Load-Displacement Characteristics of the Cervical Spine During Shear Loading

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ABSTRACT

The biomechanics of the cervical spine during shear loading are not well-established as compared to other loading regimes. The objectives of this study are to determine the load-displacement characteristics of the cervical spine during the application of pure shear loads. Shear loads were applied to fresh-frozen human cadaveric functional spine units (n=5). Loads were applied to each specimen up to 100 N via a materials testing machine and custom-designed apparatus. Three directions (anterior, posterior and right lateral) were tested in each of three specimen conditions (intact, posterior ligament removal, disc-only). Anterior shear stiffness [CI] was found to decrease significantly from 186 N/mm [98, 327] in the intact state to 105 N/mm [78, 142] in the disc-only state (p=0.03) in the 20-100 N load range. Posterior stiffness was found to have a significant decrease from 134 N/mm [92, 182] to 119 N/mm [83, 181] in the 20-100 N load range. No significant differences were found between specimen states in the lateral directions, nor in the initial stiffness between 0-20 N in any direction or any specimen condition. Coupled displacements and rotations tended to be small (less than 2 ° or 1 mm). Results suggest that the posterior elements provide resistance in the presence of shearing loads in the anterior and posterior direction, but have a lesser effect in other directions. This was expected as the facet joints in the cervical spine are oriented such that they would tend to block anterior-posterior translations. Greater shear stiffness in the lateral direction could be explained by facet-lamina interactions and uncovertebral joint interactions. Results corresponded well with existing studies concerning the biomechanics of the cervical spine in shear. These results may be used to improve the definition of and validation of existing finite element models of the human neck, where such models may eventually be used to inform injury criterion and safety design.

INTRODUCTION

Despite modern advances in automotive safety, motor vehicle accidents still comprise the single largest cause of spinal cord injury (SCI) in the United States, accounting for 38% of cases in 2015 (NSISC, 2016). In the United States, minimum safety performance standards intended to protect vehicle occupants are administered by the National Highway Traffic Safety Administration (NHTSA), and are based upon injury thresholds established through various combinations of live subject, human cadaver and animal biomechanics studies (Kleinberger *et al*, 1998). Currently, the primary injury tolerance criterion used to evaluate the risk of a severe neck injury for commercial automobiles in the United States is the Neck Injury Criterion (N_{ij}) (Eppinger *et al*, 2000). This criterion is evaluated through the analysis of load data obtained from the load cell located in the Hybrid III test dummy neck during a frontal impact test. Although this load cell is a six axis load cell, only compressive-tensile loads and flexion-extension moments are considered in the N_{ij} calculation.

While this simplified model of neck injury may be appropriate in some cases, there is evidence that other loading types may contribute to severe neck injuries. In particular, there exists evidence that shearing loads may contribute to the mechanics of bilateral facet dislocation injuries (Ivancic *et al*, 2008). This finding may be critical as fracture-dislocation injuries represent the most common spinal column injury in SCI patients (Sekhon & Fehlings, 2001). Thus, including shear loads in the assessment of neck injury risk in safety standards may improve their capacity to protect against severe injuries such as SCI.

Shear loads in the neck are not considered in any current NHTSA standards largely because there exist few biomechanics studies concerning shear loading in the cervical spine, especially at higher loads. Two relevant studies investigating the load-displacement characteristics of the cervical spine exist; a 1988 publication by Moroney *et al* and a 1991 study by Shea *et al*. In both of these studies, shear stiffness was determined in human cadaver specimens. A third study by Panjabi *et al,* also investigates the principal and coupled motions of human cervical spines when subjected to shear loads. While the Moroney study, which investigates the shear properties in each shearing direction in two specimen conditions is comprehensive, the shear loads applied to the specimens were quite low (maximum of 39N) and thus results may not be representative of greater (but still non-destructive) shear loads that might occur. In the Shea study, shear loads of 150N were applied, however neither the effect of the posterior elements nor the properties in the lateral direction were examined.

