Compressive and Flexion Stiffnesses of Human Cervical, Thoracic and Lumbar Intervertebral Discs Under High-rate Loading

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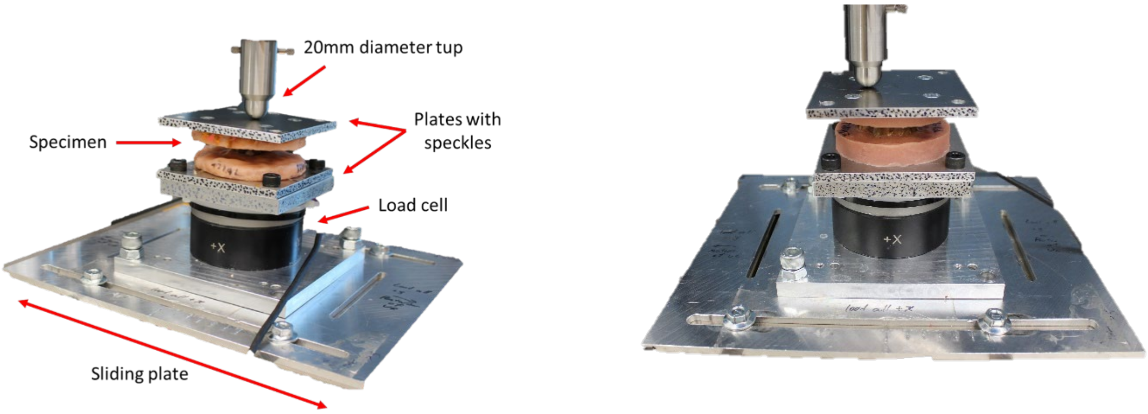
I. INTRODUCTION

Computational human body models (HBMs) are widely used to predict injury in high-rate scenarios, such as automotive collisions, aircraft ejection seats and underbody blast [1-3]. However, these models rely on the availability of accurate mechanical properties for the tissues involved in the simulation. In the case of the intervertebral discs (IVD) of the spine, existing studies in literature have predominantly focused on the lumbar spine. Additionally, the mechanical properties of the IVD have been shown to be dependent on the rate of loading [4-7]. Overall, there is a need for mechanical properties of all IVDs in the human spine, across a range of dynamic loading rates.

The aim of this study was to characterise the compressive and flexion stiffnesses of IVDs across a range of dynamic loading rates, using servo-hydraulic and drop tower testing machines. Testing was conducted on all IVDs from four human cadaveric spines. The preliminary results from the servo-hydraulic testing of a single spine are presented here.

II. METHODS

Each human cadaveric spine was cut at each vertebral body (VB) to collect VB-IVD-VB segments. All posterior elements and the anterior longitudinal ligaments were removed to ensure the IVD was the primary load path. The superior and inferior VBs were potted in polymethyl methacrylate to allow the VB-IVD-VB segments to be attached to plates in the test fixture (Fig. 1). X-ray images were taken from the coronal and sagittal planes during potting. These were used to position the centre of rotation (COR) of the IVD [8-9] in the centre of the test fixture. The images were also used to design 3D printed wedges – these were placed under the inferior VB to ensure the inferior bony endplate was parallel to the plates in the test fixture.



(a) (b)

Fig. 1. Test fixture for the servo-hydraulic materials testing machine. A point load is provided by a 20 mm diameter hemispherical tup. The sliding plate below is repositioned to load the intervertebral disc under (a) compression-only, or (b) flexion via offset compression (to replicate a spine bending forwards).

