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Validation and application of an intervertebral disc finite element model utilizing independently constructed tissue-level constitutive formulations that are nonlinear, anisotropic, and time-dependent

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ABSTRACT

Finite element (FE) models are advantageous in the study of intervertebral disc mechanics as the stress–strain distributions can be determined throughout the tissue and the applied loading and material properties can be controlled and modified. However, the complicated nature of the disc presents a challenge in developing an accurate and predictive disc model, which has led to limitations in FE geometry, material constitutive models and properties, and model validation. The objective of this study was to develop a new FE model of the intervertebral disc, to validate the model's nonlinear and time-dependent responses without tuning or calibration, and to evaluate the effect of changes in nucleus pulposus (NP), cartilaginous endplate (CEP), and annulus fibrosus (AF) material properties on the disc mechanical response. The new FE disc model utilized an analytically-based geometry. The model was created from the mean shape of human L4/L5 discs, measured from high-resolution 3D MR images and averaged using signed distance functions. Structural hyperelastic constitutive models were used in conjunction with biphasic-swelling theory to obtain material properties from recent tissue tests in confined compression and uniaxial tension. The FE disc model predictions fit within the experimental range (mean ± 95% confidence interval) of the disc's nonlinear response for compressive slow loading ramp, creep, and stress-relaxation simulations. Changes in NP and CEP properties affected the neutral-zone displacement but had little effect on the final stiffness during slow-ramp compression loading. These results highlight the need to validate FE models using the disc's full nonlinear response in multiple loading scenarios.

1. Introduction

Finite element (FE) models are advantageous in the study of intervertebral disc mechanics as the stress–strain distributions can be determined throughout the disc and the applied loading and material properties can be controlled and modified. Experimental studies are unable to isolate and quantify the role of individual tissues or specific factors correlated with aging and degeneration without invasive procedures such as nucleotomy (Johannessen et al., 2006), needle puncture (Martin et al., 2013), and enzymatic digestions (Boxberger et al., 2006; Jacobs et al., 2011), which induce structural and biochemical changes throughout the disc and obfuscate the interpretation of results. FE models have therefore been used to complement experimental studies and quantify critical elements intrinsic to both the healthy and degenerate disc that are otherwise unavailable or hard to control. FE studies have, for example, calculated the stresses experienced by annulus fibrosus (AF) fibers (Schroeder et al., 2006) and quantified the impact of disc geometry (Galbusera et al., 2011; Niemeyer et al., 2012; Noailly et al., 2007). Importantly, mechanical changes with disc degeneration have been identified, including increased range of motion and stress in compression, bending, axial rotation, and flexion/extension (Ruberte et al., 2009). FE studies have identified that failure initiates at the endplates in compressive and bending loads, and that AF tears are unlikely to occur in compression-only loading (Natarajan et al., 1994).

Intervertebral disc geometry is commonly represented in FE models using an idealized 'kidney-bean' profile (Little et al., 2007;

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Magnier et al., 2009; Motaghinasab et al., 2012; Schroeder et al., 2006; Stokes et al., 2011). Typically, the 3D shape is developed by taking multiple measurements, such as an average disc height, anterior–posterior distance, and lateral width, and extrapolating the remaining shape. This approach facilitates a geometry that is representative of a group of discs being tested because average measurements from all discs are used, however, it is often impractical to manually measure sufficient locations throughout the disc to capture its intricate 3D geometry and it is commonplace for these models to implement assumptions, such as constant disc height, to simplify the process. Yet, the importance of accurate geometry has been demonstrated; disc height and endplate dimensions affect intradiscal pressure and range of motion (Niemeyer et al., 2012), while other changes in disc geometry alter the internal stress and strain distributions (Noailly et al., 2007). FE models seeking increased geometrical accuracy have therefore used sample-specific MR or CT imaging (del Palomar et al., 2008) to generate disc geometries with superior detail and spatial resolution. Although these are highly accurate, their geometry does not represent a group average; typically, single subject samples are chosen to represent the group.

Recently, the method of signed distance functions has been applied to quantify intervertebral disc shape (Peloquin et al., 2014). This technique uses high-resolution 3D MR images of multiple discs to create a mean geometry wherein every point in 3D space is an average of all the discs from the group of interest. The resulting shape is therefore fully determined and representative of the group-set that was imaged. This effectively combines the high-resolution advantage of image-based geometry with the abilities to represent the mean shape of a group-set, where idealized geometries have previously excelled. This technique has not previously been applied to FE models of intervertebral disc.

