Influence of mechanical and demographic factors on the sagittal stiffness of C6/C7 motion segments under dynamic shear loading

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I. INTRODUCTION

Fracture-dislocation (FD) injuries are the most common injury of the cervical spine that result in spinal cord injury (SCI), making up approximately 40% of cervical SCI cases [1]. The suspected mechanism of FD injuries is head-first impact, which is known to induce significant shear loading within the cervical vertebral column, and which points to shear loading as a major contributor to the formation of FD injuries [2-4]. Despite this, most segment-level biomechanical studies of the cervical spine have focused on loading modes other than shear, or combined loading modes instead of pure shear. While there has been some valuable preliminary work in pure shear [5-7], sample size limitations have prevented the analysis of demographic and pathological factors.

The goal of this work was to characterise the biomechanics of the lower cervical spine under pure shear loading, accounting for mechanical, demographic and pathological factors. These data will fill an important literature gap in biomechanics of the cervical spine and provide a robust dataset for the validation of computer models of the human neck.

II. METHODS

A cohort of 39 Functional Spinal Units (FSUs), each consisting of a pair of vertebrae with intact osteoligamentous tissue and intervertebral disc, were extracted at the C6/C7 level from sub-axial fresh-frozen cadaveric cervical spines. Donor age and sex were collected at time of donation, and bone volume fraction (BV/TV) was collected from pQCT scans. Disc and facet joint degeneration were scored by a fellowship-trained spine surgeon following the method established by Walraevens *et al*. [8]. Each specimen was potted in bone cement, using x-ray imagery to ensure alignment of the disc with the horizontal plane, and attached to fixturing hardware in a load frame designed to deliver pure shear to cervical motion segments at controlled rates.

Experimental Testing

Specimens were loaded non-destructively to a 200 N limit in pure anteroposterior shear applied through the disc centre [5]. Specimens were tested in both anterior and posterior shear, at displacement rates of 1 mm/s, 10 mm/s and 100 mm/s, for a total of six tests per specimen. A six-axis load cell recorded the loads generated in all anatomical planes, and infrared motion markers captured 3-dimensional motion of the specimen at 1000 Hz. Specimens were unconstrained in all directions, with only displacement applied in the primary loading direction.

Data Analysis

Using a best fit bi-linear curve, the sagittal load-displacement response for each test was algorithmically separated into two loading phases, with *Phase I Stiffness* describing the initial response from a neutral posture, and *Phase II Stiffness* describing the response under higher loads. Sagittal response corridors were obtained using arc-length reparametrisation (ARCGen) [9]. The effect of mechanical (direction, rate), demographic (sex, age) and pathological (bone volume fraction, disc and facet joint degeneration) factors was statistically evaluated using Unbiased Recursive Partitioning Conditional Inference Trees (URP-CTREE) [10], which split the data into increasingly homogeneous populations based on the effect of the most significant covariate in each population.

III. INITIAL FINDINGS

The sagittal load-displacement response (Fig. 1) was found to be generally non-linear, with greater displacements corresponding with higher stiffness. The outputs of the URP-CTREE analysis (Fig. 2) show the significant covariates for the two loading phases. In both the Phase I and Phase II responses, the strongest covariate of stiffness was load direction ($p < 0.001$, in both cases), with anterior shear (Phase I: 125 (68) N/mm; Phase II: 250 (37) N/mm) inducing a stiffer response than posterior shear (Phase I: 75 (29) N/mm; Phase II: 176

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(31) N/mm).

In Phase I anterior loading, displacement rate was a significant covariate, with response at 100 mm/s being less stiff than the other rates ($p = 0.014$). In Phase II anterior loading, sex was a significant covariate ($p < 0.001$), followed by disc degeneration within the female group ($p = 0.001$). In posterior Phase II loading, disc degeneration was a significant covariate ($p < 0.001$), and within the less degenerated of these specimens rate had a significant effect, with the response at 1 mm/s being less stiff than at higher rates ($p = 0.016$).