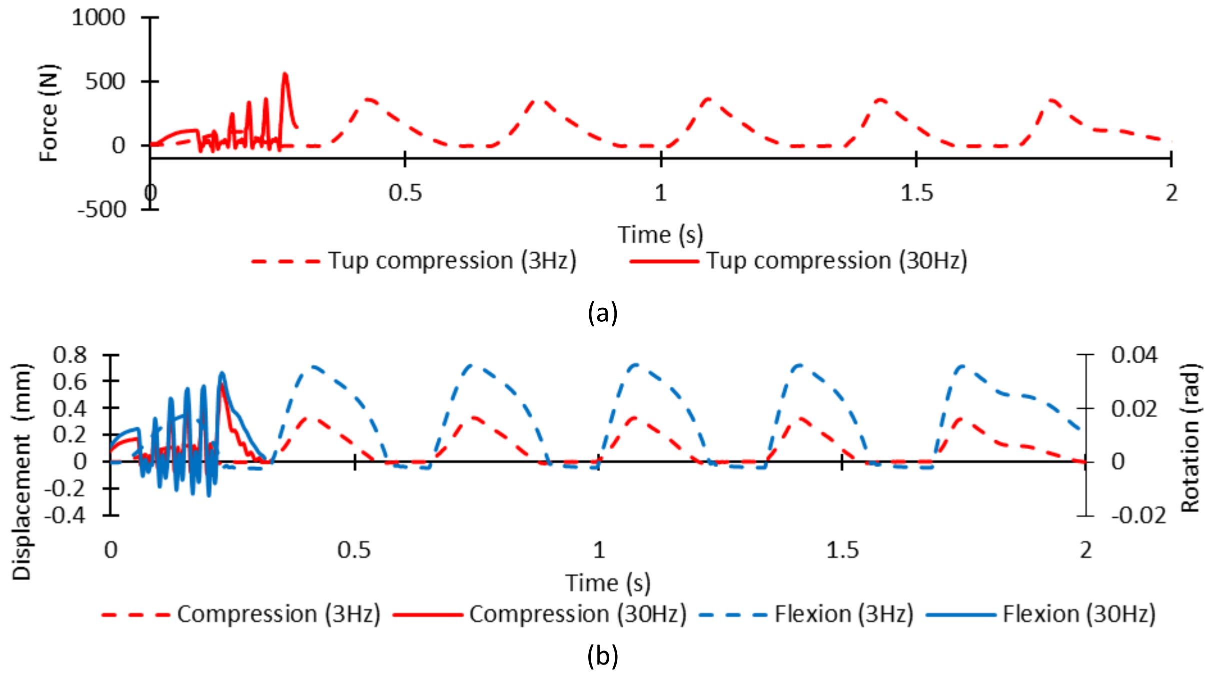


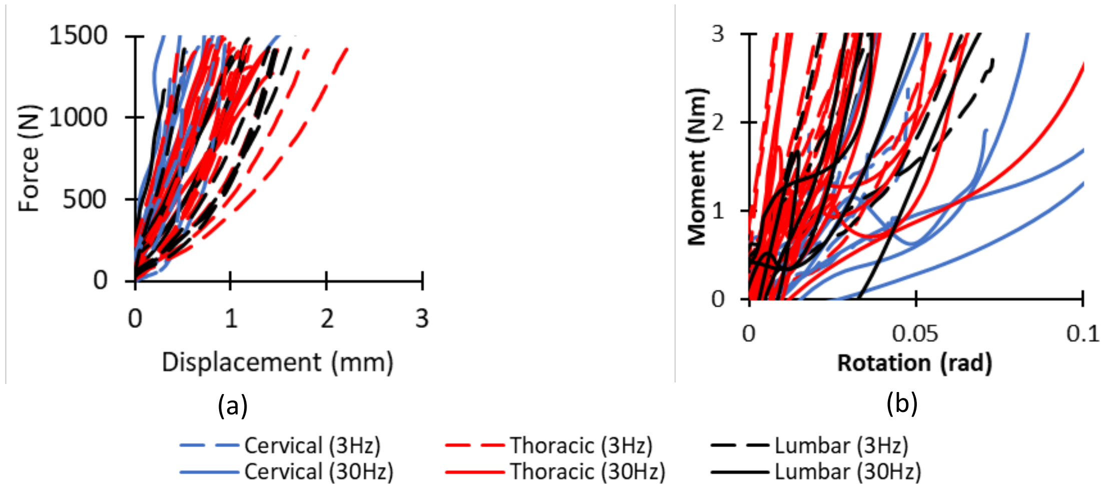
Fig. 2. Representative plots for the (a) time-history of the compressive force at the servo-hydraulic tup, during a flexion test via offset loading, and (b) the resulting compressive displacement and flexion of the IVD.