The present study aims to confirm and expand upon these existing studies by addressing the deficits outlined previously. In doing so, it is possible that the shear properties of the cervical spine may be used to inform existing finite element models of the human neck, where such models may eventually provide insight leading to more protective vehicle design and safety standards. Therefore, the objective of this study is to determine the shear stiffness and kinematics of the cervical spine functional spine unit (FSU) as a function of inflicted damage to the posterior elements in the anterior, posterior and right lateral shearing directions. It was hypothesized that progressive removal of the posterior elements would result in decreasing shear stiffness, and that the load-displacement curve would be linear with minimal coupled rotations and displacements.

METHODS

Eight human cadaveric FSUs were subjected to non-destructive shear loads applied via a custom-designed testing apparatus. Each specimen was tested in the anterior, posterior and right lateral in three specimen conditions: intact, with the posterior ligaments severed and with the posterior elements removed (disc-only). Motion capture data and load cell data were used to determine the shear stiffness and three-dimensional kinematics throughout the loading cycle.

Specimen Preparation

Individual FSUs were dissected from fresh-frozen whole cervical spines. Prior to dissection, donors' medical records were screened for histories of spine surgery, spine trauma and or other pathologies affecting the mechanics of the spine. Lateral and frontal radiographs of each cervical spine were examined for evidence of major bony abnormalities.

Seven C6-C7 FSUs and one C2-C3 FSU were selected for testing from seven donors (Table 1). The median age of the donors was 53 years. Following dissection, specimens were frozen at -20 °C until use.

Specimens were fixed rigidly in cylindrical polymethylmethacrylate (Keystone Industries, Gibbstown, NJ, USA) potting cups. Four wood screws were inserted into each endplate and wire was wrapped around the screws prior to fixation to prevent pullout during testing. Specimens were fixed such that the intervertebral disc was aligned parallel to the ground. This was achieved by visual inspection of the superior-most endplate with a laser level.

Of the eight specimens tested, three were excluded from the results due to experimental errors or intrinsic anatomical issues with the specimen. One specimen experienced a modified experimental protocol, and was thus excluded from some results.

Table 1: Specimen and Donor Information

Donor ID	**Level**	**Sex**	**Age**	**Notes**
H1412	C6-C7	M	55	
H1418	C6-C7	M	53	
H1410	C2-C3	M	54	omitted: potting error
H1421	C6-C7	F	29	omitted: soft tissue failure
H1419	C6-C7	F	50	
H1410	C6-C7	M	54	
H1415	C6-C7	F	64	partially omitted: missing data
H1423	C6-C7	M	50	omitted: fusion

Shear Test Apparatus Design & Load Application

Shear loads were applied to the specimens via a custom-designed apparatus interfaced with an Instron materials testing machine (ElectroPuls E1000, Instron, Norwood, MA, USA). The apparatus was designed to apply pure shear loads at the shear center of the intervertebral disc. The inferior vertebra of the FSU was fixed while the shear load was applied through the superior vertebra, where the location of force application was aligned to the center of the disc. The sensitivity of this alignment to small (~0.5 mm) deviations was assessed post-test. A counterbalance system off-loaded half the mass of the specimen plus the mass of all hanging apparatus components that would otherwise impart artefact loads or moments on the specimen.

Specimens were tested in two cyclic loading regimes. During anterior-posterior shear loading, the specimen was loaded to 100 N in each direction during one continuous loading cycle. For these tests the loading plate of the specimen was connected rigidly to the Instron actuator through an X-Y translation table and a mounted bearing, allowing for testing in both shearing directions in a single cycle. During right lateral shear loading, the specimen was rotated in the apparatus and loaded between 20 N and 100 N in the right direction only. For these tests, the mounted bearing was replaced by a cable, giving the superior vertebra 6 degrees of freedom. The different loading regimes were established through pilot testing, where it was found that additional constraints in the lateral direction imposed restrictions on the specimens' motion, but that such effects were minimal during anterior-posterior loading, and that allowing only flexion-extension was appropriate.

