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Towards a More Robust Lower Neck Compressive Injury Tolerance - An Approach Combining Multiple Test Methodologies

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ABSTRACT

Objective. The compressive tolerance of the cervical spine has traditionally been reported in terms of axial force at failure. Previous studies suggest that axial compressive force at failure is particularly sensitive to the alignment of the cervical vertebra and the end conditions of the test methodology used. The present study was designed to develop a methodology to combine the data of previous experiments into a diverse dataset utilizing multiple test methods to allow for the evaluation of the robustness of current and proposed eccentricity based injury criteria.

Methods. Data was combined from two studies composed of dynamic experiments including whole cervical spine and head kinematics that utilized different test methodologies with known end conditions, spinal posture, injury outcomes and measured kinetics at the base of the neck. Loads were transformed to the center of the C7-T1 intervertebral disc and the eccentricity of the sagittal plane resultant force relative to the center of the disc was calculated. The correlation between sagittal plane resultant force and eccentricity at failure was evaluated and compared to the correlation between axial force and sagittal plane moment and axial force alone.

Results. Accounting for the eccentricity of the failure loads decreased the scatter in the failure data when compared to the linear combination of axial force and sagittal plane moment and axial force alone. A correlation between axial load and sagittal plane flexion moment at failure (R^2 = 0.44) was identified. The sagittal plane extension moment at failure did not have an identified correlation with the compressive failure load for the tests evaluated in this data set (R^2 = 0.001). The coefficients of determination for the linear combinations of sagittal plane resultant force with anterior and posterior eccentricity are 0.56 and

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0.29 respectively. These correlations are an improvement compared to the combination of axial force and sagittal plane moment.

Conclusions. Results using the outlined approach indicate that the combination of lower neck sagittal plane resultant force and the anterior-posterior eccentricity at which the load is applied generally correlate with the type of cervical damage identified. These results show promise at better defining the tolerance for compressive cervical fractures in male Post Mortem Human Subjects (PMHS) than axial force alone. The current analysis requires expansion to include more tolerance data so the robustness of the approach across various applied loading vectors and cervical postures can be evaluated.

Key Words Neck Injury; Fracture; Injury Criteria; Biomechanics

INTRODUCTION

Approximately 12,000 spinal cord injuries occur each year in the United States, not including those who sustain immediate fatal injuries. Catastrophic cervical spinal cord injuries are most often associated with compression mechanisms of the cervical column (Roaf, 1972; Torg et al., 1990; Yogananadan et al., 1989; McElhaney et al., 2002). This can occur in any environment in which the apex of the head is loaded in a direction parallel to the alignment of the cervical column including automobile crashes, swimming and diving, football, hockey, and motor sports. McElhaney et al. (2002) reported that automobile accidents account for 37% of all cervical spinal cord injuries. The majority of non-fatal cervical fractures, dislocations and subluxations are sustained in the lower (C3-C7) cervical spine (Yoganandan et al., 1989; Goldberg et al., 2001). Miller (2001) has estimated

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medical costs alone for spinal cord injuries in vehicle accident survivors range from 330,000 dollars for AIS 3 injuries to over 1 million dollars for an AIS 5 injury on a per case basis. Prevention and mitigation of these costly and devastating injuries through engineering is predicated upon the accurate biomechanical understanding of compressive cervical spine mechanics.

Biomechanical investigations using PMHS (Post Mortem Human Subjects) have been an essential element in the current understanding of the complex dynamics of compressive cervical spine injury including cervical column buckling, injury timing with respect to head motion, and the effects of contact surface padding on neck injury risk (Nusholtz et al., 1983; Alem et al., 1984; Yoganandan et al., 1986; Pintar et al., 1990; Nightingale et al., 1996a; Nightingale et al., 1996b; Camacho et al., 2001). Compressive injury tolerance has historically been reported by identifying the peak axial force at injury measured at the base of the neck (Pintar et al., 1995; Nightingale et al., 1997). However, as an injury predictor, compressive force at failure exhibits wide variation and this has been attributed to the alignment of the cervical vertebra and the end conditions of test methodology used. The axial force at failure in male PMHS increases by 68% as the spine moves from the natural lordotic posture to an aligned posture (Nightingale et al., 1997; Pintar et al., 1995) and by 180% when the cervical spine end conditions change from rotational constraint to full constraint (Myers et al., 1991). These differences in cervical alignment and end conditions result in differing injury mechanics based on axial load eccentricity at the location of injury. Thus while the axial load is the driving factor for the dynamic compressive injury mechanics, its actual magnitude at the time of injury varies based on cervical alignment and axial load eccentricity. Development and refinement of an injury criterion that incorporates the effects of compressive load eccentricity across the range of studies performed to-date that include lower neck kinetics has the potential to lead to a more sensitive and robust injury predictor than axial force alone.

