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# A computational spinal motion segment model incorporating a matrix composition-based model of the intervertebral disc

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ABSTRACT

The extracellular matrix of the intervertebral disc is subjected to changes with age and degeneration, affecting the biomechanical behaviour of the spine. In this study, a finite element model of a generic spinal motion segment that links spinal biomechanics and intervertebral disc biochemical composition was developed. The local mechanical properties of the tissue were described by the local matrix composition, i.e. fixed charge density, amount of water and collagen and their organisation. The constitutive properties of the biochemical constituents were determined by fitting numerical responses to experimental measurements derived from literature. This general multi-scale model of the disc provides the possibility to evaluate the relation between local disc biochemical composition and spinal biomechanics.



## 1. Introduction

The biomechanical behaviour of the intervertebral disc (IVD) is governed by the extracellular matrix (ECM) properties of its two tissues, the nucleus pulposus (NP) and the annulus fibrosus (AF). Both tissues are composed mainly of proteoglycans (PGs) and collagen fibres, but they differ in their amount and organisation (Antoniou et al., 1996; Lyons et al., 1981). The NP is rich in water and PGs containing fixed negative charges that create a Donnan osmotic potential (Donnan, 1911) within the nucleus. The tissue tends then to attract water to balance this potential (Urban and McMullan, 1985). The collagen, in the nucleus, forms a loose network of randomly oriented fibres. The AF is characterized by a high concentration of collagen fibres, organised in a lamellar structure whose fibres are oriented at alternating angles (Marchand and Ahmed, 1990). This anisotropy enables the disc to withstand bending and twisting (Meakin and Hukins, 2000). The annulus structure, quite stiff in tension in the circumferential direction, confines the swelling nucleus. This leads to an osmotic pressure between 0.1 and 0.4 MPa (Nachemson and Morris, 1964; Wilke et al., 1999) at rest,

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allowing the disc to support compressive loading. Degeneration and aging of the IVD alters its biochemistry and the tissue morphology (Antoniou et al., 1996; Buckwalter, 1995; Lyons et al., 1981; Pearce et al., 1987). In moderately degenerated discs, a loss of water and PGs is observed in the nucleus, altering its osmotic potential. The tissue also deteriorates by becoming more fibrous, i.e. increase in collagen and change in collagen type (Antoniou et al., 1996). These changes affect its ability to sustain and transfer load appropriately (Adams et al., 1996; Tanaka et al., 2001).

Current finite element (FE) IVD models are mostly phenomenological (Malandrino et al., 2009; Noailly et al., 2007; Ruberté et al., 2009; Schmidt et al., 2006, 2010). The osmotic swelling in the IVD is generally simulated by prescribing a constant pore pressure on the boundary of the outer AF (Galbusera et al., 2011). Only few studies have introduced an osmotic pressure based on the fixed charge density (FCD) into bi- (Ehlers et al., 2009; Schroeder et al., 2010), tri- or quadriphasic models (Frijns et al., 1997; Iatridis et al., 2003; Jackson et al., 2011) of the IVD tissue, providing more accurate results (Galbusera et al., 2011). But, all these studies model the IVD without considering the influence of vertebrae and ligaments on disc kinematics. Moreover, most of these multi-phasic models (Malandrino et al., 2009; Noailly et al., 2007; Rohlmann et al., 2006; Ruberté et al., 2009; Schmidt et al., 2010) often consider AF tissue as a fibre-reinforced ground substance, taking into account the highly organised ultrastructure of the AF. However, they do not take into account the content of the tissue. Thus, these approaches do not capture the relationship between the ECM composition, well characterized for various ages and degeneration stages, and the biomechanical behaviour of the spinal motion segment (SMS). Our approach consists of modelling the IVD by assuming that the mechanical properties of the tissue are directly related to the local ECM composition and organisation. Thus, the AF and NP properties would depend on the constituent (water, fixed charged density, collagen and ground substance) material properties and also proportional to their content within the tissues. Such an approach would allow us to evaluate the influence of changes at the biochemical composition level, occurring with degeneration or regeneration, on the mechanical function of the spine and consequently allows to investigate mechanoregulated changes of ECM composition at the tissue level due to degeneration or intervention. Schroeder et al. (Schroeder et al., 2010) developed an osmo-poro-viscoelastic biochemical composition based-model of the IVD where the constitutive equations defining the constituent properties were determined by fitting numerical models to experimental tests performed on isolated nucleus and annulus tissue samples. However, only a simplified geometry of the IVD was used and only behaviour under compressive loading was examined. In this paper, the material model of the disc was improved to capture more sophisticated known phenomena of the ECM and the IVD model was also extended to an SMS model to be able to evaluate spinal biomechanics.

