Mechanical characterisation of bovine intervertebral discs at a range of strain rates

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I. INTRODUCTION

Intervertebral discs (IVDs) are fibrocartilage pads that lie between vertebrae of the spine [1]. An understanding of their material behaviour is of interest for research associated with injuries sustained during vehicle accidents, airplane ejection and under-body blasts [2-3]. The last three decades have seen a large increase in the number of finite element (FE) models of the intervertebral disc. The accuracy of such FE models depends on appropriate characterisation of the material properties [4].

The IVD consists of the anulus fibrosus (AF), which surrounds the compliant nucleus pulposus (NP) and is encapsulated, above and below, by cartilage endplates (CEPs) [1]. The AF consists of 15–25 concentric layers, and each layer consists of strong collagen fibre bundles with their orientation at approximately ±30 degrees to the transverse plane [1]. The close bonds, and often unclear boundaries, between the AF, the NP and the CEP make separating components of the IVD for mechanical characterisation a challenging task [5]. In addition, regional and level differences exist within the IVD components. In other soft tissues, where acquisition of samples appropriate for mechanical testing is challenging, an inverse-FE approach has been adopted [6-8]. This approach involves developing a model that incorporates the whole system (e.g. the whole IVD) and optimising material properties of the individual components to ensure a close match between the experimental data and the numerical results.

The aim of this project is to characterise the compressive material properties of bovine IVDs at a range of strain rates.

II. METHODS

While the final aim of this project is to characterise human IVDs, the present study used bovine specimens because they offer two distinct advantages over human specimens. First, healthy bovine specimens are readily available, negating the complicating factor of IVD degeneration that is common in older human specimens; secondly, bovine IVDs are almost perfectly round [9], and therefore allow the opportunity to model their behaviour using a simple axisymmetric model. For this study, seven motion segments were obtained fresh from the two most caudal intervertebral joints from adult bovine tails. Specimens were frozen at -20°C prior to use and CT scans of the specimens were acquired such that end-plate curvature, disc height and disc width measurements could be obtained. Prior to testing, specimens were defrosted overnight and fixed in mounting pots using polymethylmethylacrylate (PMMA). A custom-built potting rig was used to ensure the horizontal alignment of the IVD. The potted specimen was positioned in a drop-weight test rig that allowed a 2 kg mass to be dropped onto the potted test specimen from a range of heights. Data were acquired at 25 kHz from an accelerometer that was attached to the top pot and a 6-degree of freedom load cell that was positioned below the test specimen. Each specimen was impacted from heights of 2, 4, 8, 16, 32 and 64 cm. After each increase in height, a repeat of the 2 cm drop was carried out. If the peak force recorded in the repeat 2 cm test was within 5% of the original 2 cm test, then no damage was assumed to have been inflicted on the specimen and the drop height was increased. Throughout testing, specimens were kept hydrated by regularly spraying with phosphate buffered saline (PBS) and specimens were allowed a five-minute period of relaxation between tests.

Seven subject-specific, non-linear, implicit axisymmetric FE models were created using measurements taken from pre-test CT scans. Internal geometry (NP:AF ratio) and number of lamellae included in the model were based upon previous imaging studies of bovine IVDs [9]. Fibre bundles in the AF were modelled using rebar elements, while the AF matrix and NP were modelled using Mooney-Rivlin hyperelastic material properties. The input displacement applied to the top surface of the IVD was calculated from the accelerometer that was fixed to the top pot during the experiments. Initially, the material properties were based on literature values [10-11], before being optimised using a non-linear inverse-FE optimisation algorithm. Each drop test was simulated

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numerically while the material constants of each structure were altered until the numerical and experimental results were matched to a minimum error.

III. INITIAL FINDINGS

Average force-time curves from all drop heights and typical curves from the 2 cm drop heights are shown in Figure 1.

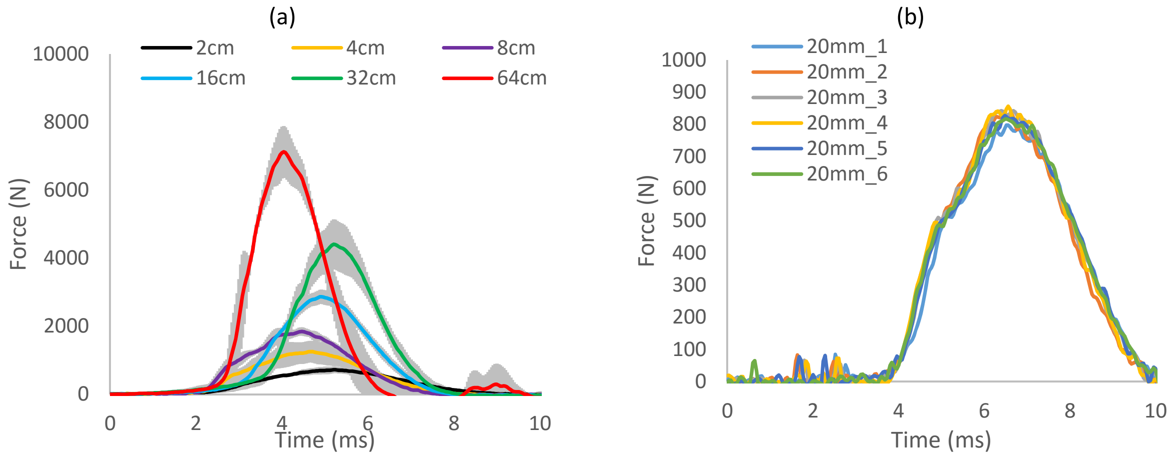

Fig. 1. (a) Average force-time curves, and (b) typical force-time graphs from all 2 cm tests on one specimen.

Averaged optimised values for each of the specimens at each drop height are shown in Table I. C10 and C01 refer to Mooney-Rivlin material coefficients [12], and YM refers to Young's Modulus.

TABLE I
AVERAGED OPTIMISED MATERIAL PROPERTIES. STANDARD DEVIATIONS ARE PRESENTED IN BRACKETS.

	AF matrix	*NP*	*AF Fibres*
C10 (MPa)	*0.089 (0.063)*	*0.019 (0.012)*	-
C01 (MPa)	*0.276 (0.249)*	*0.058 (0.033)*	-
YM (MPa)	-	-	*473.1 (201.1)*

IV. DISCUSSION

Material properties of bovine IVDs have been characterised across strain rates and a method of optimising strain rate-dependent material properties has been proposed. Further work can be carried out to develop strain rate-dependent material properties and a similar technique can be used to obtain human IVD material properties.

V. REFERENCES

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