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Review

What have we learned from finite element model studies of lumbar intervertebral discs in the past four decades?

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A B S T R A C T

Finite element analysis is a powerful tool routinely used to study complex biological systems. For the last four decades, the lumbar intervertebral disc has been the focus of many such investigations. To understand the disc functional biomechanics, a precise knowledge of the disc mechanical, structural and biochemical environments at the microscopic and macroscopic levels is essential. In response to this need, finite element model studies have proven themselves as reliable and robust tools when combined with in vitro and in vivo measurements.

This paper aims to review and discuss some salient findings of reported finite element simulations of lumbar intervertebral discs with special focus on their relevance and implications in disc functional biomechanics. Towards this goal, the earlier investigations are presented, discussed and summarized separately in three distinct groups of elastic, multi-phasic transient and transport model studies.

The disc overall response as well as the relative role of its constituents are markedly influenced by loading rate, magnitude, combinations/preloads and posture. The nucleus fluid content and pressurizing capacity affect the disc compliance, annulus strains and failure sites/modes. Biodynamics of the disc is affected by not only the excitation characteristics but also preloads, existing mass and nucleus condition. The role of fluid pressurization and collagen fiber stiffening diminish with time during diurnal loading. The endplates permeability influences the time-dependent response of the disc in both loaded and unloaded recovery phases. The transport of solutes is substantially influenced by the disc size, tissue diffusivity and endplates permeability.

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1. Introduction

Lumbar intervertebral disc is a complex structure that experiences large deformations as it provides for spinal flexibility and large loads as it resists and transmits loads along the spinal column. The disc consists of an inner gelatinous core, the nucleus pulposus, a surrounding ring, the annulus fibrosus, and the cartilaginous endplates at extremities (Fig. 1a). While the cartilaginous endplate is comparable to the articular cartilage, the annulus is made of a multilamellar fibrocartilage with highly aligned collagen fiber networks within discrete lamellae that provide tensile properties and help supporting a multiaxial loading environment (Inoue, 1981; Marchand and Ahmed, 1990). The disc is composed mostly of water (65–90% volume), collagen (15–65% dry weight), proteoglycans (10–60% dry weight), and other matrix proteins (15–45% dry weight) (Ghosh et al., 1977).

To understand the functional biomechanics of lumbar intervertebral discs, a precise knowledge of the mechanical, structural and biochemical environments at the disc microscopic (molecular and cellular) and macroscopic levels is needed (Urban, 2002). In vivo and in vitro studies have been of great value in this regard albeit their limitation to accurately quantify the spatial and temporal variations of internal stresses and strains throughout the tissue, the influx and efflux of fluid as well as the transport of solutes and parameters affecting them. In response to this need, the finite element (FE) method acts as a complementary approach in providing valuable insights into how discs function and fail. The FE method originated from the urgent need for solving rather complex continuum elasticity and structural analysis problems in civil and aeronautical engineering in the early 1950s and flourished right after to diverse application domains encompassing material science, fluid mechanics, transport phenomena, bioengineering, etc. The first FE application in biomechanics was reported in 1972 by Brekelmans et al. (1972) who studied the stress and strain distributions within a femur. Since then, the number, depth and extent of biomechanical applications have substantially grown aiming ultimately for improved insights into complex physiological systems with coupled biological–mechanical interactions. With steady increase in availability and affordability of computational power, sophisticated multiphysics formulations, imaging techniques as well as material and structural properties, FE models and applications have experienced tremendous growth. They cover nowadays a wide range of complex phenomena involving irregular geometries (Fig. 1b), nonlinearities, contacting bodies, remodeling, degradation, failure and multi-physics couplings.

The present paper aims to review and discuss the findings of reported FE simulations of healthy lumbar intervertebral discs

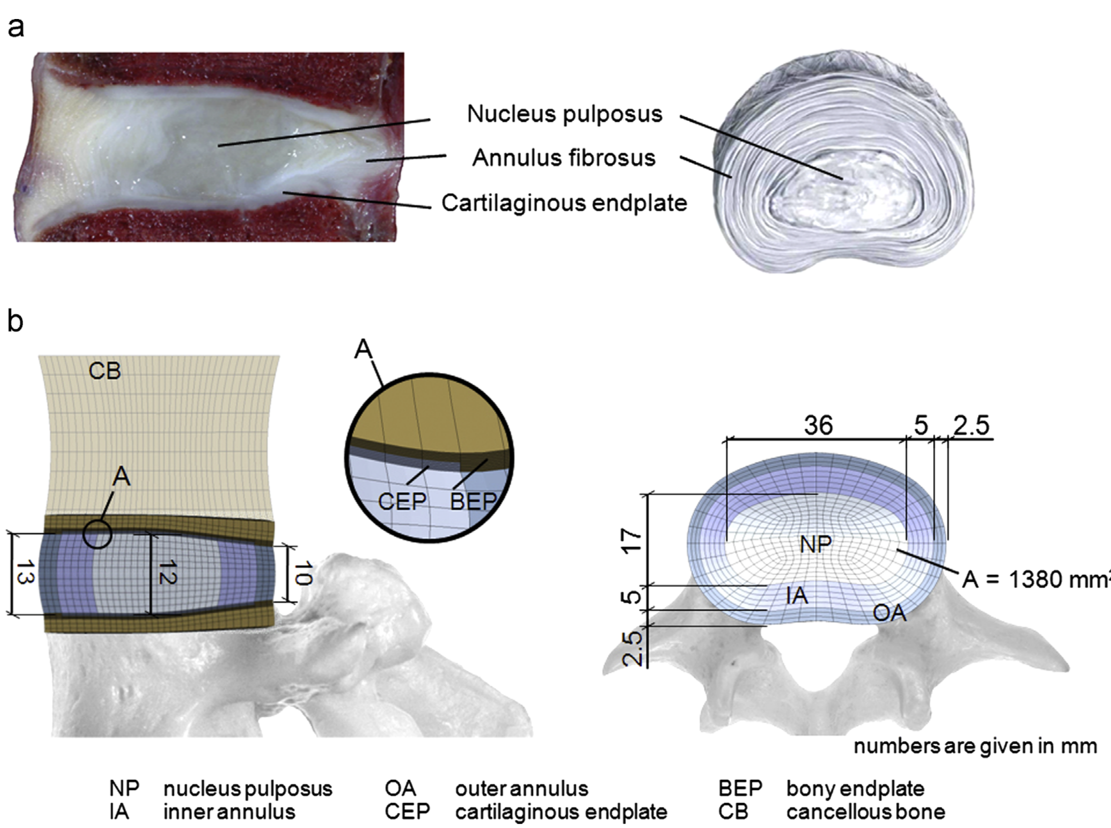

Fig. 1. (a) Sagittal (adapted from Schmidt (2006)) and transversal (adapted from Schünke et al. (2005) views of the lumbar intervertebral disc and (b) 3D finite element model of the human L4–L5 lumbar disc with adjacent vertebral bodies (adapted from Schmidt and Reitmaier (2013)).