Journal of Biomechanics 42 (2009) 2780–2788

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Statistical factorial analysis on the poroelastic material properties sensitivity of the lumbar intervertebral disc under compression, flexion and axial rotation

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ARTICLE INFO

Article history:
Accepted 29 July 2009

Keywords:
Intervertebral disc
Permeability
Fractional factorial design
Design of experiments
Finite element analysis

ABSTRACT

A statistical factorial analysis approach was conducted on a poroelastic finite element model of a lumbar intervertebral disc to analyse the influence of six material parameters (permeabilities of annulus, nucleus, trabecular vertebral bone, cartilage endplate and Young's moduli of annulus and nucleus) on the displacement, fluid pore pressure and velocity fields. Three different loading modes were investigated: compression, flexion and axial rotation. Parameters were varied considering low and high levels in agreement with values found in the literature for both healthy and degenerated lumbar discs. Results indicated that annulus stiffness and cartilage endplate permeability have a strong effect on the overall fluid- and solid-phase responses in all loading conditions studied. Nucleus stiffness showed its main relevance in compression while annulus permeability influenced mainly the annular pressure field. This study confirms the permeability's central role in biphasic modelling and highlights for the lumbar disc which experiments of material property characterization should be performed. Moreover, such sensitivity study gives important guidelines in poroelastic material modelling and finite element disc validation.

1. Introduction

Fluid flow plays a key role in form, function and pathologies of human intervertebral disc (IVD). For example, around 25% of the disc fluid is expelled and re-imbibed over a diurnal cycle, causing a loss and regain of around 1–2 cm in height (Bibby et al., 2001). Also, loss of water and progressive solid-phase disruption alter the normal nutrition of intervertebral disc which is fundamental in disc degeneration understanding (Iatridis et al., 1998; Johannessen and Elliott, 2005; Natarajan et al., 2006). Poroelastic theories implemented in finite element (FE) analyses are able to investigate fluid flow paths and pressure distribution within the disc, and draw valuable clinical conclusions (Ferguson et al., 2004; Argoubi and Shirazi-Adl, 1996). Moreover, to treat disc degeneration, disc substitutes and tissue engineered IVD scaffolds have been proposed (Gan et al., 2000; Revell et al., 2007). FE parametric studies can be performed to help in the design of such engineered structures and in the determination of the most sensitive parameters. To these purposes, the inclusion of fluid flow and velocity, coupled with stress and strain field distributions knowledge is relevant in a spinal segment FE model. However, sensitivity of each fluid and solid parameter on the poromechanic model response should be explored.

Several poroelastic models of lumbar motion segments (or only IVD) have been published in the literature, experimentally compared and partially validated (Argoubi and Shirazi-Adl, 1996; Ferguson et al., 2004; Iatridis et al., 2003; Laible et al., 1993; Natarajan et al., 2004; Williams et al., 2007). These models have shown the evident link between fluid flow and mechanical response of the spinal segments in clinically relevant degeneration applications. These studies included strain-dependent permeability and swelling pressure as important modelling features. However, clinical use of computational models depends on their validation (Viceconti et al., 2005). Model geometry and choice of fluid- and solid-phase poroelastic parameters from experimental literature should be properly addressed. Conversely, reliability on the parameters choice depends on the ability of the model to represent the physical problem. Due to the difficulty in (i) reproducibility of soft tissue experimentation, (ii) anatomical and subject variability of *in-vitro* specimen tested, and (iii) measurements techniques, some important parameters used in poroelastic formulation, i.e. hydraulic permeability, porosity, Young's modulus, show a lot of variability. Moreover, highly

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doi:10.1016/j.jbiomech.2009.07.039

variable phenomenology of disc degeneration makes difficult any experimental comparison, in particular when liquid phase is considered. The lack of a comprehensive validation for both healthy and degenerated FE poroelastic models could lead to great uncertainty during the selection of material properties.

Several material parametric studies have been performed, drawing some guidelines on the choice of linear and non-linear elastic material parameters, and exploring the response sensitivity of the FE model under different loading conditions. Rao and Dumas (1991) examined the compressive response of a lumbo-sacral segment varying the non-linear material properties of each structural component. Fagan et al. (2002) examined the geometric and material non-linearity of the IVD under three physiological loadings. These parametric studies have been conducted varying one parameter at a time and interaction between parameters has not been investigated. Although viscoelastic disc behaviour was represented, both studies did not consider any explicit fluid parameter. Ng et al. (2004) used a statistical factorial approach to determine the effect of linear elastic material properties variation of the cervical segment response. Again, the linear elastic assumption for disc sub-tissues mechanical properties does not provide any further outcome for fluid coupling. Moreover, most evident variations of fluid and solid parameters in the human IVDs are due to degeneration, as stiffening of the solid phase of annulus fibrosus (AF) and nucleus pulposus (NP) ground matrix and local and global permeability change in all disc sub-structures (Iatridis et al., 1998; Johannessen and Elliott, 2005; Natarajan et al., 2006). In such cases the sensitivity of the FE model on the parameter variation would ensure its reliability in the poromechanic representation of healthy and degenerated IVDs.

The aim of the present work was to study the poromechanical response of a L3–L4 intervertebral disc FE model under compression, flexion and axial rotation, varying Young's moduli and permeabilities of the principal disc sub-tissues. For this purpose, a statistical factorial approach using a design of experiment (DOE) was used to analyze the model sensitivity (Montgomery, 2004). It was hypothesized that the permeability and stiffness values of some tissues in the IVD are critical on the overall response whereas other components do not influence significantly the IVD behaviour.