Each specimen underwent cyclic anterior-posterior and right lateral shear loading in the previously described specimen conditions (intact, ligaments severed and disc-only). The order in which the directional tests were done was randomized between specimens. For each direction and specimen condition test five complete loading cycles were performed, where the third cycle was used for subsequent data analysis. A quasi-static loading rate of 15 N/s was used for all tests.

As noted in Table 1, one specimen was partially omitted from the results due to missing data (H1415). In this case, the specimen was tested using the cable for some anterior-posterior tests. Because of this, the 0-20 N stiffness could not be assessed for this specimen for all conditions.

Data Collection & Analysis

Load was captured using an inline 10 kN DynaCell load cell (Instron) and data was collected via the Optotrak ODAU analogue input. The load cell and motion capture data were synchronized and collected at 50 Hz.

Three-dimensional kinematics were collected using a motion capture system (Optotrak Certus, Northern Digital Inc., Waterloo, ON, Canada). Four-marker rigid body plates were fixed to the inferior and superior potting plates to measure relative motion between the two vertebral bodies on either side of the intervertebral disc.

Kinematics were transformed from the Optotrak global coordinate system to the anatomical coordinate system. The anatomical coordinate system and rigid body origins were defined with digitized landmarks on the specimen. The anatomical coordinate system was defined as follows: x – positive anterior, y – positive superior and z – positive to the right. The origin for each rigid body was as follow: inferior rigid body – middle of the anterior superior endplate; superior rigid body – middle of the anterior inferior endplate.

Displacements were expressed according to the anatomical axes of the specimen while flexion-extension, axial rotation and lateral bending rotations were expressed as Euler angles about the anatomical axes of the specimen in order z, y, x. Displacements and rotations were considered as the difference between the position of the specimen at 100 N of applied shear load and the position at 0 N (anterior and posterior shear) or 20 N (lateral shear) during the third cycle.

Stiffness was determined from the load-displacement curve of the third loading cycle for each respective direction. Stiffness was calculated as the slope of the line of best fit between two load ranges: 0-20 N and 20-100 N. Thus, in the anterior and posterior directions two stiffness values are reported, while in the lateral direction only one is reported. All load and displacement data were analyzed in Matlab (MathWorks, Natick, MA, USA).

A Friedman's test with a one-tailed Wilcoxon post-hoc ($\alpha=0.05$) was used to assess the significance of any decreases in stiffness between progressive specimen conditions. Statistical analyses were performed in R (R Foundation, Vienna, Austria). As a result of specimen H1415's partial omission from some tests, statistical significance could not be assessed for certain pairwise comparisons as the minimum number of paired samples required to be able to obtain a significant result for this test is five.

RESULTS

Stiffness

Anterior stiffness

A significant decrease in stiffness was found in the anterior direction from 186 N/mm [98-327 N/mm] in the intact condition to 105 N/mm [78-142 N/mm] in the disc-only condition in the 20-100 N range (p=0.03). While no other significant differences were found between the two stiffness ranges, specimens tended to exhibit lower stiffness in the 0-20 N range, ranging from 100 N/mm [32-205 N/mm CI] to 49 N/mm [30-120 N/mm CI] between the intact and disc-only conditions. The significance of the difference between specimen conditions in the lower 0-20N stiffness could not be evaluated as specimen H1415 was not tested in the 0-20N range in the ligaments-severed and disc-only states. However, all four pairs where a comparison was possible exhibited a decrease in stiffness from the intact to disc-only state.

Posterior stiffness

A significant decrease in stiffness was found in the posterior direction from 134 N/mm [92-182 N/mm] in the intact condition to 119 N/mm [83-181 N/mm] in the disc-only condition (p=0.03). Again, no significant differences were found between the two stiffness ranges, but specimens tended to be less stiff in the lower 0-20 N range than in the 20-100N range, ranging from 61 N/mm [21-137 N/mm] to 54 N/mm [12-101 N/mm] between the intact and disc-only states. The effect of specimen condition on the lower force range stiffness was less pronounced than for the higher force range, where three specimens experienced small decreases in stiffness and one experienced a slight increase in stiffness.