A custom test fixture (Fig. 1) was designed to fit into a servo-hydraulic testing machine (8874, Instron, Norwood, USA). Two loadcases were conducted on each IVD: a compression of 0–1500 N, achieved by compression on the COR of the IVD; and a flexion (to replicate a spine bending forwards) of 0–3 Nm, achieved by offset compression of the IVD at the anterior edge of the inferior VB (Fig. 2). Each loadcase was conducted at 3 Hz and 30 Hz, resulting in a total of four tests per IVD. Each test consisted of five cycles, as the literature has found that three to five cycles are sufficient to precondition an IVD [6-7].

Displacements and rotations were calculated using DICe (DZ Turner) to track speckles on the superior plate from high-speed camera recordings (Phantom VEO710L, Vision Research, New Jersey, USA). A 6-DOF load cell (M3944, SRI, Canton, USA) recorded the compressive force and flexion moments. The data collection rate of both the load cell and the high-speed camera was 1000 Hz for the 3 Hz tests and 3000 Hz for the 30 Hz tests.

The compressive and flexion stiffnesses were calculated from predefined forces and moments in the linear, post-toe region of the fifth load cycle. Compressive stiffness was calculated from 800 N to 1200 N, and flexion stiffness was calculated from 0.5 Nm to 1 Nm in the cervical spine and from 2 Nm to 2.5 Nm in the thoracic and lumbar spines.

III. INITIAL FINDINGS



(a) (b)

Fig. 3. (a) Force-displacement in compression. (b) Moment-rotation in flexion for all intervertebral discs in a

single human spine.

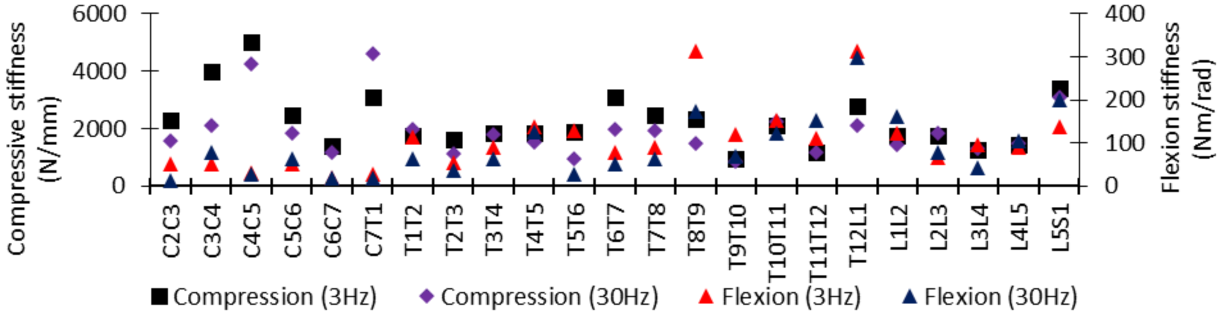


Fig. 4. Stiffness of all intervertebral discs in compression (left y-axis) and flexion (right y-axis) in a single human spine.

IV. DISCUSSION

This paper analysed the mechanical behaviour of all IVDs in a human spine (74-year-old male, 173 cm height and 61.2 kg weight) at two rates of loading, in compression and in flexion (Fig. 3 and Fig. 4).

In compression, the cervical spine was found to have the highest mean compressive stiffnesses at 3 Hz – 3048 N/mm – compared to the thoracic (1992 N/mm) and lumbar (1920 N/mm) spines. In flexion, the thoracic spine had the highest mean stiffness at 3 Hz – 142 Nmm/rad – compared to the cervical (39 Nm/rad) and lumbar (102 Nm/rad) spines. The mean stiffness at each spinal region varies less than 20% between 3 Hz and 30 Hz tests, except the thoracic spine where the flexion stiffness at 30 Hz was 27% lower than at 3 Hz.

Further analysis needs to be conducted on test data from three additional spines (two males and one female, average age 67 years, average height 176 cm and average weight 75.5 kg). This will show if the difference in mean stiffness between each spinal region is consistent between all cadavers. Additionally, the inconsistent trend where most but not all IVDs were more compliant at the higher loading rate can be compared between spines and against the Pfirrman grade of the IVDs. The result of the drop tower test will show if the stiffness continues to stay within 20% as the loading rate increases.

V. REFERENCES

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