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The effect of lateral eccentricity on failure loads, kinematics, and canal occlusions of the cervical spine in axial loading

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ABSTRACT

Current neck injury criteria do not include limits for lateral bending combined with axial compression and this has been observed as a clinically relevant mechanism, particularly for rollover motor vehicle crashes. The primary objectives of this study were to evaluate the effects of lateral eccentricity (the perpendicular distance from the axial force to the centre of the spine) on peak loads, kinematics, and spinal canal occlusions of subaxial cervical spine specimens tested in dynamic axial compression (0.5 m/s). Twelve 3-vertebra human cadaver cervical spine specimens were tested in two groups: low and high eccentricity with initial eccentricities of 1 and 150% of the lateral diameter of the vertebral body. Six-axis loads inferior to the specimen, kinematics of the superior-most vertebra, and spinal canal occlusions were measured. High speed video was collected and acoustic emission (AE) sensors were used to define the time of injury. The effects of eccentricity on peak loads, kinematics, and canal occlusions were evaluated using unpaired Student *t*-tests. The high eccentricity group had lower peak axial forces (1544 ± 629 vs. 4296 ± 1693 N), inferior displacements (0.2 ± 1.0 vs. 6.6 ± 2.0 mm), and canal occlusions (27 ± 5 vs. $53 \pm 15\%$) and higher peak ipsilateral bending moments (53 ± 17 vs. 3 ± 18 Nm), ipsilateral bending rotations (22 ± 3 vs. $1 \pm 2^\circ$), and ipsilateral displacements (4.5 ± 1.4 vs. -1.0 ± 1.3 mm, $p < 0.05$ for all comparisons). These results provide new insights to develop prevention, recognition, and treatment strategies for compressive cervical spine injuries with lateral eccentricities.

1. Introduction

Current injury criteria for the cervical spine, which are used to evaluate the efficacy of airbags and seatbelts, define loads that represent thresholds of injury to the spinal column (Eppinger et al., 2000; Mertz et al., 2003). While enforced limits for loading in flexion, extension, axial compression, and tension are based on experimental testing and accident reconstructions (Mertz and Patrick, 1971; Mertz et al., 1978; Nyquist et al., 1980; Prasad and Daniel, 1984), those for lateral bending are not in use by government standards and the moment limits that have been suggested are simply the average of those in flexion and extension (Mertz et al., 2003). This indicates a need for further understanding of the tolerance of the cervical spine in lateral bending.

"Lateral flexion" injuries to the cervical spine are well recognized in clinical practice (Roaf, 1963; Chrisman et al., 1965; Schaaf et al., 1978; Scher, 1981) and clinical studies have hypothesized lateral bending in combination with other loads as mechanisms for unilateral injuries (Allen et al., 1982; Lee and Sung, 2009). Experimental studies have indicated that lateral bending may occur simultaneously with axial compression, in particular during rollover motor vehicle crashes (MVCs) (Bahling et al., 1990). Axial loading of the cervical spine is the primary mechanism leading to spine and spinal cord injury in football, diving, hockey, and rollover motor vehicle crashes (Bahling et al., 1990; Bailes et al., 1990; Torg et al., 2002; Tator et al., 2004; Thompson et al., 2009) and lateral bending may be present in real-world axial loading events. Numerous experiments have investigated the response of the cervical spine to lateral bending without an external compression force (Gadd et al., 1971; Patrick and Chou, 1976; Kallieris and Schmidt, 1990; Kettler et al., 2004; McIntosh et al., 2007; Yoganandan et al., 2009, 2011); however, very few studies have evaluated the cervical spine in lateral bending with combined axial compression (Selecki and Williams, 1970; Toomey et al., 2009). Due to this paucity of data, the tolerance and injury mechanisms of the cervical spine in compression-lateral bending are not well understood. An understanding of these mechanisms is essential for advancing injury prevention approaches such as helmets, neck protectors, and automotive restraints and to facilitate recognition of clinical injury patterns that would guide surgical treatment.

