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Three-dimensional inhomogeneous triphasic finite-element analysis of physical signals and solute transport in human intervertebral disc under axial compression

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Abstract

A 3D inhomogeneous finite-element model for charged hydrated soft tissues containing charged/uncharged solutes was developed and applied to analyze the mechanical, chemical, and electrical signals within the human intervertebral disc during an axial unconfined compression. The effects of tissue properties and boundary conditions on the physical signals and the transport of fluid and solute were investigated. The numerical simulation showed that, during disc compression, the fluid pressurization and the effective (von Misses) solid stress were more pronounced in the annulus fibrosus (AF) region near the interface between AF and nucleus pulposus (NP). In NP, the distributions of the fluid pressure, effective stress, and electrical potential were more uniform than those in AF. The electrical signals were very sensitive to fixed charge density. Changes in material properties of NP (water content, fixed charge density, and modulus) affected fluid pressure, electrical potential, effective stress, and solute transport in the disc. This study is important for understanding disc biomechanics, disc nutrition, and disc mechanobiology.

Keywords: Intervertebral disc; Triphasic theory; Finite-element method; Solute transport; Soft tissue mechanics

1. Introduction

The intervertebral disc (IVD) is the largest cartilaginous structure in human body that contributes to flexibility and load support in the spine. To accomplish these functions, the disc has a unique architecture consisting of a centrally located nucleus pulposus (NP) surrounded superiorly and inferiorly by cartilage endplates and peripherally by the annulus fibrosus (AF) (Lundon and Bolton, 2001). Because the disc is avascular and experiences mechanical loads, the cells in IVD tissues live in a complex physical environment. Many studies have shown that changes in nutrient levels and physical signals will affect the activity of disc cells (Horner and Urban, 2001; Urban, 2002). The cellular response, in turn, can alter matrix and thereby initiate structural remodeling. These processes are important for disc homeostasis, yet they can also lead to tissue disorganization and dysfunction (e.g., disc degeneration). During the past decade, increasing attention has been focused on the biological responses of IVD to mechanical forces and other physical stimuli to understand cellular mechanotransduction mechanisms. The identification of such mechanisms will give rise to tremendous potential for clarifying disease mechanisms, establishing prevention strategies, and defining regeneration techniques. However, the physical stimuli are very complex, comprised of mechanoelectrochemical events within the extra-cellular matrix (ECM), such as stress, strain, ion concentrations, fluid pressure, electrical potential, transport of water, ions, and other solutes, etc. As a first step in understanding the relationships between physical stimuli and cell response, it is essential to quantify the physicochemical environment within the disc tissues with an appropriate theoretical model. To this end, many attempts have been

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done by different investigators using various computational models (see recent papers by Soukane et al., 2005; Yao and Gu, 2006b for summary).

From an engineering point of view, IVD is an inhomogeneous, anisotropic, charged, porous fibrous material. Due to its unique structure, it is a challenge to simulate its mechanical, chemical, and electrical signals as well as solute transport under different loading conditions. The objective of this study was to develop a three-dimensional (3D), inhomogeneous finite-element model (FEM) for human IVD for analyzing the physical environment and solute transport within the tissue under different mechanical loading conditions. A case of IVD under axial compression was simulated and reported. Because of the complex nature of the problem, the analysis of this simple loading condition is useful for elucidating the effects of changes in material properties (due to degeneration or growth) on solute (nutrients or growth factors) transport in IVD. It could also serve as a baseline for comparison of different theoretical models as well as for experimentally extracting material properties that may be difficult to measure directly.

2. Methods

In this study, the IVD is modeled as an inhomogeneous material with two distinguishing regions, i.e., NP and AF regions (Fig. 1a). Responses of physical signals and solute transport in the human lumbar disc (Fig. 1a) to unconfined compression (stress-relaxation test, Fig. 1) were analyzed in this study. The size and geometry of a representative disc are shown in Fig. 1a (Iatridis et al., 2003). The thickness of the disc was $h = 10$ mm. The disc sample was initially equilibrated with a bathing solution of 0.15 M NaCl. An uncharged solute was introduced into the bathing solution at $t = 0$, and the disc was subjected to ramp compression (10% strain in 10,000 s) between two endplates (Fig. 1d). For the control case, two endplates were assumed to be perfectly permeable to water and solutes. The effect of endplate calcification on water and solute transport was investigated by assigning impermeable boundary condition to the portion of endplate adjacent to AF or to the portion adjacent to NP (Fig. 1c). In this study, the human disc was modeled as an isotropic inhomogeneous mixture consisting of an intrinsically incompressible elastic solid (with fixed charge), water, ion (Na^+ and Cl^-), and uncharged solute (uncharged growth factor) phases.

