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Material properties of bovine intervertebral discs across strain rates

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ABSTRACT

The intervertebral disc (IVD) is a complex structure responsible for distributing compressive loading to adjacent vertebrae and allowing the vertebral column to bend and twist. To study the mechanical behaviour of individual components of the IVD, it is common for specimens to be dissected away from their surrounding tissues for mechanical testing. However, disrupting the continuity of the IVD to obtain material properties of each component separately may result in erroneous values. In this study, an inverse finite element (FE) modelling optimisation algorithm has been used to obtain material properties of the IVD across strain rates, therefore bypassing the need to harvest individual samples of each component. Uniaxial compression was applied to ten fresh-frozen bovine intervertebral discs at strain rates of 10^{-3}–$1/s$. The experimental data were fed into the inverse FE optimisation algorithm and each experiment was simulated using the subject specific FE model of the respective specimen. A sensitivity analysis revealed that the IVD's response was most dependent upon the Young's modulus (YM) of the fibre bundles and therefore this was chosen to be the parameter to optimise. Based on the obtained YM values for each test corresponding to a different strain rate ($\dot{\varepsilon}$), the following relationship was derived:$YM = 35.5 \ln \dot{\varepsilon} + 527.5$. These properties can be used in finite element models of the IVD that aim to simulate spinal biomechanics across loading rates.

1. Introduction

The intervertebral disc (IVD) is located between adjacent vertebral bodies of the spine and consists of three components; the nucleus pulposus (NP), annulus fibrosus (AF), and cartilaginous endplates (CEP). These components interact with one another such that the disc is able to distribute compressive loading on adjacent vertebral bodies, while allowing the vertebral column to bend and twist (Bogduk, 2005; Humzah and Soames, 1988). The functional anatomy of the IVD is determined by its complex material behaviour. As a viscoelastic structure, the IVD has material properties that are sensitive to strain rate (Virgin 1951). Capturing the behaviour of each of its components is important to understand better processes such as ageing, degeneration, and traumatic injury. It is also of importance for finite element (FE) simulations of the IVD or indeed the spine where accurate material models are essential to ensure valid predictions in mechanical response under loading.

Disrupting the continuity of the disc to test each component separately may have an effect on the obtained response and so result in erroneous material properties (Adams and Green, 1993). In particular, this is an issue for the most complex structure of the IVD, the AF, which incorporates concentric layers, known as lamella, with embedded fibres at alternating orientations. Inverse FE modelling provides the opportunity to obtain material properties of the individual components without disrupting the continuity of the IVD. The method involves developing an FE model with an accurate geometry, simulating a controlled experiment and then altering material properties until experimental and numerical responses of the IVD are in good agreement. This method has been used previously for other tissues that have complex interactions with surrounding components, for example the heel fat pad (Erdemir and Viveiros, 2006; Grigoriadis et al., 2017), the lung (Sadeghi Naini et al., 2011), and the cornea (Nguyen and Boyce, 2011), but, to the authors' knowledge, not the IVD.

Therefore, the aim of this study was to obtain material properties of components of the IVD at a range of loading rates without having to disrupt its structural integrity. We hypothesised that some components will have a greater influence on the IVD's mechanical response than others, and therefore, a specific objective was to perform a sensitivity study to identify these.

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2. Methods

2.1. Specimen preparation

Ten vertebral body-disc-vertebral body (VB-disc-VB) specimens were harvested from six bovine tails that had been obtained from a local abattoir. Each specimen was Computed Tomography (CT) scanned (IVIS SpectrumCT Imaging System, Caliper Life Sciences, Hopkinton, MA, USA – voxel size 0.15×0.15×0.15 mm) to check for vertebral fractures or any other signs of pathology that may affect the properties of the IVD, and to allow accurate measurements of the geometry of the disc. Specimens were stored frozen at −20°C and each tail was thawed overnight at room temperature before dissection and testing. Two separate motion segments were obtained from each tail by cutting transversely through the first, second and third caudal VBs at mid-height. Surrounding soft tissues were carefully removed leaving VB-disc-VB specimens. Throughout the preparation process specimens were regularly sprayed with phosphate buffered saline (PBS, 0.15 mol/l) to keep them hydrated.

Using a custom built alignment jig the superior VB of the specimen was positioned such that the mid-plane of the disc was parallel to the ends of, and centred within, a 90 mm diameter pot. The superior VB was then fixed in position using polymethyl-methacrylate (PMMA) bone cement before being turned upside down allowing the inferior VB to be lowered into a second pot and again secured into position using PMMA.