In addition, current neck injury criteria do not incorporate measures of spinal cord injury (Eppinger et al., 2000), one of which is canal occlusion as it relates to the mechanical trauma to the spinal cord and

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the degree of resulting dysfunction (Kearney et al., 1988; Chang et al., 1994; Panjabi et al., 1995; Wilcox et al., 2002). This would be invaluable as the focus of injury prevention measures could be on reducing the likelihood of paralysis, which is the most devastating result of spine injury. Although neuropathologic changes in rat spinal cords following lateral dislocations have been evaluated (Clarke et al., 2008), to our knowledge, canal occlusions during lateral loading of the human cervical spine have not been previously reported.

The primary objectives of this study were to evaluate the effects of lateral eccentricity (perpendicular distance from the axial force to the centre of the spine) on peak loads, kinematics, and spinal canal occlusions of subaxial cervical spine specimens tested in dynamic axial compression. Because failure loads are often identified subjectively, secondary objectives were to evaluate the use of acoustic emission (AE) signals (Van Toen et al., 2012) in detecting the time of injury of multiple vertebrae and to determine which anatomic variables correlated with failure loads.

2. Methods

2.1. Specimens

Ten fresh-frozen human cadaveric cervical spines were obtained and stored at −20 °C until use. Specimens were separated into 12 three-vertebra segments and they were dissected free from musculature while the ligaments and intervertebral discs (IVDs) were preserved (Tables 1 and 2). The coronal and sagittal diameters of the superior-(cranial) and inferior-most (caudal) vertebral bodies and specimen heights were measured using vernier calipers. Specimens were scanned with CT (Xtreme CT, Scanco Medical, Brüttisellen, Switzerland, resolution 246 μm) before and after testing. Average volumetric bone mineral density (vBMD) was calculated for each specimen (Tables 1 and 2) using Scanco software (μCT Evaluation Program v6.0). Degeneration of the IVDs and facet joints were evaluated by a spine surgeon (author JS) and scored as normal (0), mild (1), moderate (2), or severe (3). Total degeneration scores for each specimen were the sum of the disc and facet scores, with maximum possible values of 6 and 12 for the disc and facet, respectively (Tables 1 and 2). Specimens were potted in polymethylmethacrylate (PMMA) (Fig. 1), such that a line through the points in the sagittal plane representing the approximate instantaneous axes of flexion–extension rotation of the superior and inferior functional spinal units was vertical (Amevo et al., 1991).

2.2. Loading

A custom loading apparatus was used (Fig. 1), which consisted of two bearing rollers (model CF-1-S, McGill Mfg Co, Valparaiso IN) that were placed anterior and posterior to the specimen, equidistant from the geometric centre of the inferior IVD. Preload was applied to specimens, through the loading yoke and bending fixture (Fig. 1), as the actuator of a servohydraulic materials test system (model 8874, Instron, Canton MA) was lowered until a compression force of 50 N was reached and this displacement was held constant for approximately 6 min. Specimens were then tested in dynamic eccentric axial compression to a set displacement at a rate of 0.5 m/s, held at this position for 0.1 s, and unloaded at a rate of 50 mm/s using the servohydraulic materials test system. Although an impact velocity of 3 m/s is generally considered to be the minimum required to result in clinically relevant cervical spine injuries in head-first impacts (McElhaney et al., 1979; Nightingale et al., 1996), this rate is expected to be distributed across all levels of the cervical spine and reduced velocities are thought to be relevant for small segment testing (Edwards, 1998; Carter, 2002). Specimens were randomly assigned to one of two test groups: low or high eccentricity, where the eccentricities (randomly assigned to the right or left) were set to 1 and 150% of the average lateral dimension of the

