

Strain Rate Dependence of Internal Pressure and External Bulge in Human Intervertebral Discs during Axial Compression

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I. INTRODUCTION

Intervertebral discs (IVDs) lie between vertebrae of the spine [1]. An understanding of their material behaviour is of interest for research studies associated with injuries sustained during vehicle accidents, airplane ejections, sports injuries, and under-body blasts [2-3], and is particularly important for the development of biofidelic finite element (FE) models of these injurious events. The accuracy of such FE models depends on appropriate characterisation of the material properties [4].

The IVD consists of the annulus fibrosus (AF), which surrounds the nucleus pulposus (NP) and is encapsulated, above and below, by cartilage endplates (CEPs). The AF consists of 15–25 concentric layers, and each layer consists of collagen fibre bundles that have an orientation of approximately ± 30 degrees to the transverse plane [1]. The boundaries between the AF, the NP and the CEP are often unclear, which makes separating components of the IVD for mechanical testing a challenging task [5]. The authors have previously used an inverse FE approach to obtain material properties of these components in bovine specimens [6-7]; this approach involves obtaining subject-specific geometry of the whole IVD and optimising individual components to ensure a close match between the experimental data and the numerical results.

The aim of this study was to characterise experimentally the response of four human IVDs across strain rates. The results will be used to obtain material properties of the constituent components using an inverse FE approach.

II. METHODS

For this study, four lumbar motion segments (vertebra-IVD-vertebra) were obtained from human cadaveric specimens (40 ± 18 years, mean $\pm$ SD). Specimens were fresh frozen at -20°C and CT scans were acquired before and after cutting through the mid-height of the vertebral bodies. From these scans, disc height and disc width measurements were obtained, as well as measurements of the angle and direction of the IVD relative to the angle of the cuts that had been made through the mid-height of the vertebral body. This process enabled the design of custom 3D wedges, which were 3D printed and placed in the testing pots to ensure the specimen was resting with the IVD parallel to the workbench. Once positioned, the vertebrae were fixed in the mounting pots using polymethylmethacrylate (PMMA). The experimental set-up is shown in Fig. 1.

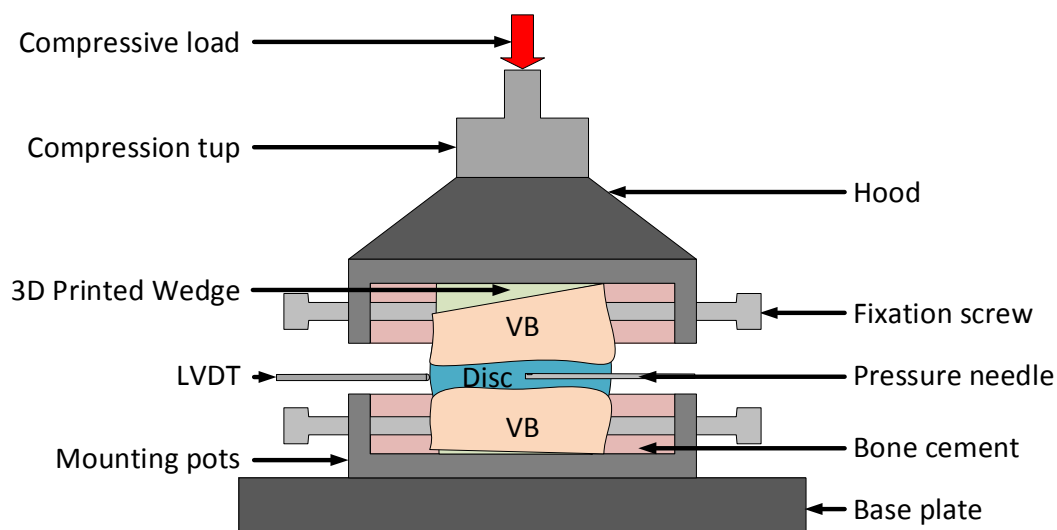


Fig. 1. Experimental set-up. Two vertical LVDTs were also attached to the top pot and rested against the bottom pot, but they are not included in this diagram.

