Towards a dynamic experimental model of cervical facet dislocation

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I. INTRODUCTION

Cervical facet dislocation (CFD) has devastating consequences and is most often a result of a head-first impact in which the head's motion is arrested and the following torso compresses the neck [1]. The injury mechanisms underlying CFD are not well understood, limiting the development of improved injury prevention devices and strategies. Subaxial CFD has been reliably produced in C0-T1 specimens under quasi-static compression loading when the head-end constraint permitted the occiput to translate anteriorly, causing an eccentric posture [2-3]. Comparable head-impact experimental models have rarely produced this posture, and have not reliably produced CFD. The aim of this study was to measure cervical spine kinematics and kinetics during head-first impacts with various combinations of pre-impact eccentricity and head-end constraint.

II. METHODS

Six osteoligamentous cervical spines (C0-T1) were prepared [HREC approval, 2018-261]. The inverted specimens were mounted at the occiput to an apparatus that applied one of three head-end constraints: head flexion and anterior translation (unconstrained, UC); head anterior translation (rotationally constrained, RC); or fully constrained (FC) (Fig. 1A). T1 was attached to a vertical linear rail, which restricted T1 to downward translation only. Specimens were aligned on the end-condition assembly in the neutral, intermediate, or maximum eccentric posture (Fig. 1B), determined via a pre-conditioning protocol. A 16 kg carriage [4] was raised to pre-determined heights to achieve caudal-end impact velocity of 1, 2, or 3 m/s. A stopper limited specimen deformation to 40 mm. A ratchet mechanism mitigated subsequent impacts from carriage rebound prior to the stopper engaging. A damping disc placed at the impact site eliminated "ringing" of the caudal-end load cell; the disc's impact response mimicked the isolated head's response during a head-first impact at 1–3 m/s [5]. Cranial and caudal (inertially compensated) loads were measured by 6-axis load cells and carriage displacement was measured by a linear encoder (both 50 kHz). Frontal and right lateral high-speed video was obtained (2 kHz). Kinematics were obtained by tracking retroreflective pins embedded at each spinal level with a motion-capture system (Vicon; 2 kHz). Specimens were impacted in various configurations of initial eccentricity and end-condition (Table I), until failure was observed. After each impact the specimens were visually inspected, x-rays were taken, and the preconditioning protocol was performed to compare the pre- versus post-impact response. When failure was observed the testing was concluded and post-test CT scans were obtained.

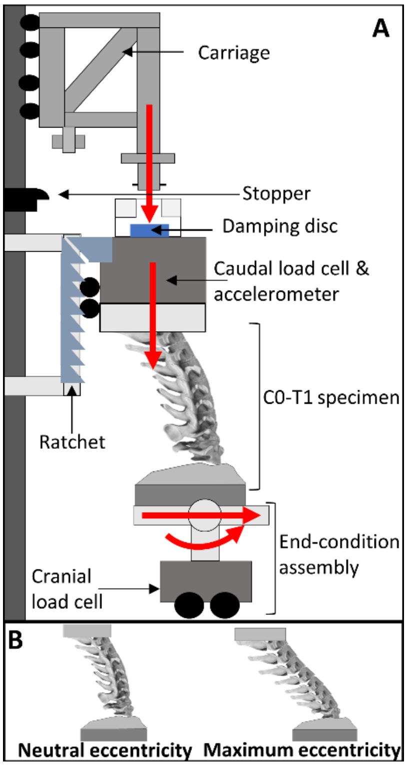

Fig.1. A) The cervical spine impact model; B) the neutral and maximum eccentricity postures.

TABLE I
TEST MATRIX COLOUR CODED TO THE PRODUCTION OF INJURY

ID	1 m/s UC			1 m/s RC			1 m/s FC			2 m/s RC	3 m/s FC	3 m/s RC
	N	Int	Max	N	Int	Max	N	Int	Max	Int	Int	Max
1												C7/T1 CFD
2										C7/T1 CFD		
3	C4/5 CFD											
4								C6/7 soft tissue				
5				C6/7 CFD								
6											C6/7 CFD	

Green: No injury, Red: Injury produced in the primary impact, Yellow: Injury produced in the secondary loading.
UC: Unconstrained, RC: Rotationally constrained, FC: Fully constrained.
N: Neutral eccentricity, Int: Intermediate eccentricity, Max: Maximum eccentricity.

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III. INITIAL FINDINGS

To date, six specimens have been tested in the 1 m/s test configurations, of which three were also impacted at 2 m/s or 3 m/s. At 1 m/s, the carriage did not compress the specimen to the designated displacement limit so the carriage stopper did not engage; the ratchet mechanism mitigated rebound, as intended. Following this primary impact event, the carriage then settled on the specimen, causing a secondary loading event.

In all 1 m/s RC and UC tests, head-end motion did not occur during the primary impact event (i.e. the occiput was effectively fully constrained during the primary impact). In the neutral posture, specimens exhibited a similar force-deformation response between end-conditions (Fig. 2A). With an eccentric posture, specimens were generally less stiff, resulting in greater deformation and smaller peak force, compared to the neutral responses.