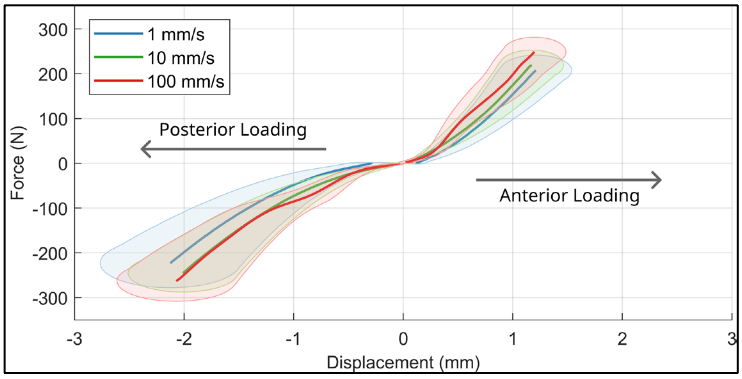

Fig. 1. Anteroposterior corridors of 39 C6/C7 specimens at each direction and displacement rate. Shaded boundaries denote +/- 1 standard deviation.

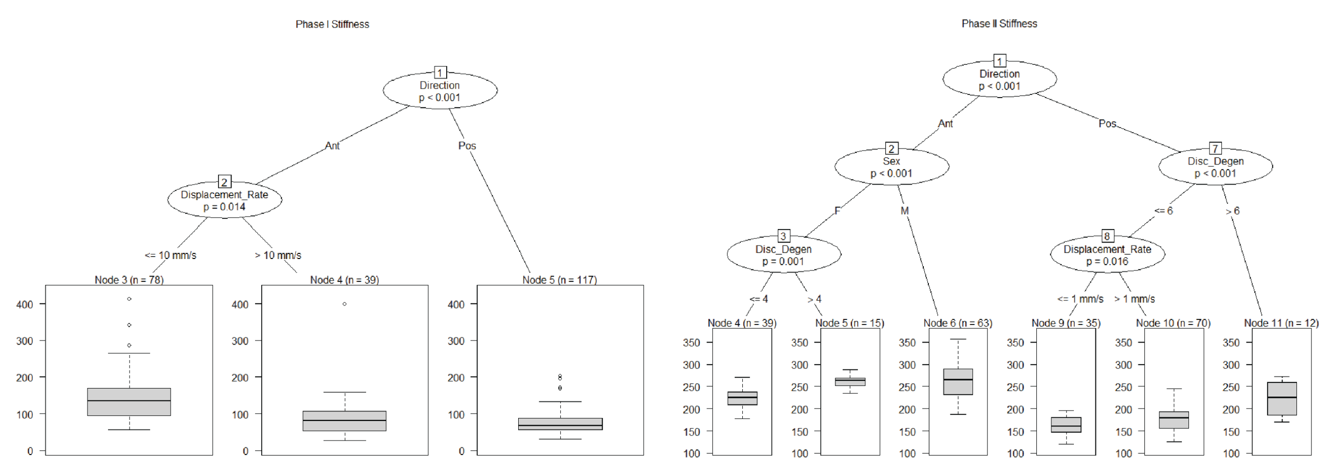

Fig. 2. URP-CTREE outputs of Phase I (left) and Phase II (right) stiffnesses. Each node represents a population split on a given significant covariate, with the stiffness of the final homogenized populations described in the bottom row (i.e. the leaves of the decision tree). Sizes of the final populations are denoted above each leaf.

IV. DISCUSSION

The sagittal load displacement-response of the cervical spine to pure shear loading was generally non-linear, with the overall stiffness increasing as the FSU was displaced. In both loading phases, specimens are significantly stiffer in the anterior direction than the posterior, likely due to compression of the facet joints [5-7]. Disc degeneration has a significant effect on stiffness, in agreement with prior work [6], although this effect is only notable at higher (i.e. phase II) loads, and not in males in the anterior loading direction. Males had a stiffer anterior response than females in Phase II loading, suggesting a possible anatomical difference between the sexes. Displacement rate had a significant effect on stiffness under certain boundary conditions, but the precise mechanics of this effect require deeper investigation. The work presented here is part of a study encompassing a total of 162 FSUs at all cervical levels.

V. REFERENCES

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