The objective of this study was to develop and validate a biochemical composition-based FE model of a lumbar healthy IVD within an SMS, including the adjacent vertebrae, the cartilage and bony endplates and major ligaments, able to capture the relationship between disc ECM biochemical composition and SMS kinematics. The properties of the adjacent vertebrae, cartilage and bone endplates and the major ligaments were taken from previously validated phenomenological L3–L5 SMS model (Noailly et al., 2012), the methodology to model a composition based disc was similar as in the study of Schroeder et al. (2010). First, a set of constitutive parameters was determined for healthy IVD tissue, by fitting the model to experimental tests done on isolated AF and NP tissues. Then, a biochemical composition-based IVD model was implemented in a L3–L4 SMS model, and its kinematics under axial compression and pure moments was evaluated and compared to *in-vitro* data. By doing this, the limitations of both models, the lack of the composition based behaviour of the IVD in the model of Noailly et al. (2012) and the simplified geometry as well as the limited usability of the model of Schroeder et al. (2010), were overcome.

## 2. Material and methods

A biochemical composition-based FE model of the IVD within a L3–L4 SMS was developed with FE software Abaqus 6.10EF (Simulia, Providence, RI, USA). First, a set of constitutive parameters was determined by fitting the model to experimental tests done on isolated tissues. Second, a biochemical composition-based IVD model was implemented in a L3–L4 SMS model, and its kinematics under axial compression and pure moments was evaluated and compared to *in-vitro* data.

### 2.1. *Fibre-reinforced osmo-poro-viscoelastic model of the IVD*

The model of the disc was based on Schroeder et al. (2010) with extensions in the constitutive equations of the biochemical constituents of the IVD. The disc is described as a biphasic material saturated with water, with the material properties depending on the local ECM composition. The solid phase consists of a fibrillar part, the collagen fibre network, embedded in a non-fibrillar part, the ground substance, composed mainly of proteoglycans. Two improvements were made to the total stress $\sigma_{tot}$ as described by Schroeder et al. (2010) and Wilson et al. (2006b): the isotropic stiffness of the collagen fibres $\sigma_{f_{iso}}$ was taken into account and the stress in the solid phase was divided by the volumetric deformation $J$ to account for changes in solid volume fraction due to volumetric changes of the tissue, as described by

$$\sigma_{tot} = \frac{n_{s,0}}{J}\left((1-\sum_{i=1}^{tot_f}\rho_c^i)\sigma_{nf} + \left(\sum_{i=1}^{tot_f}\rho_c^i)\sigma_{f_{iso}} + \sum_{i=1}^{tot_f}\rho_c^i\sigma_f^i\right)\right) - \mu^f I - \Delta\pi I \quad (1)$$

where $n_{s,0}$ is the initial solid volume fraction, $J$ the determinant of the deformation tensor $\mathbf{F}$, $\sigma_{nf}$ the stress in the non-fibrillar matrix, $\sigma_{f_{iso}}$ the isotropic stress in the collagen fibres, $\sigma_f^i$ the tensile stress in the $i^{th}$ fibril, $\rho_c^i$ the fibril density, $tot_f$ the amount of fibrils, $\mu^f$ the water chemical potential, $\mathbf{I}$ the unit tensor and $\Delta\pi$ the osmotic pressure relative to the external physiological salt concentration. The distinction between AF and NP tissue properties results from the differences in the