Neutral posture 1 m/s impacts were sub-injurious during the primary impact event, but during RC and UC tests the specimen subsequently moved into a forward or forward-flexed posture, respectively, which resulted in the production of CFD in two specimens. For the 1 m/s intermediate eccentricity FC impact, local C6/7 supraphysiological flexion was observed qualitatively on high-speed footage, followed by lower cervical spine soft tissue failure. For the 2 m/s and 3 m/s RC impacts, local supraphysiological flexion and anterior shear at the level of injury led to bilateral facet dislocation (Fig. 2B-C). Analysis of the motion capture data to fully describe the intervertebral kinematics is ongoing.

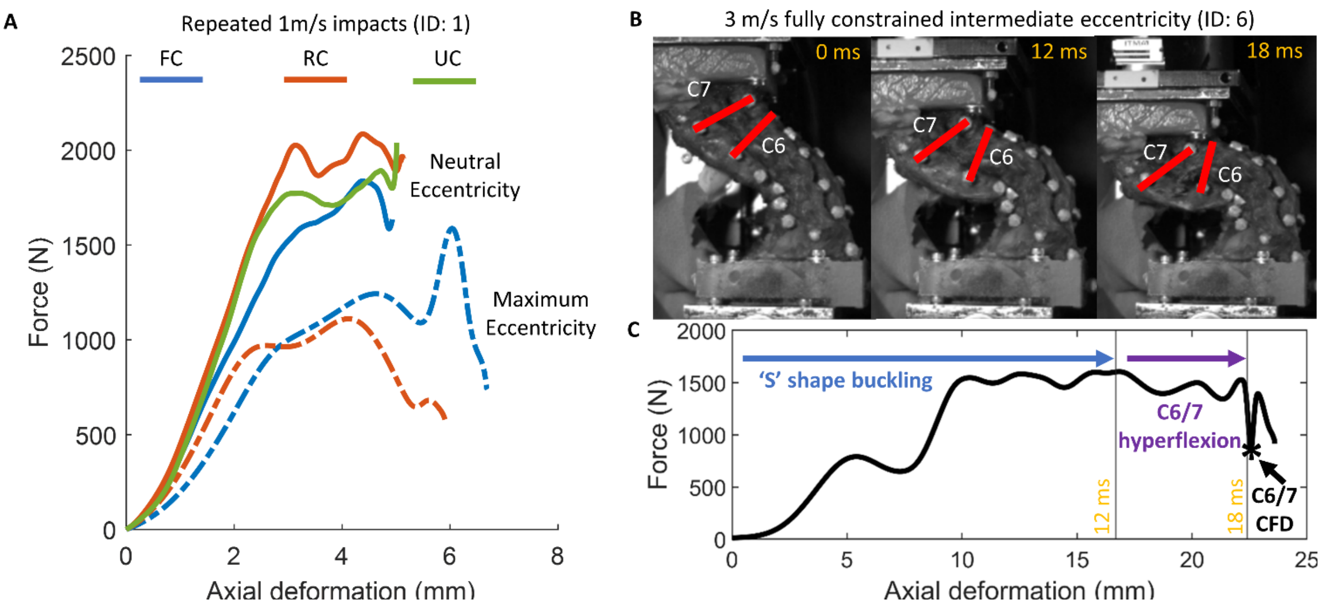

Fig. 2. A) Exemplar (ID: 1) force vs. axial deformation for the 1 m/s fully constrained (FC), rotationally constrained (RC) and unconstrained (UC) conditions in the neutral (solid line) or maximum eccentricity posture (dashed line). High-speed images (B) and the associated force vs. axial deformation (C) illustrating the specimen (ID: 6) buckling under the axial compression, resulting in CFD. Data presented are from the onset of contact (0 ms) to peak deformation within the primary impact.

IV. DISCUSSION

The preliminary results suggest that the neck's response to axial head-end impact loading, when in a natural posture, is not influenced by head-end motion constraints. This finding is inconsistent with the outcomes of a comparable quasi-static study [3], likely due to the disparity between the finite kinetic energy imparted by the carriage (i.e. torso) and the continuous input energy imparted by the materials testing machine. Cervical spine injuries have been produced reliably at 3 m/s in previous head-impact tests with a neutral spine [4][6], but they have not been produced in 1–2 m/s axial impacts in inverted full cadavers [7] or cadaveric head-necks [8]. The preliminary findings suggest cervical spine vulnerability at lower impact energies in an eccentric posture. Further experiments will be performed with the aim of developing a dynamic, cadaveric cervical spine model that can reliably produce CFD.

V. ACKNOWLEDGEMENTS

This research was supported by an Australian Research Council Discovery Project (DP190101209).

VI. REFERENCES

[1] Nightingale, *et al.*, *Clin Biomech*, 2016. [2] Bauze, *et al.*, *J Bone Joint Surg*, 1978. [3] Nightingale, *et al.*, *Stapp J*, 1991. [4] Nightingale, *et al.*, *J Biomech*, 1996. [5] Thompson-Bagshaw, *et al.*, ABME (under review), 2023. [6] Saari, *et al.*, *J Biomech*, 2011. [7] Nusholtz, *et al.*, *Stapp J*, 1983. [8] Yoganandan, *et al.*, *Stapp J*, 2018.