2. Materials and methods

2.1. IVD base model

A L3–L4 intervertebral disc FE model was extracted from a previously validated model of a spinal L3–L5 segment (Noailly et al., 2007). The isolated disc model included two layers of elements representing partially superior and inferior vertebral bodies attached, and included the anterior and posterior longitudinal (ALL and PLL) ligaments. Also, AF natural composite behaviour was represented like the previous model maintaining the collagen fibres material properties and orientation. Geometry and hypoelastic material properties of fibres and ligaments are detailed in Noailly et al. (2007). Material properties of all model sub-structures were changed to poroelastic formulation, i.e. cortical shell, trabecular bone, bony endplate, AF ground matrix, NP and cartilage endplate (CEP). In the frame of poromechanics, we considered IVD tissues as fluid-saturated porous media. In such a formulation, the total stress σ can be decomposed into a pore pressure component p and the deviatoric effective stress σ_d:

$$\sigma = \sigma_d - pI$$

The fluid flow behaviour can be modelled using Darcy's law, in which the fluid mass flow rate q is related to the spatial gradient of the pore pressure,

$$q = -\frac{k}{\mu}\nabla p$$

where k is the intrinsic permeability and μ is the dynamic viscosity of water. The solid grains are assumed to be incompressible whereas the fluid is slightly compressible with a constant bulk modulus equivalent to water, i.e. 2200 MPa. In Fig. 1, the sectioned model is visible, with all tissues modelled. Poroelastic solid-phase material properties are summarized in Table 1.

Three physiological loading scenarios were simulated, a disc compression of 1000 N in vertical direction, an anterior flexion and a clockwise axial rotation. The moment value chosen for flexion and rotation was 7.5 Nm, in agreement with other FE and experimental studies (Heuer et al., 2007; Noailly et al., 2007). For the three cases, the same load cycle was simulated, consisting in a 60 s of linear loading increase, from zero to the maximum value. This loading was chosen to study the physiologic short-term disc behaviour. Common boundary conditions were used for the three cases. A zero pore pressure was applied in the superior and inferior part of the model in order to simulate the condition of free fluid flux through the porous vertebrae. An initial pressure of 0.2 MPa was considered for the nucleus in the unloaded state of the disc (see results for the initial pressure value chosen). The inferior part was fixed in displacement and loads were applied in the superior part.

In order to assess the sensitivity of the material properties on the viscoelastic long-term disc behaviour, four models with different material properties combinations were loaded with a compressive 1000 N force during 16 h and then the force was removed for 8 h. Disc height change was compared with stature change hypothesizing that lumbar spine is responsible for one third of the total stature loss and that lumbar discs deforms equally (Krag et al., 1990). The *in vivo* circadian experiment values from Tyrrell et al. (1985) were used as a reference in order to assess whether the model variations were within the same order of magnitude found by Tyrrell et al. (1985) and how the low and high levels affect the global response.

2.2. Choice of factors and levels for statistical analysis

To determine how experimental variability of poroelastic material properties affects mechanical behaviour of IVD in different loading conditions, a preliminary review was performed to choose the studied parameters. First of all, the stiffness's of annulus and nucleus were considered, i.e. Young's moduli. According to the literature, reported AF Young's modulus varies from 2.56 to 12.29 MPa, corresponding to healthy and highly degenerated AF, respectively. In the case of NP, Young's modulus varies from 1 (healthy) to 1.66 MPa (degenerated) (Iatridis et al., 1998; Natarajan et al., 2006).

Permeability is a key factor in poroelastic FE analysis. Permeability represents the ability of the interstitial fluid to flow within the tissues. Experimental ;results have shown a large variation of this parameter. Reynaud and Q uinn (2006) indicated that articular cartilage permeability typically ranges two orders of magnitude. Nauman et al. (1999) measured the intertrabecular permeability and found values ranging three orders of magnitude. Gu et al. (1999) and Johannessen and Elliott (2005) correlated anisotropic AF and NP permeabilities with disc degeneration. In the present study, four hydraulic permeabilities were chosen as statistical factors: AF, CEP, NP and trabecular bone permeability. This choice allowed us to study fluid–solid interactions significance in the whole disc, since the principal fluid IVD pathways (external AF and vertebrae) were included (Ayotte et al., 2001). An interval of values (levels) was assigned to each factor, based on most used values in poroelastic IVD simulations. Table 2 summarizes those six parameters and the ranges of variation studied.

2.3. Design of experiment statistics—screening experiment

In order to perform a statistical factorial analysis, different FE models with the same geometry but different material properties were created. A full factorial analysis with two levels for each of the six factors (i.e. material parameters) studied would require $2^6=64$ runs for each loading condition. In such a full analysis, only 6 of the 63 statistical degrees of freedom correspond to the principal effects (Montgomery, 2004), i.e. material parameter single influence. For that reason and in order to limit the computational cost, a 1/4 fractional design was used. It consisted in $2^{6-2}=16$ runs for each loading condition. The combination of parameters was automatically generated by the statistical software (Minitab Inc., 2006) corresponding to a IV resolution factorial design as indicated in Table 2. This resolution allows screening out the main effects easily when interaction effects (i.e. the effect of two or more factors varying simultaneously) are not considered.

2.4. Studies of strain-dependent permeability and initial pressure effects

The study of strain-dependent permeability implies the study of its influence on four factors. It cannot be considered as a factor itself but the effect of strain dependence of all permeabilities on the poromechanical responses can be studied using blocks in DOE. In a factorial design of resolution IV this side study does not affect the statistical analysis outcomes since three-way factor interactions were not considered (Montgomery, 2004). With two blocks in the design matrix, for each loading condition studied, 8 runs were performed using a constant permeability and 8 runs were performed using a strain-dependent permeability