The purpose of the current study is to lay the foundation and methodology to combine the results of multiple cervical spine compressive injury studies where cervical kinetics are well defined. If studies including cervical kinetics at the base of the neck can be combined in to a single dataset that spans large variations in cervical alignment and load eccentricity, it may be possible to further refine the tolerance of the cervical spine in compression. This may allow for the development of more robust lower neck injury risk assessments that effectively predict the probability of injury across a range of exposures for evaluation of safety intervention strategies. First, we present a brief background review of the influence of cervical column alignment and eccentricity on axial compressive force at failure followed by a review of mechanistic cervical injury criteria and the fundamental mechanics of structures under compressive loads.

Influence of Cervical Column Alignment and Eccentricity

Cervical spine compressive injury prediction has primarily relied upon the overall axial compressive load directly measured at the base of the neck for tolerance, but the average compressive failure load between studies varies greatly. Previous studies suggests that a large source of the variation in compressive load at failure may be a function of cervical alignment prior to impact and the end conditions of test methodologies used. Indeed, the cervical tolerance at failure reported by Pintar et al.

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(1995) for pre-aligned PMHS impacted on the apex of the head by a Material Testing System (MTS) machine was 3,326 N (3,767 N for male PMHS) while Nightingale et al. (1997) preserved the natural cervical lordosis of PMHS spine while conducting inverted drop tests and found failure loads of 2,243 N for male PMHS.

In addition to sagittal plane cervical alignment, the anterior-posterior eccentricity (Winkelstein and Myers, 1997; Maiman et al., 2002) and lateral eccentricity (Toomey et al., 2009) of the applied forces to the cervical spine are also suggested to be factors affecting spinal injury dynamics and injury outcomes but have rarely been quantified. Studies by Myers et al. (1991) and Carter et al. (2002) have indicated the axial force tolerance decreases with increased eccentricity. Magnitudes of eccentricity are typically referenced to the center of either the vertebral body or the inferior vertebral disc nearest the point of load measurement. Winkelstein and Myers (1997) summarized the influence of anterior eccentricity of the resultant force at the site of injury on the type of clinically recognized injuries that have been replicated in the laboratory (Figure 1). The sensitivity and predictive ability of cervical spine compression injury criteria may be improved by accounting for combined loading, eccentricity of the applied load, and/or anatomical alignment.

Mechanistically Relevant Injury Criteria

Several composite neck injury tolerance criteria for compressive loading events have been proposed for both the upper and lower cervical spine that incorporate the effects of combined compressive loading modes. Prasad and Daniel (1984) proposed the first combined axial load and sagittal plane bending moment injury criterion for combined tension and extension loading of the cervical spine. The concept of linearly combining axial load and sagittal plane bending moment was expanded to include compression and flexion (Klinich et al., 1996). The combined loading neck injury criterion, Nij, defined for the Hybrid III anthropomorphic test device (ATD) is calculated using Eq. (1) where the intercept values F_{int} and M_{int} vary depending on the whether the loading mode is compression or tension and flexion or extension respectively.

$$Nij = \frac{Fz}{F_{\text{int}}} + \frac{My}{M_{\text{int}}} \tag{1}$$

The linear combination of axial force and bending moment has a basis in generalized mechanics. The upper neck Nij intercepts for combined tension and extension loading were derived by calculating the approximate maximum normal stress in the anterior longitudinal ligament (ALL) at the level of the occipital condyles (Mertz and Prasad, 2000). In compressive loading, the maximum normal stress in a structural member (or strut), takes the form:

$$\sigma_{\max} = \frac{P}{A} + \frac{My_{\max}}{I} = \frac{P}{A} + \frac{Pey_{\max}}{I} \tag{2}$$

where P is the axial force, M is the moment, A is the cross sectional area of the strut, I is the second moment of the area, e is the distance from the central axis that the load is applied (eccentricity) and y is the distance from central axis for the location the stress is being calculated (see Figure 2A).