A theoretical model (Yao and Gu, 2006b), developed based on the works by Lai et al. (1991) and Gu et al. (1998), was used in this study. In the model, strain-dependent hydraulic permeability and strain-dependent diffusivity were considered (Table 1) using the constitutive relations for AF and gels (Gu et al., 2003, 2004; Gu and Yao, 2003). The FEM formulation (weak form) was based on the work by Sun et al. (1999). The formulation of this 3D initial and boundary-value problem was solved using FEMLAB software (FEMLAB3.1, COSMOL Inc., Burlington, MA).

The upper quadrant of the disc was modeled with a mesh of 4306 second-order, tetrahedral Lagrange elements (Fig. 1b). The maximum time-step of 100 s was used during the ramp phase, and variable maximum time-steps from 5 to 1000 s were used during the relaxation phase. The convergence of the numerical model was examined by refining the mesh and tightening the tolerance. The accuracy of the numerical method was

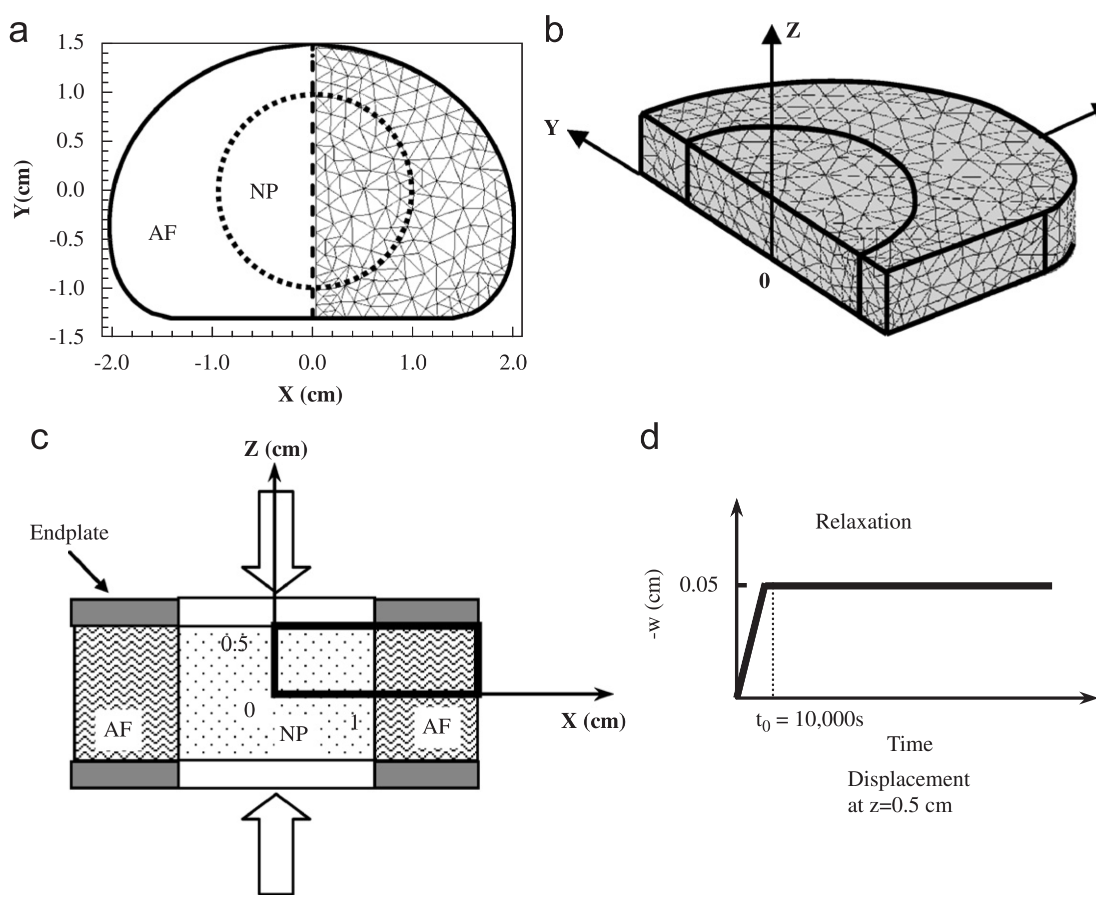

Fig. 1. (a) Disc geometry, (b) mesh, (c) test configuration, and (d) testing protocol.