Dynamic Shear Loading in the Cervical Spine: Replicating Impact Boundary Conditions

Luis F. M. Dias, Shun Yamamoto, Thomas R. Oxland, Peter A. Cripton

I. INTRODUCTION

Fracture-Dislocations (FD) are serious injuries of the spine, often resulting in severe neurological damage, paralysis, or death. Cervical FD injuries occur in Head-First-Impacts (HFIs), which are known to induce significant shear and compressive loads in the cervical spine [1–4]. A number of cadaveric inertial impact studies have pointed to shear as an important loading mode in the formation of these injuries, yet most available segment-level biomechanical work in the cervical spine has focused on flexion/extension or combined loading modes, rather than pure shear. Some valuable preliminary work exists for non-injurious pure shear [5–7], but very little has been done in injurious pure shear [8], and no work has been performed to our knowledge that replicates the boundary conditions during an injurious HFI - namely, dynamic shearing rates and impact-relevant compressive loads.

This work reports a protocol for testing cervical spine segments in pure shear loading, with the aim to recreate the boundary conditions present during an FD-causing impact event, by incorporating dynamic shearing rates and head-first impact-relevant compressive preloads. Data from the first 2 of 41 specimens is presented.

II. METHODS

Defining Boundary Conditions

Data on the shearing rates of FD injuries during a HFI are sparse due to the limited success researchers have had in experimentally recreating these injuries using inertial cadaveric tests. To determine the target shearing rate, we reviewed footage from one of the only experiments to successfully create FDs in an inverted cadaveric neck drop, and calculated a rate of roughly 1-2 m/s along the shearing plane [9]. These numbers are from C1/C2 injuries, and we expect the rate to match or exceed these values for more clinically relevant injuries in the lower cervical spine. Data on compressive loading during HFI of a cadaveric full cervical spine are readily available, with reported loads between 750 and 3050 N [9–10] and these loads cause fractures in the spinal column. A load of 1500N was selected as a realistic representation of impact-relevant axial compression while minimising the risk of immediate specimen failure when the axial compression was applied.

Specimen Preparation

Pairs of vertebrae with intact osteoligamentous tissue, known as Functional Spinal Units (FSUs), were dissected at the C6/C7 level and CT scanned. All FSUs were fitted with metal anchoring hardware and partially encapsulated in bone cement while preserving full disc and facet joint flexibility. Donor age and sex were collected at time of donation, trabecular bone volume fractions were obtained from CT data, and disc and facet joint degeneration scores were generated based on the Walraevens *et al*. method [11]. A total of 41 FSUs were selected for this study (20 F, 21 M, Age: 60 +/- 10 years), two of which have been tested at time of writing.

Setup and Methodology

A custom-built servohydraulic load frame was commissioned, nominally capable of displacement rates up to 5000mm/s. Specimen fixturing was designed such that the inferior vertebra of an FSU was fixed to the frame's load cell, and shear loads were imparted to the superior vertebra with the line of action parallel to the mid-disc plane. A pneumatically-driven preloading system was added to simulate compressive loading during HFI, by loading the FSU along the cranial-caudal axis. Specimens were fully rotationally constrained, but sagittal-plane translation was allowed. Figure 1 shows the setup for one specimen.

The test protocol covers six test conditions, at three rates (1, 500, and 2000 mm/s), and two compressive preload levels (0 and 1500N). Each FSU is preloaded with 5N of shear to ensure a consistent initial position, and subsequently preconditioned with five cycles of 0.5mm amplitude at 1 Hz. If applicable, a compressive load is then applied, and the specimen is actuated to failure. The superior vertebra is displaced through the full

*L. Dias is a MASc. Student at the University of British Columbia (Corresponding author: +17789531801 & LDias@icord.org). S. Yamamoto is a spine surgeon at the Jikei University School of Medicine T. R. Oxland and P. A. Cripton are Professors at the University of British Columbia.

anteroposterior width of the specimen, to achieve 100 % disc strain. Shear load data is recorded with a 15kN load cell, while displacements are tracked using TEMA T2021b from high-speed videos recorded at 6144 Hz.