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As the cross sectional geometry of a compressive strut decreases while holding the length the same, the likelihood of buckling increases as is often the case in cervical spinal column compressive dynamics (Nightingale et al., 1997; Myers and Nightingale, 1999). In this case of a slender column, as shown in Figure 2B, the maximum moment in Eq. (2) is a function of not only the axial load and its eccentricity but also the transverse deflection, δ, of the column (Eq. 3). After solving for this deflection, the maximum normal stress is represented by Eq. (4) and is known as the secant column formula (Shigley and Mischke, 1989).

$$M_{\max} = -P(e+\delta) \qquad (3)$$

$$\sigma_n = \frac{P}{A}\left[1+\frac{ec}{k^2}\sec\left(\frac{l}{2k}\sqrt{\frac{P}{EA}}\right)\right] \qquad (4)$$

For further background on combined bending and axial loading of columns, see Strength of Materials Part 1 (Timoshenko, 1940). Regardless of whether the cervical spine is thought of as a compressive strut or slender column, the combination of axial force and the eccentricity at which it is applied has merit as a potential injury criterion for both a pre-straightened and buckled cervical column based on fundamental mechanics.

METHODS

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Selection of PMHS Studies for Combined Data Set

In order to account for a range of applied loading vectors and cervical postures, a combined data set of relevant cervical spine tolerance data needs to include dynamic studies of whole cervical spine kinematics and inertial loading by the head. The minimum number of quantified parameters includes; known end conditions, spinal posture, injury outcomes and the kinetics at the base of the neck. After identifying studies that meet the above criteria, the kinetics at the base of the neck must be reported at the same anatomical location which was defined in the current study as the center of the C7-T1 intervertebral disc. Additionally, the injury classification and severity scaling used in the various studies must be correlated. Research conducted by three investigating groups meet the above criteria. They include Pintar et al. (1995 and 1998), Nightingale et al. (1997) and Toomey et al. (2009). Amongst these three groups, two primary test methodologies have been used. Pintar et al. aligned the cervical column of a PMHS head-neck complex by pre-straightening the neck and impacted the apex of the head using an MTS machine. In contrast, Nightingale et al. designed an inverted drop track with a simulated torso mass and mounted a PMHS head-neck complex with the cervical spine resting lordosis maintained. Toomey et al. adopted the inverted drop track methodology of Nightingale at al. to investigate combined compression and lateral bending loading scenarios.

The results of studies conducted by Pintar et al. (1995) and Toomey et al. (2009) have been analyzed using the presented methodology. The tests conducted by Toomey et al. maintain the cervical spine's natural lordotic posture and investigated the influence of lateral bending on compressive cervical tolerance and response. These experiments included two test configurations, the first evaluated a naturally lordotic spine impacting a laterally inclined (15 degrees) surface and the second investigated a laterally pre-flexed cervical spine impacting a flat surface (see Figure 3). Further detail of both of the experimental setups for the studies evaluated can be found in the underlying studies. The 12 experiments that included a male PMHS and resulted in a cervical fracture were included in the current evaluation.

Moment Transformation

Data processing was conducted in accordance was SAE J211. All head and neck forces were digitally filtered at SAE channel filter class 1000 (CFC 1000) and neck moments at CFC 600 (SAE J211-1). The SAE coordinate system outlined in J211 was used. The neck axial load and sagittal and frontal plane moment reaction loads at the sensitive axis of the load cell were transformed to the center of the C7-T1 intervertebral disc. The axial load was adjusted to account for the dynamic effect of the mass present between the sensitive axis of the load cell and the center of the C7-T1 intervertebral disc. The neck forces were filtered at CFC 600 for the sagittal and frontal plane moment transformation process. The location of the center of C7-T1 intervertebral disc was determined using pre-test radiographs. Eqs. (5) and (6) were used to transform the measured moments and are depicted in Figure 4.

$$My = My_{LC} + (Fx \times z) + (Fz \times x) \tag{5}$$

$$Mx = Mx_{LC} - (Fy \times z) - (Fz \times y) \tag{6}$$

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In head-neck complex experimentation, the center of the C7-T1 intervertebral disc represents a convenient and repeatable anatomical landmark nearest the end of the tested subject that does not move relative the load cell sensitive axis. Combined with the relative ease in which the center of the disc can be defined in a radiograph, this ensures accurate moment transformation.

