Journal of Biomechanics 49 (2016) 919–925

Contents lists available at ScienceDirect

Journal of Biomechanics

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

Image driven subject-specific finite element models of spinal biomechanics

Sahand Zanjani-Pour [a], C. Peter Winlove [a], Christopher W. Smith [b], Judith R. Meakin [a,*]

[a] Biophysics, University of Exeter, Exeter, UK
[b] Engineering, University of Exeter, Exeter, UK

ARTICLE INFO

Article history:
Accepted 5 February 2016

Keywords:
Finite element model
Lumbar spine
Magnetic resonance imaging

ABSTRACT

Finite element (FE) modelling is an established technique for investigating spinal biomechanics. Using image data to produce FE models with subject-specific geometry and displacement boundary conditions may help extend their use to the assessment spinal loading in individuals. Lumbar spine magnetic resonance images from nine participants in the supine, standing and sitting postures were obtained and 2D poroelastic FE models of the lumbar spine were created from the supine data. The rigid body translation and rotation of the vertebral bodies as the participant moved to standing or sitting were applied to the model. The resulting pore pressure in the centre of the L4/L5 disc was determined and the sensitivity to the material properties and vertebral body displacements was assessed. Although the limitations of using a 2D model mean the predicted pore pressures are unlikely to be accurate, the results showed that subject-specific variation in geometry and motion during postural change leads to variation in pore pressure. The model was sensitive to the Young's modulus of the annulus matrix, the permeability of the nucleus, and the vertical translation of the vertebrae. This study demonstrates the feasibility of using image data to drive subject-specific lumbar spine FE models and indicates where further development is required to provide a method for assessing spinal biomechanics in a wide range of individuals.

1. Introduction

Establishing the loads present in the human spine and its associated tissues is of significant importance for understanding normal spinal function and problems such as degeneration (Adams, 2012), functional instability (Mulholland, 2008), manual handling injury (Potvin, 2008), and back pain (Yang et al., 2011) and for designing successful regenerative therapies and implants for degenerative disc disease (Weber et al., 2015). It is known that the spinal anatomy, spinal shape (Meakin et al., 2008; Roussouly et al., 2005) and the supporting musculature (Meakin et al., 2013) exhibit extensive variation between healthy individuals and as a result of age and disease (Roussouly et al., 2006). This variability, together with other variables such as body mass and stature, leads to variation in spinal loading (Meakin and Aspden, 2012; Niemeyer et al., 2012). Determining load in an individual is therefore important for being able to assess subject-specific risks and to estimate the range of spinal loads present in the population.

Measuring spinal load in individuals in vivo, however, poses a considerable biomechanical challenge. Loads have been measured in vivo using modified spinal implants (Dreischarf et al., 2010; Rohlmann et al., 1997, 2008) but this method is limited to people who have had surgical intervention and may not represent the loading present in the normal spine due to the inclusion of a stiffer component. Loads may also be estimated with reasonable accuracy (Dreischarf et al., 2013) from measurements of pressure in the intervertebral discs (Nachemson and Morris, 1964; Sato et al., 1999; Schultz et al., 1982; Wilke et al., 1999) and this method has been used to explore loading in a variety of postures and tasks. These measurements, however, are limited to single discs and, with concerns over puncturing healthy discs (Iatridis and Hecht, 2012; Kang, 2010), are not practical for routine or widespread use. Non-invasive methods such as stadiometry, that allow loading to be inferred from measurements of spinal height (Althoff et al., 1992), do not give detailed information about loading in specific discs and may not fully account for an individual's posture (Dreischarf et al., 2010). Measurements of nucleus pulposus water content determined from magnetic resonance (MR) images (Nazari et al., 2015) also allows relative loading to be inferred, but the validity of this method is yet to be confirmed.

* Correspondence to: University of Exeter, Physics Building, Stocker Road, Exeter EX4 4QL, UK. Tel.: +44 1392 724109.
E-mail address: j.r.meakin@exeter.ac.uk (J.R. Meakin).

http://dx.doi.org/10.1016/j.jbiomech.2016.02.025
0021-9290/

Computational modelling provides an alternative method that has the advantage of being non-invasive and can incorporate subject-specific information concerning anatomy and posture. Approaches include musculoskeletal modelling (de Zee et al., 2007; Han et al., 2013) and finite element (FE) analysis (Shirazi-Adl et al., 2005); the latter which allows the distribution of load between, and within, the components of the spine to be deduced. To be relevant to a given individual, a computational model needs to include subject-specific geometry, material properties, and boundary conditions. Many contemporary spinal models involve applying forces and moments (Dreischarf et al., 2014), deriving values for these using inverse statics (Zhu et al., 2013) and kinematics (Shirazi-Adl et al., 2005).