2.2. Experimental procedure

Experiments were carried out using a servo-hydraulic materials testing machine (8872; Instron, Canton, MA, USA). The potted specimens were placed into the testing machine with a custom designed hood that allowed the compressive load to be spread across the whole pot (Fig. 1). The cross-head was lowered until a small compressive load (~5N) was recorded by the testing machine indicating that the compression tup was in contact with the top pot. The specimen was subjected to three preconditioning cycles of compression from 10 to 50 N at 1 Hz. A similar preconditioning sequence has been used previously (Adam et al., 2015), and preliminary tests suggested that this range was sufficient to ensure a repeatable response. Following the preconditioning cycles, the specimen was subjected to a main cycle to 15% strain. This strain was determined for each individual specimen based upon central disc height measurements taken from the CT scans and was chosen to ensure that the disc was not damaged, thus enabling multiple tests on a single specimen. Each disc was compressed at four strain rates (0.001, 0.01, 0.1, and 1/s), again calculated from central disc height measurements taken from the CT scans. Preliminary investigations showed that a 5 min relaxation period between tests was sufficient to obtain a repeatable force-displacement response.

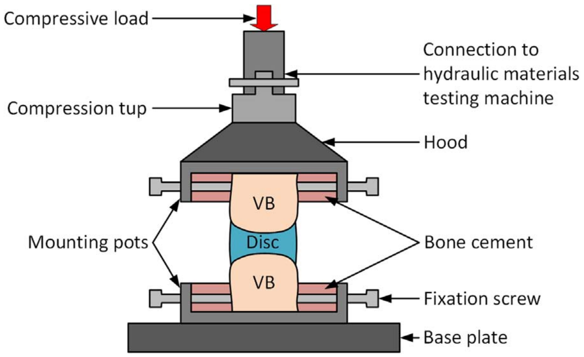

Fig. 1. Diagram of the experimental setup allowing compression of the VB-disc-VB specimen.

2.3. FE model development

Ten subject-specific, non-linear, implicit, axisymmetric FE models (MSC.Marc, v2015, MSC.Software, Santa Ana, CA, USA) were developed based on the CT scans of each specimen. The average of three measurements of the central disc height, peripheral disc height, and disc radius obtained from the CT scans were used to modify a generic geometry and ensure that the developed models were subject specific (Fig. 2). Internal geometry (NP:AF width ratio=3.72:1) and the number of lamellae (16) included in the model was based upon previous imaging studies of bovine IVDs (Adam et al., 2015). Fibre bundles in the AF were modelled using rebar elements while the AF matrix and NP were represented by quadrilateral 4-node axisymmetric elements. The fibre bundles were only present in the AF region of the disc and were assigned a constant Young's modulus in tension, but were not allowed to resist compression. The AF matrix and the NP were assigned non-linear hyperelastic material properties (Mooney-Rivlin). The strain energy function for this material model is shown in Eq. (1), where W is the strain-energy density function, I_1 and I_2 are strain invariants, and C_{10} and C_{01} are material constants (Mooney, 1940):

$$W = C_{10}(I_1\text{-}3) \; + \; C_{01}(I_2\text{-}3) \qquad 1$$

The fibre bundles were aligned at ± 30° to the transverse plane. The cross-sectional area of each bundle was assigned to be 3.212×10^{-2} mm, and spacing of the bundles was set to 0.23 mm or 4.35 bundles/mm (Adam et al., 2015; Marchand and Ahmed, 1990). Average element edge length ranged between 1.0 and 1.2 mm for the ten models and the results from a mesh convergence study ensured that this mesh density was sufficient. The discs were assumed to have vertical sides prior to loading although were allowed to bulge during the simulation, this assumption has previously been proven to be reasonable for bovine IVDs through assessment of polarised light micrographs (Adam et al., 2015). A preliminary numerical investigation demonstrated that modelling the endplates and vertebral bodies as deformable bodies with material properties from the literature (*YM* of cortical bone=11300 MPa, ν =0.2 (Little et al., 2007; Lu et al., 1996), *YM* of trabecular bone=140 MPa, ν=0.2 (Little et al., 2007; Lu et al., 1996), *YM* of endplate=23.8 MPa, ν=0.4 (Belytschko et al., 1974; Ueno and Liu, 1987; Yamada, 1970)), or rigid structures made little difference to the peak force ($<$ 2.5%) or the final central disc height ($<$ 0.9%) when a displacement that caused the disc to strain approximately 15% was applied at a range of strain rates. Therefore, to reduce computational cost, VBs and endplates were not modelled separately and were represented by rigid curves (Fig. 2).

The input to the model was the displacement-time history profile of the superior VB that was calculated from the displacement data recorded by the testing machine and was applied via a ‘control node’ to the upper rigid boundary. Apart from the VBs and the endplates, bone cement and pots were also assumed to be rigid since their stiffness is much greater than the components of the disc; therefore, the inferior boundary of the IVD was fixed while the superior boundary was assumed to have the same kinetic response as the compression tup in the experimental setup. Since the model was axisymmetric, nodes along the axis of symmetry (shown by the dotted lines in Fig. 2) were fixed in the radial direction.

2.4. Sensitivity study

A sensitivity study, to assess the contribution of the material properties of the various components of the IVD to its behaviour was conducted by adjusting the initial material properties, taken from literature (Table 1), by ± 20% on one of the subject-specific models that was selected due to its typical geometry (Specimen 1). Each property was adjusted one-at-a-time such that its effect on the force-time response could be determined. For the sensitivity study an intermediate strain rate was used (0.1/s).