Influence of mechanical and intrinsic factors on the sagittal stiffness of C6/C7 functional spinal units under pure shear loading

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Introduction: Fracture-dislocation (FD) injuries of the cervical spine have a high incidence and often result in permanent and severe neurological damage. The suspected mechanism of FD injuries is head-first impact, which is known to induce a significant shear load within the cervical vertebral column secondary to column buckling, suggesting that shear plays a major role in FD injury formation (1-2). While cervical biomechanics have been well-studied in bending and combined loading modes, pure shear loading remains under-investigated. Of the existing work in pure shear, most studies have featured low sample sizes, limited loading ranges, and focused on quasi-static loading. Therefore, the objective of this work was to characterize the biomechanics of the lower cervical spine under pure shear loading at dynamic displacement rates, and to determine the effect of various intrinsic factors on anteroposterior stiffness.

Methods: 1) Specimen preparation: With approval of the UBC Clinical Research Ethics Board, 39 Functional Spinal Units (FSUs), consisting of two adjacent vertebrae with intact intervertebral disc and ligaments, were extracted at the C6/C7 level from cadaveric donor spines. Donor age and sex were collected at time of donation, and CT scans were used to measure bone volume fraction (BV/TV) and to grade disc and facet joint degeneration per Walraevens et al (3). Specimens were potted in polymethylmethacrylate, taking care to not restrict the disc or facet joints, such that the mid-disc plane was aligned within 0.5mm of the line of action and plane of motion of the experimental force application. 2) Mechanical Testing: Potted specimens were fixed to a servohydraulic load frame and loaded under a servohydraulic load frame and loaded into increasingly homogenous populations, until all significant covariates are identified. Additionally, sagittal response corridors were obtained using arc-length reparametrization (ARCGen) (5).

Results: Response corridors (Figure 2) depict the non-linear mechanical responses in both loading directions. Mean phase I stiffness (100 N/mm) across all specimens was significantly lower than the mean phase II stiffness (213 N/mm). URP-CTREE analysis (Figure 3) identified load direction as the most significant covariate in both phases, with a significantly stiffer (p < 0.001) mean response in anterior shear (phase I: 125 N/mm, phase II: 250 N/mm) than in posterior shear (phase I: 75 N/mm, phase II: 176 N/mm). Three other covariates were identified as significant under certain conditions. Firstly, displacement rate had a significant effect in the anterior phase I response (p = 0.014) and the posterior phase II response for specimens with a disc degeneration grade below or equal to 6 (p = 0.016). Secondly, sex had a significant effect (p < 0.001) in the anterior phase II response, where male specimens exhibited a stiffer response than females. Finally, disc degeneration grade had significant effects in the phase II response, both in the posterior direction, where specimens of both sexes with a grade greater than 6 exhibited a stiffer response (p < 0.001), and in the anterior direction, where female specimens with a grade greater than 4 exhibited a stiffer response (p = 0.001).

Discussion: As shown by the corridors and the difference between mean phase I and II stiffness, the sagittal shear response is generally non-linear, with increasing stiffness as load is applied. The stiffer response in the anterior direction agrees with the known role of the facet joints, which engage in anterior shear, partially inhibiting and guiding joint motion (6). The effect of sex in the anterior phase II response is notable, and may support the existence of a sex-based difference in bony anatomy and/or material properties in the osteoligamentous tissues, but more work is needed to identify the underlying mechanism. In the phase II response, greater disc degeneration positively correlated with stiffness, in agreement with prior work (7). This effect was not observed in males in the anterior direction, again pointing towards a potential sex difference in cervical spine biomechanics under certain conditions. The effect of displacement rate was not fully conclusive: the stiffening effect of increasing rate in the posterior phase II response agrees with expected viscoelastic behavior, but contrasts with the opposite observation in the anterior phase I response. Overall, the effect of displacement rate was mild.

Significance: To our knowledge, this is the first study using a large ex vivo cohort to characterize the effect of mechanical, demographic, and pathological factors on the biomechanics of the lowest segment of the cervical spine under pure shear loading at dynamic displacement rates. This data fills a literature gap on cervical biomechanics, provides data for the validation of computer models of the human neck, and furthers our understanding of the important fracture-dislocation injury mechanism.


Figure 1 - Sample raw data from one test (shown in blue) with overlaid best-fit bi-linear curve (shown in red). Slopes of each segment of this best-fit line represent the stiffness: the lower segment is the phase I stiffness, and the upper segment is the phase II stiffness.