An alternative approach is to apply displacement boundary conditions to the vertebrae that are derived from medical images. Wang et al. (2013) have assessed this approach using a 3D elastic model of an in vitro functional unit with vertebral displacements derived from fluoroscopy and found the predicted loads to differ from the experimentally measured loads by an average of 20%. They have further used their model to assess loading in vivo during a lifting task (Wang et al., 2014). Although 3D is useful for assessing the motion of the vertebrae in all planes, is required for accurate prediction of disc behaviour, and would allow load sharing between the disc and facet joints to be determined, a 2D model is more pragmatic as a preliminary step in developing and evaluating this new approach and where the spinal motion out of the sagittal plane is minimal. We have previously piloted this approach using a 2D in vivo lumbar spine model that derived its geometry and vertebral displacements from postural MR images (Zanjani-Pour et al., 2014). In this previous work, models for four individuals were created using an isotropic linear elastic material model for the disc. This does not represent the non-isotropic, time dependent behaviour of the disc, which will be particularly important when considering motion, and a poroelastic, fibre reinforced material model may be more relevant (Freutel et al., 2014; Williams et al., 2007).

The aim of the current study was therefore to further develop our previous work by incorporating poroelastic properties in the discs and vertebrae. The sensitivity of the pore pressure predicted by the model to the input parameters was performed to determine the most important parameters that need to be considered in future subject-specific models. A larger sample of subject-specific models was also created to estimate the extent to which subject-specific variation in geometry and vertebral displacement leads to variation in predicted pore pressures.

2. Methods

2.1. Image data

The MR data used in the current study were originally acquired for a study by Hirasawa et al. (2007) using a Fonar 0.6 T Upright TM positional MRI scanner (Fonar Corporation, Melville, New York). The study had received ethical approval and all participants had given their informed consent. Each participant had been scanned in a variety of recumbent and upright postures. Images in the sagittal place were acquired using a T2 weighted sequence with a slice thickness of 4.5 mm and an in-plane pixel size of 1.17 mm. Further details on the positioning of the participants and the scanning sequences are given in Hirasawa et al. (2007). All of the 32 participants were male with a mean age of 32 years (range 21–61 years) and none reported having back pain.

In previous work on sagittal lumbar spine shape (Meakin et al., 2009), the MR scans of the participants in the supine, upright standing and neutral sitting postures had been annotated. The images located at the mid-sagittal plane of the lumbar spine had been identified and the location of the vertebral bodies from S1 to L1 had been defined by manually placing a series of landmark points along the boundary of each vertebral body (28 points per vertebrae) as shown in Fig. 1.

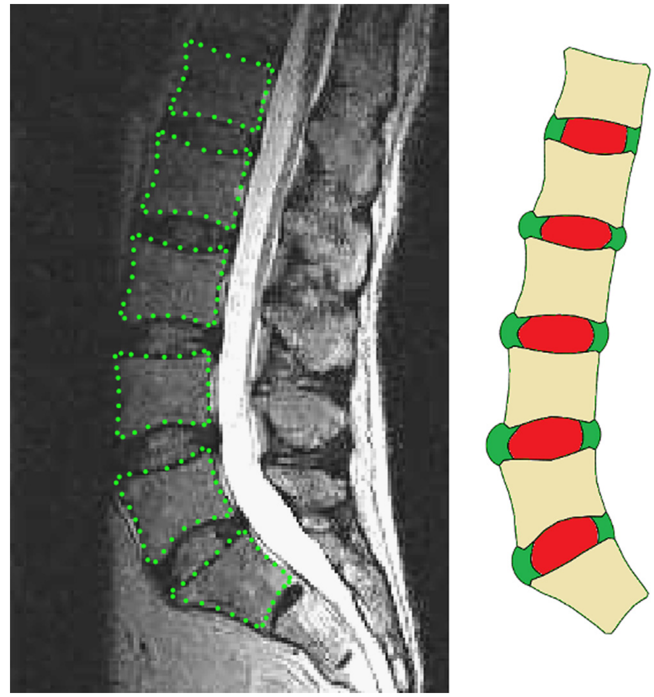

Fig. 1. Creation of subject specific FE model. (a) MR image with landmark points defining the vertebral bodies from S1 to L1. (b) Model geometry including the vertebral bodies and discs.

In the current study, the mid-sagittal plane images and landmark points from nine of the participants were used to create subject-specific FE models and derive displacement boundary conditions for the vertebrae. The nine participants (mean age 29 years, range 20–55 years) were chosen on the basis of having no radiological signs of disc degeneration.

2.2. FE models

Two-dimensional FE models of the lumbar spine from S1 to L1 were created and analysed using ABAQUS (version 6.14, Dassault Systèmes Simulia Corp.). The geometry of the model was defined using the vertebral body landmark points taken from the MR images acquired in the supine posture. Additional points were determined from the images and used to define arcs for the borders of the annulus and nucleus (Fig. 1).

The models were meshed using 8-node biquadratic displacement, bilinear pore pressure, reduced integration, hybrid plane strain elements, CPE8RPH (note that although hybrid elements were used, they were not required for the model presented here since the elastic properties in the model were far from incompressible (Table 1); however, a test using non-hybrid elements showed that the use of hybrid elements made little difference to the results). A uniform mesh density was used with the total number of elements in each model being between 80,000 and 110,000 (depending on the physical size of the spine). The density of the mesh was determined using a mesh convergence test. Each component (vertebral body, annulus and nucleus) was meshed individually and then connected to its neighbouring components using tie constraints. A reference point at the centre of each vertebral body (defined as the mean of the vertebral body landmark point coordinates) was created and coupled kinematically to the