Potted specimens were positioned in a servo-hydraulic materials testing machine (8872; Instron, Canton, MA, USA) and exposed to four axial compressive cycles to 15% strain at strain rates of 0.001/s, 0.01/s, 0.1/s, and 1/s. During testing, two linear variable displacement transducers (LVDTs) were attached to the top mounting pot, so that vertical displacement experienced by the disc could be measured. An LVDT was also positioned horizontally, touching the most anterior part of the IVD, to measure bulge during the compressive cycles. A pressure transducer (Gaeltec, Dunvegan, Scotland) was inserted through the right lateral AF into the NP of each IVD during testing. Force was measured using a load cell attached to the crosshead of the testing machine. Data were acquired at 1000 Hz, 1000 Hz, 100 Hz, and 10 Hz for the 1/s, 0.1/s, 0.01/s, and 0.001/s tests, respectively. Preliminary studies indicated that a repeatable response (in terms of force-displacement) could be obtained with a 5-minute relaxation period between tests, apart from when the disc was compressed at a strain rate of 0.001/s, therefore this slow-rate test was always carried out last. Throughout testing, and between tests, specimens were kept hydrated by wrapping them in PBS-soaked paper.

III. INITIAL FINDINGS

Data from the final cycle were analysed. As expected, a general increase in stiffness of the IVDs was observed with strain, and strain rate (Fig. 2(a)). In addition, a rise in peak pressure and maximum disc bulge was also recorded with increasing strain rates (Fig. 2(b)).

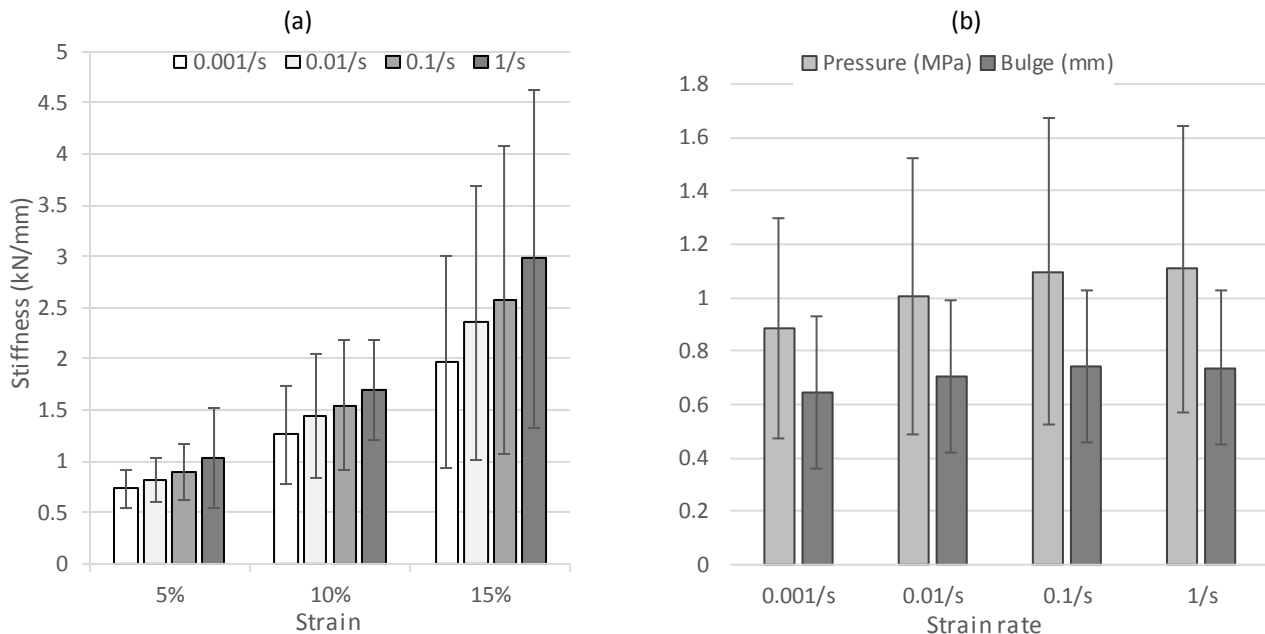


Fig. 2. (a) Average stiffness at 5%, 10%, and 15% strain at each strain rate. (b) Maximum anterior disc bulge and peak pressure within the IVD during axial compression.

IV. DISCUSSION

The response of human IVDs to axial compression of varying strain rates has been recorded, including dynamic measurements of the NP pressure and disc bulge. The structural response presented here can be used for validation of models, and to investigate and quantify the rate-dependent material properties of the components of the IVD using an inverse FE approach.

V. REFERENCES

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