Lateral stiffness

No significant decrease in stiffness was found in the lateral direction between specimen conditions. While there was a slight decrease in the mean stiffness from the intact condition to the disc-only condition from 233 N/mm [124-408 N/mm] to 208 N/mm [115-296 N/mm], three specimens experienced some decrease in stiffness, while two experienced slight increases in stiffness. Pooling all lateral stiffness values gives a mean stiffness of 214 N/mm [137-291 N/mm] for all specimen conditions.

Kinematics

Displacements

No significant increase in displacement was found between specimen conditions for each respective shearing direction. In the anterior and posterior directions, there was a trend towards increasing displacements from the intact to disc-only conditions, but the significance of any change could not be evaluated as only four pairs of results existed. In the anterior direction, displacements ranged from 0.84 mm [0.34-1.37 mm] to 1.40 mm [0.78-1.87 mm] between the intact and disc-only conditions. In the posterior direction, displacements ranged from 1.07 mm [0.58-1.61 mm] in the intact condition to 1.37 mm [0.75-2.52 mm] in the disc-only condition. In the lateral direction there was no trend in displacement with specimen condition. The mean lateral displacement for all specimen conditions was found to be 0.43 mm [0.32-0.52 mm]. Coupled displacements in the non-shearing directions were less than 1 mm in all tests.

Rotations

Coupled rotations were minimal up to 100 N (less than 1°), except in a five individual trials, described more specifically in the following paragraph. During anterior-posterior tests, axial rotation and lateral bending were constrained by the test apparatus, while during lateral tests, no rotational constraints existed.

Considering all anterior and posterior tests performed (n=14), the majority (n=11) experienced small flexion-extension rotations (between 1.1° flexion and 0.5° extension), which were not correlated with the anterior or posterior direction. Three specimens experienced larger flexion-extension rotations, all with extension angles during posterior shear in their disc-only and ligaments severed conditions (between 0.9-2.1°). Specimen H1419 experienced considerable flexion during posterior shear, reaching a maximum of 11° flexion at 48.5 N of posterior shear.

In the lateral direction, all couple rotations were less than 1.5°, except for specimen H1415 in the disc-only state; during posterior shear, this specimen experienced a maximum of 2.9° flexion.

DISCUSSION

As hypothesized, shear stiffness decreased in the cervical spine FSU with progressive damage to the posterior elements in the anterior and posterior directions. This result was expected as the posterior elements and ligaments, namely the facet joints tend to be oriented such that they would tend to impede anterior-posterior translation in the cervical spine. While the decreases in stiffness in both the anterior and posterior directions were significant in the 20-100 N range, the effect was more pronounced in the anterior direction (81 N/mm mean decrease) as compared to the posterior direction (15 N/mm mean decrease) between the intact and disc-only conditions. This is also expected because the facet joints are oriented at approximately 45° in the cervical spine, giving greater protection against anterior translations than posterior translations.

This effect is further demonstrated by comparing the stiffness as a function of shearing direction. In the intact state, the mean stiffness was greater in the anterior direction than the posterior direction by 52 N/mm (non-significant result), but the stiffness values begin to converge with progressive damage to the posterior elements.

While differences between the intact to ligaments severed and ligaments severed to disc-only conditions did not reach significance for any pairwise comparison over any load range, the stiffness values for the ligaments severed condition tended to be closer to the intact state in the 20-100 N range. In the 0-20 N range, differences were less pronounced between all specimen states, but the ligaments severed 0-20 N stiffness tended to be more similar to the disc-only state. This would indicate that the bony posterior elements have a greater contribution to the mechanics of the cervical FSU at more extreme anterior and posterior shear loads, whereas the posterior ligaments contribute more to the mechanics during very small shear loads and displacements.

It was initially hypothesized that the load-displacement curve during shear loading would be linear and yield a single stiffness value over the full load range, based on the works of Moroney *et al* and Panjabi *et al*. However, it was found that in some specimens, a low stiffness zone, more typically observed as the neutral zone in flexion-extension loading, existed between approximately 0 and 20 N, regardless of specimen condition. Thus, two stiffness values were computed for all specimens in order to better represent the load-displacement behavior.