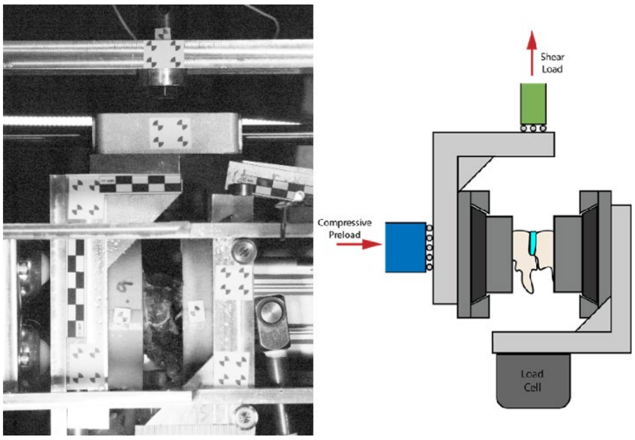

Figure 1 – Basic schematic of test fixture (right) and image of FSU loaded into fixture (left).

III. INITIAL FINDINGS

The two first FSUs in the cohort have been tested at time of writing. Both were from 49-year-old male donors with mild disc and facet joint degeneration. Bone volume fractions were 0.67 and 0.92 for specimens 1 and 2, respectively. Data from both tests is summarised in Figure 2.

Specimen 1 was tested at a nominal setting of 2000 mm/s without any compressive preload, and experienced dislocation followed by potting failure of the superior vertebra. Initial failure occurred at 1.7kN, after 1.2 mm of shear, and the specimen had reached 1048 mm/s. Total failure occurred at 2.0kN, at 2.6 mm and 1692 mm/s. Specimen 2 was tested at the same nominal rate, but with an added 1500N compressive preload, and experienced injurious failure of the inferior vertebra and posterior elements. Initial failure for specimen 2 occurred at 3.4 kN, at 3.4mm and 1809 mm/s, and total failure at 3.0 kN, 6.23mm, and 2442 mm/s.

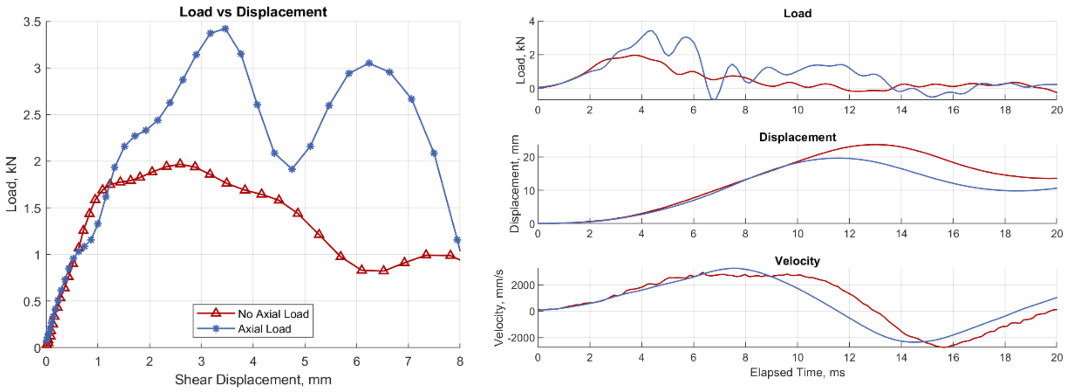

Figure 2 – Sagittal stiffness (left) and time traces (right) for the two FSUs tested to date.

IV. DISCUSSION

To our knowledge, this is the first time that cervical FSUs have been tested in pure shear under boundary conditions representing an FD injury in a HFI scenario. Under dynamic loading, the two specimens tested so far have had pre-failure stiffnesses of 1.0 and 1.4 kN/mm, which is 2.8 to 4 times higher than the maximum stiffness reported under quasi-static rates in similar constrained shear conditions (0.35 kN/mm) [5]. Testing is ongoing, and once complete, the full cohort will allow us to determine the effect of shear rate, compression, and demographic covariates on cervical stiffness and failure loads.

V. REFERENCES

[1] Nightingale R *et al*. Clin Biomech 2019.
[2] Ivancic P *et al.* Traffic Inj Prev 2008.
[3] Bauze R J *et al.* J Bone Joint Surg Br 1978.
[4] Roaf. Bone Joint J 1960.
[5] Moroney S P *et al.* J Biomech 1988.
[6] Dowling-Medley J *et al.* Proc ImechE 2020.
[7] Whyte T *et al.* J Biomech Eng 2021.
[8] Quarrington R *et al.* J Biomech Eng 2021.
[9] Saari A *et al.* J Biomech Eng 2013.
[10] Myers B *et al.* Traffic Inj Prev 1999.
[11] Walraevens *et al.* Eur Spine J 2009.