There is great diversity in the material models used in FE studies of the disc. The utilization of biphasic-swelling theory using anisotropic, nonlinear and inhomogeneous structural continuum models is becoming prevalent (del Palomar et al., 2008; Malandrino et al., 2009; Schroeder et al., 2010; Stokes et al., 2011). The material parameters used within these advanced constitutive theories are frequently selected from combinations of tissue-testing studies in the literature. However, the elastic and permeability properties of the CEP have only recently been determined through experimental tissue tests. Additionally, the published permeability properties for the NP and AF span several orders of magnitude, likely due to different initial conditions of the tissue and different testing protocols. Importantly, recent work has demonstrated that fitting material parameters to the standard biphasic model (without swelling) provides a different set of elastic and permeability parameters compared to the biphasic-swelling model (Cortes et al., 2014). Therefore, when constructing a biphasic-swelling disc model, it may be precarious to use the elastic and permeability parameters from the standard biphasic model and append an osmotic pressure contribution. In response to the aforementioned limitations, a new set of biphasic-swelling material parameters has recently been obtained (Cortes et al., 2014), wherein all of the disc soft tissues, including the CEP, were tested using a consistent protocol, and with initial conditions that would be similar to those of the FE disc model.

Validation is critical in order to confidently apply the findings of disc FE models. Validation is frequently performed only at the end-points of loading using global disc metrics such as total disc displacement, intradiscal pressure, and bulge. The reported values in experimental motion segment testing have large variability and are thus easily matched within a standard deviation. Especially problematic, this approach neglects the nonlinearity of disc stress–strain behavior and the time-dependent response, both essential to disc function. Calibration methods have been used to tune the material parameters of FE models, especially those of the AF fibers, in order for FE results to fit experimental data (Malandrino et al., 2013; Schmidt et al., 2006, 2007). Many studies that do include validation of the nonlinear stress–strain response use a similar procedure to calibrate or tune their material parameters (Noailly et al., 2011). Recently, the nonlinear response of a cervical disc was validated in flexion and extension without tuning or altering material parameters, but only for quasi-static loading (del Palomar et al., 2008).

The objective of this study was to develop a new FE model of the intervertebral disc utilizing an analytically based geometry, with material properties obtained from tissue-tests fit to biphasic-swelling theory, and to validate the model's nonlinear and time-dependent responses without tuning or calibration. Additionally, this model was used to elucidate the contributions of the NP, CEP, and AF to the disc response in multiple axial compression experiments including quasi-static loading, creep, and stress relaxation.

2. Methods

2.1. Finite element mesh

In order to obtain the disc geometry for the FE simulations, 7 human L4/L5 intervertebral discs with a degeneration score of 3 were imaged using a high-resolution (200μm isotropic) 3D MR sequence. The volumetric shape of each disc was averaged using signed distance functions following the methods outlined in Peloquin et al. (2012) and Tsai et al. (2003), resulting in an analytically-based 3D geometry that represented the mean shape of the group of discs imaged (Fig. 1).

The mean disc shape was processed using a custom Matlab (MathWorks, MA) routine to generate the FE mesh (Fig. 2A). An intermediate 2D quad mesh of the disc's axial silhouette was created, formed using a combination of concentric contours of quad elements and a central rectangular grid (Fig. 2B). This arrangement of concentric contours allowed the AF elements to be aligned with the disc's circumferential axis, such that each element's local coordinate frame could be used to define the local collagen fiber direction, which was oriented at ± 25° to the disc circumferential axis (Guerin and Elliott, 2006). The NP encompassed 31% of the disc axial area and the center of the NP was positioned with a posterior offset equal to 10% of disc anterior–posterior length (O'Connell et al., 2007).

The 3D mesh (Fig. 2C) was composed of 8-node hexahedral elements (10,625 elements, 11,336 nodes), created initially by stacking copies of the 2D quad mesh in vertical layers along the axis of the disc height and subsequently projecting the surface nodes to the boundary of the average human disc geometry. The cartilage and bony endplates were then created by extruding the superior and inferior element layers of the disc by 500 μm, which was chosen based on recent histological and MR measurements of CEP (Moon et al., 2013). A similar process was used to create vertebral bodies, with a height of 0.5 mm and 3-element layers. In order to establish the final geometry, hydration for 24 h in PBS was simulated. During this time the vertebral bodies were constrained, causing the disc to pressurize and bulge outwards, achieving its final geometry (Fig. 2D).

2.2. Constitutive models

Structurally based hyperelastic continuum models were used, which are advantageous as they link the mechanical response of tissues to their constituent

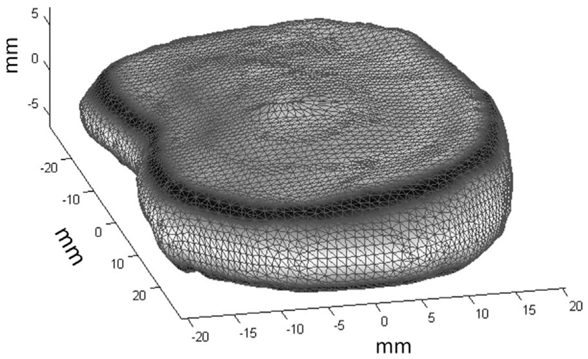

Fig. 1. Mean shape (not-meshed) of L4/L5 human disc based on principal component analysis of high resolution MRI (200 μm isotropic) of seven human discs.