A Method for Defining Failure Tolerance of the Lumbar Spine in Combined Loading

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I. INTRODUCTION

Vertebral body fractures in the lumbar spine have received increased attention, with compression and burst fractures the most commonly reported in frontal vehicle crashes [1]. These injuries result from high levels of compression and flexion. However, the lumbar spine injury threshold for combined compression-flexion has not been well-defined experimentally. Previous studies, in which loading is primarily axial, have measured compression and flexion at failure [2-4], but these test fixtures were designed to apply dynamic vertical loading via a dropping mass without controlling flexion. In addition, recent recline human body modelling studies have shown that lumbar spine injury risk may increase in this new seating position due to greater compression during pelvis restraint followed by flexion of the spine during torso pitch [5-8]. Therefore, the objective of the present study was to develop a methodology for assessing the lumbar spine injury tolerance in controlled combined compression-flexion and to describe the unique technical features and verification of the experimental design.

II. METHODS

Five fresh-frozen post-mortem human subject (PMHS) lumbar spines were separated into nine three-vertebrae segments (T12–L2, L3–L5; 7 M, 2 F; average: 61 years old (yo), range: 47–74yo). The PMHS were obtained and treated in accordance with ethical guidelines established by NHTSA and UVA. Spines with pre-existing injuries, deformities and significant ossification and degeneration were not considered.

Segments were denuded, removing all surrounding soft tissue and leaving bone, ligaments and intervertebral discs intact. Using a custom potting jig, superior and inferior vertebrae were rigidly secured in potting cups with several screws and potting resin, but middle vertebrae and soft tissue connections between middle and superior/inferior vertebrae remained unconstrained. Using custom CT jigs, pre-test CT scans were performed on segments in the exact orientation they would be initially positioned on the test fixture. Six-axis load cells, tri-axis accelerometers and angular rate sensors were attached to both potting cups, and a four-marker 3D-motion tracking array, two strain gauges and an acoustic sensor were secured to the middle vertebra of the specimen.

Segments were tested on a Dr Steffan Datentechnik (DSD) single intrusion cylinder modified to provide high-rate, well-controlled rotational motion (Fig. 1). The superior end of the segment rotated about an offset, fixed Y-axis, while the inferior end remained constrained in rotation but could translate in the X-direction along a linear rail-bearing, minimising anterior-posterior shear forces by creating a pure bending moment boundary condition. The centre of rotation was chosen as the inferior endplate on the inferior vertebrae of the segment (L2, L5) to minimise motion on the linear rail-bearing and reduce the effect of inertial constraints. Before testing, both ends of the fixture were adjusted in X-, Y-, Z-translation to align the specimen centre of rotation to the fixture rotation axis, accommodating for variation in specimen size and curvature. Additionally, the fixture design allowed for both potting cups to be adjusted about the Y-axis so that segments began in a natural position, with compression applied perpendicular to the mid-plane of the middle vertebrae. Natural curvature of segments and angles of the superior and inferior potting cups relative to the mid-plane of the middle vertebrae were determined from initial CT scans of each whole lumbar spine. Upon verification of segment position on the fixture, constant compression within a 2–5 kN range was selected for each specimen, applied quasi-statically prior to testing via a spring/honeycomb system, and maintained throughout the test. The upper compression limit was established

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from the average failure load of the lumbar spine in axial loading [9]. The DSD pulse was tuned to ramp from zero to approximately 600°/s, a value determined from in-house data from previous studies [8][10], and rotate the superior end of the segment to approximately 45° (Fig. 2), targeting failure via fracture in the middle vertebra. The flexion pulse remained the same for all tests, but the magnitude of superimposed compression for each segment was chosen from one of several levels based on the size of the honeycomb. Load cell, accelerometer and angular rate sensor data were collected in a local coordinate system, inertially compensated, and transformed to the middle vertebrae joint coordinate system (JCS). Bending moment at the JCS was compensated using forces measured at the load cells and 3D-motion-tracking position data since high levels of force applied at an increasing moment arm largely contributed to flexion moment. Post-test CT scans were performed to visualise and quantify fractures before confirming fracture timing with principal strain, acoustic sensors, loads and high-speed videos. All fractures were verified by a board-certified radiologist.

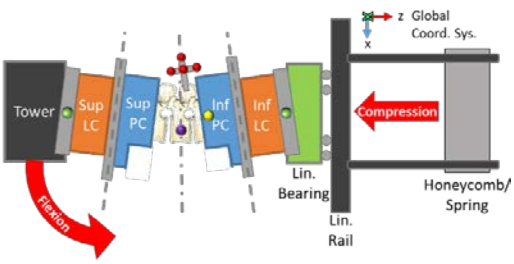

Fig. 1. Fixture schematic with superior (Sup) and inferior (Inf) potting cups (PC) and load cells (LC). Additional features include: RY adjustability (green circles), centre of rotation (yellow circle), middle vertebra JCS (purple circle), and 3D motion-tracking markers (red circles, additional markers not shown).

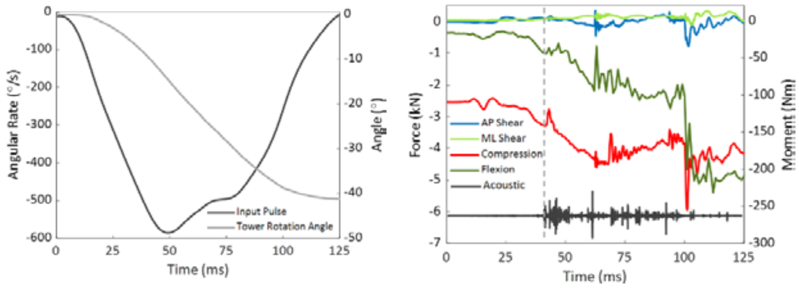

Fig. 2. Tuned DSD input pulse and resulting tower rotation angle (left). Example data for verification of the method, including forces and flexion moment transformed to the middle vertebra with respect to the global coordinate system and overlaid with acoustic sensor output for the purpose of displaying timing of sustained middle vertebra compression. Timing of the first fracture is noted with a dashed vertical line.

III. INITIAL FINDINGS

The test device accomplished the desired boundary conditions throughout controlled flexion with several levels of constant superimposed compression. The linear rail-bearing minimised anterior/posterior shear forces when applying compression and initialising flexion (Fig. 2). Tissue relaxation occurred between compression application and dynamic flexion (approximately 10 minutes). However, due to the honeycomb crushing to maintain constant force, compression was sustained as flexion was applied. Fracture timing was consistent within 1 ms in all data capture methods (load cells, acoustic sensor, strain gauges, and high-speed videos).

IV. DISCUSSION

The developed new methodology has been used to produce clinically-relevant vertebral body fractures described in the field data and to quantify the failure tolerance of the lumbar spine in controlled combined compression-flexion loading. The test fixture allowed variation in the amount of superimposed compression, while permitting loading in bending to failure with well-defined boundary conditions that eliminate shear forces. The data capture and processing procedure enabled calculation of forces and moments at the centre of the middle vertebrae, which makes this data ideal for human body model simulation and injury risk development. Thus far, 23 tests have been completed using the methodology and failure thresholds have varied widely, likely due to sex differences, age, segment type (upper/lower), segment curvature, trabecular density, or cortical thickness. Experiments will continue to complete a minimum dataset of 40 PMHS segments, with approximately equal spread in male and female specimens and upper and lower segments (average: 49yo, range: 21–74yo) to better understand how superimposed compression affects bending moment tolerance of the lumbar spine.

V. REFERENCES

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