extension bending of porcine motion segments caused nucleus tracking through the posterior annulus, while cyclic axial rotation resulted in the radial delamination of the annulus. In case of the human cadaver studies, it is difficult to obtain a large number of specimens without disc degeneration or pre-existing annular disruptions. With current

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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) modelling has been used extensively to explore 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). Damage to disc structure had been studied using FE models but there is no FE study for lumbar spine that investigates the degradation of the disc due to cyclic loading to the best of the authors' knowledge (Shirazi-Adl, 1989; Natarajan et al., 1994; Schimdt et al., 2009). Initiation and progression of structural damage can be tracked in a motion segment by employing user written codes in conjunction with the FE model. The purpose of this study was to employ continuum damage mechanics methodology to predict damage initiation and progression in the disc under cyclic loading using a poro-elastic FE model of a lumbar motion segment. The current analysis was restricted to the damage analyses in the annulus only. The FE model considered annulus as a single continuum body reinforced by collagen fibres instead of multilayered structure. It was hypothesised that the (a) number of load cycles to disc failure will decrease as the motion segment is subjected to complex loading rather than uni-axial compressive loading and (b) damage will initiate and progress preferentially in the posterior region of the disc under all loading conditions.

2. Materials and method

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

A previously validated (Natarajan et al., 2006; Natarajan et al., 2008; Williams et al., 2007; Tyrrell et al., 1985) 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. FE analyses were carried out using a commercially available software package ADINA (ADINA R&D Inc., Watertown, Massachussetts).

2.2. Continuum damage mechanics

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 methodology (Verdonschot and Huiskes, 1997) for the prediction of degradation of materials under cyclic loading based on Kachanov's concept was employed in the current study to investigate the failure progression in the annulus. Continuum damage mechanics formulation along with the FE modelling was employed to simulate the fatigue behaviour of the human cortical bone (Taylor et al., 1999a, b). Jeffers et al. (2007) and Lennon et al. (2007) also used it to investigate the cement mantle failure and loosening of femoral components in total hip arthroplasty respectively.

2.3. Application of continuum damage methodology to lumbar spine FE model

In the FE model, annulus was divided into 1920 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 as

$$(d_i)_t = (d_i)_{t-1} + (N_{\min}/N_i)_t$$

where i represents the integration point and t represent the iteration number.

When damage d for an integration point reached a predefined limit, the corresponding integration point in the element was assumed unable to share any load. The elastic modulus at the damaged integration points was reduced to a predetermined value thus introducing the degradation of the material at that location in the annulus. Even though the damage to the tissue occur only in the direction of tensile principal stress, the algorithm assumes damage equally occurs in all the three principal directions at each integrating point within an element. 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 procedure was implemented by introducing a FORTRAN code in the ADINA subroutine ("User Supplied Material") that allowed changing elastic modulus at each integration point of the annulus.

2.4. Stress–failure (S–N) curve for annulus

The S–N curve for the annulus was developed by using the data from a cyclic cadaver study carried out by Green et al. (1993). They tested 22 annulus slices from the anterior and posterior regions of the lumbar discs (age range 19–71 years) under different magnitudes of tensile stress for up to 10,000 cycles. In situ tensile strength of the annulus was then estimated based on the size of the specimens. The numbers of cycles to failure at different magnitudes of stress for individual specimens were plotted. A curve fit based on the power–law represents the S–N curve for the annulus (Fig. 2). The logic behind using power–law model rather than a linear model as reported for other biological tissues (Schechtman and Bader, 1997; Wang et al., 1995) was to include the effect of endurance limit observed during cyclic testing of annulus fibrosus (Green et al., 1993).

2.5. Effect of magnitudes of elastic modulus and damage parameter at damaged integrating points on the damage progression

Analyses were carried out to investigate the effect of elastic modulus and damage parameter value at the damaged integration points on the damage accumulation in the annulus. For this the motion segment was subjected to

Table 1
Element and material model information for L4L5 finite element model. (Ebara et al., 1996; Elliott and Setton, 2001; Goel et al., 1988; 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 fibres	–	–	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	–