In the lateral direction, there were no significant differences in stiffness with increasing damage to the posterior elements. In this direction, the mean stiffness was greater than the anterior and posterior stiffness in all specimen conditions. It is reasonable that specimen condition did not affect lateral stiffness because the geometry of the posterior elements does not provide much constraint against lateral translation and, therefore, their removal would have a minimal effect. Greater stiffness in the lateral direction can be explained by the paired curved uncovertebral joints, which lie lateral to the disc center, and would tend to impede lateral translation. In the present experiment, these structures were left intact for all specimen conditions.

The stiffness values from the present study compare well with existing reports. Moroney *et al*. tested cervical FSUs in the intact and disc-only state in anterior, posterior and lateral shear directions to ~1 mm displacement in a repeated measures study design; this resulted in force ranges of 10-39 N for intact specimens, and 4-16 N for disc-only specimens. Moroney found the intact anterior, posterior and right lateral stiffness values to be 131 N/mm (29-631 N/mm range), 49 N/mm (14-96 N/mm) and 119 N/mm (28-226 N/mm). The disc-only stiffness was found to be 62 N/mm (12-317 N/mm), 50 N/mm (13-169 N/mm) and 73 N/mm (17-267 N/mm). In this study, small (<1°) coupled rotations were found. Though the stiffness values and coupled rotations found in the present study were slightly larger on all counts, the shear load ranges were greater in the present study compared to those of the Moroney study. It would be reasonable to expect larger stiffness and greater coupled rotations in the present study because bony structures would be more likely to come into contact at higher loads.

Shea *et al*. loaded intact 3-vertebra cervical spine segments to 150N in the anterior and posterior directions. The anterior stiffness was found to be 123 N/mm (±0.35 N/mm standard deviation) and the posterior stiffness was found to be 114 N/mm (±0.69 N/mm standard deviation) at 100 N. These values are similar to those reported in the present study.

The primary limitation of the present study was the small sample size. As there was great variability between specimens in this study, having a larger sample size may have resulted in significance of some of the observed trends. In addition, a larger sample size may have allowed us to tease out the effect of subject-specific intrinsic characteristics on stiffness. By accounting for factors such as disc and facet degradation, specimen size, age, and bone mineral density, the variability between specimens might have been reduced. Analyzing the effect of such factors would also be useful for those developing subject-specific FE models to better capture at-risk populations.

A second limitation was the design of the test apparatus. It was found that in specimens that were subjectively noted to be more flexible, small misalignments of the counterbalance or shear load line-of-action would result in artefact moments that caused large flexion-extension rotations. This issue tended to affect female specimens more prominently, and resulted in a few specimens being omitted (or partially omitted) from the results. It is suspected that this issue is related to the size of the specimen and balance point in the cervical spine, as opposed to the sex of the specimen, where this sensitivity to alignment is more critical in smaller specimens. A similar apparatus was used previously in our lab to load lumbar FSUs in anterior shear and instability (large coupled rotation) was not observed in male or female specimens until the nucleus of the disc was removed and only annular disc fibers and partial facets contributed to the specimen's stiffness (Melnyk *et al*, 2015). An analysis of how various apparatus design parameters affect loading in the cervical spine is currently underway. It is hoped that resolving these issues will enable further shear testing of the cervical spine, where the effect of dynamic loads and simulated muscle loads might be investigated.

CONCLUSIONS

In the present study the shear load-displacement characteristics of five C6-C7 cervical spine FSUs was reported, where the effects of both shearing direction and specimen condition were examined. The anterior and posterior stiffness was found to decrease significantly from the intact condition to the disc-only condition in the upper 20-100 N load range. No significant decrease in right lateral stiffness was found as a function of specimen condition. Coupled rotations and displacements tended to be small up to 100 N of shear. These results correspond well with existing studies examining cervical spine shear biomechanics, and are reasonable given the structure of the cervical spine FSU. These results will be of use to developers of FE models, where it is hoped that a more complete and biofidelic representation of the human neck will enable the use of such models to inform the design process in the automotive and sporting industries.

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