Table 1
Summary of the specimen and donor details for the low eccentricity group as well as the major injuries experienced by these specimens. 'NA' indicates that the data was not available. Specimens H1275 and H1975 (Table 2) were from the same donor and specimens H1298 and H1998 (Table 2) were from the same donor. The average vertebral body area of each specimen was calculated assuming an elliptical cross section. Disc degeneration and facet osteoarthritis columns indicate the total rating of all joints (2 discs, 4 facet joints) in the specimen (0: normal, 1: mild, 2: moderate, 3: severe). DD: disc degeneration, EP: endplate fracture, FJ: articular facet fracture, FO: facet osteoarthritis, inf: inferior, LAM: lamina fracture, sup: superior, V1: superior vertebra, V2: middle vertebra, VB: vertebral body fracture, VBA: vertebral body area.

Specimen number	Level	Age, gender	Average vBMD (mg HA/cm^3)	Average VBA (mm^2)	Initial eccentricity (mm)	Total DD	Total FO	Major injuries
H1318	C57	72, F	620	317	0.3	1	5	V1: EP (inf), VB
H1323	C35	NA, M	597	358	0.3	1	0	V2: EP (sup), VB, LAM
H1321	C46	72, M	604	405	0.3	2	8	V2: EP (sup), VB
H1298	C35	68, F	536	343	0.3	3	4	V2: EP (sup), LAM
H1975	C6T1	79, M	581	467	0.3	1	5	V2: EP (sup & inf), VB
H1274	C35	78, M	578	433	0.2	5	10	V1: VB V2: FJ (sup)
Average (standard deviation)		74 (5)	586 (29)	387 (58)	0.3 (0.0)	2 (2)	5 (3)	

Table 2
Summary of the specimen and donor details for the high eccentricity group as well as the major injuries experienced by these specimens. 'NA' indicates that the data was not available. Specimens H1275 and H1975 (Table 1) were from the same donor and specimens H1298 and H1998 (Table 1) were from the same donor. For the specimens marked with *, donor genders were determined using DNA (deoxyribonucleic acid) microsatellite analysis performed on donor muscle tissue. The average vertebral body area of each specimen was calculated assuming an elliptical cross section. Disc degeneration and facet osteoarthritis columns indicate the total rating of all joints (2 discs, 4 facet joints) in the specimen (0: normal, 1: mild, 2: moderate, 3: severe). ALL: anterior longitudinal ligament tear, DD: disc degeneration, EP: endplate fracture, FC: facet capsule tear, FO: facet osteoarthritis, inf: inferior, ISL: interspinous ligament tear, IVD: intervertebral disc injury, LF ligamentum flavum tear, PLL: posterior longitudinal ligament tear, sup: superior, V1: superior vertebra, V2: middle vertebra, V3: inferior vertebra, VB: vertebral body fracture, VBA: vertebral body area.

Specimen number	Level	Age, gender	Average vBMD (mg HA/cm^3)	Average VBA (mm^2)	Initial eccentricity (mm)	Total DD	Total FO	Major injuries
H1125	C46	NA, M*	523	390	39.9	1	1	V2/3: FC, LF, ALL, IVD
H1329	C57	NA, M*	566	469	48.1	2	2	V2/3: FC, LF, ISL, ALL, PLL, IVD
H1275	C35	79, M	599	392	41.4	1	8	V2/3: FC, LF, ISL, ALL, PLL, IVD; V2: VB
H1286	C46	66, F	623	370	38.3	3	6	V1/2: FC, LF, ISL, ALL, PLL, IVD; V2: EP (sup)
H1998	C6T1	68, F	526	410	43.6	1	2	V2/3: FC, LF, ISL, ALL, IVD; V2: EP (inf); V3: EP (sup)
H1292	C35	67, M	580	443	42.6	4	4	V2/3: FC, LF, ISL, ALL, PLL, IVD; V2: EP (inf); V3: EP (sup)
Average (standard deviation)		70 (6)	569 (40)	412 (37)	42.3 (3.4)	2 (1)	4 (3)	