Applied Load Eccentricity

During impacts to the apex of the head, the location, magnitude and direction of the resultant load applied to the head directly influence the magnitude and direction of the lower neck reaction force and moment response. Figure 5 shows three equivalent depictions of a general loading scenario. In the example given, the sagittal plane eccentricity (Exz) relative to the center of the C7-T1 intervertebral disc can be calculated using Eq. (7) that only incorporates the neck reaction forces and moments. Eccentricity is fundamentally the perpendicular distance between the force line of action and center of the intervertebral disc.

$$Exz = \frac{My}{Fxz} = \frac{My}{\sqrt{Fx^2 + Fz^2}} \tag{7}$$

The use of sagittal plane resultant force combined with either sagittal plane moment or eccentricity of the applied force relative to the center of the C7/T1 intervertebral disc allows for comparison of a range of initial neck orientations.

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Identification of Failure Loads

For the current evaluation, only male PMHS experiments from the current data sets that resulted in cervical fracture were included. Analyses of the additional right-censored data points, two from Pintar et al. (1995) that resulted in minor ligamentous damage and two from Toomey et al. (2009) that resulted in no cervical damage, are beyond the scope of the current study. The load at fracture was determined based on the measured neck load responses and the associated high speed video. Traditionally, compressive failure has been defined as a decrease in axial load while displacement is still increasing. In the case of the cervical spine, a change in geometry due to neck buckling or a change in end conditions (head translation on the impact surface) can also lead to a decrease in axial load on the spine. The fracture loads identified are the first decrease in axial load that could not be attributed to another cause. Similar approaches to identifying failure loads have been used by other researchers (Nightingale et al., 1997; Carter et al., 2002).

RESULTS

Neck compressive failure loads and concurrent shear forces, bending moments, and calculated sagittal plane resultant force eccentricity for each of the tests are summarized in Table 1. The documented cervical damage for each test is also reported. The tests are ordered from the most negative or posterior eccentricity to the most positive or anterior eccentricity. Since the tests conducted by Pintar et al. were limited to sagittal plane kinematics, the lateral shear force and lateral and axial torsion

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bending moments are not reported. In the tests conducted with an aligned cervical column by Pintar et al. (1995), the orientation of the cervical spine was varied by locating the occipital condyles posterior (-0.5 cm), in-line with (0 cm) or anterior (0.5 cm) to the T1 vertebrae. This orientation is defined in the Test Condition column of Table 1. In tests conducted by Toomey et al. (2009), naturally lordotic spines were dropped onto a laterally inclined surface (Config 1) and laterally pre-flexed spines onto a flat surface (Config 2).

The cervical damage reported for the twelve tests is limited to lower cervical vertebral damage ranging between C3 and C7 except for Test 1 where a C1 unilateral lateral mass fracture was identified along with posterior element fractures of the lower vertebrae. The damage reported is generally consistent with the relationship between the applied force eccentricity and the mechanism of cervical injury identified by Winkelstein and Myers (1997) in Figure 1. Posterior element fractures were identified in tests 1-4 where the eccentricity was less than or equal to -5 mm, or posterior of the center of the C7/T1 disc. Vertebral body vertical, wedge, and burst fractures were identified in tests 5–12 where the eccentricity was greater than -5 mm.

The anterior-posterior and lateral shear components (Fx and Fy) of the neck load were small compared to the compressive load component. The measured neck shear loads contributed minimally to the resultant load. Among the tests evaluated and listed in Table 1, shear forces increased the resultant load by 2% or less in all but one case. The shear force in Test 10 increased the resultant load by approximately 8%. Similarly, lateral moment (Mx) magnitudes at the time of fracture were generally small in

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comparison to both sagittal plane moments and axial torsion. In the test conducted by Toomey et al., the lateral bending moment contributed less than 3% to the resultant moment for tests 1 and 4 and approximately 13 % in test 3. The mean axial twist moment contribution to the resultant moment at the time of failure was approximately 37%. The contribution of shear forces and lateral bending to the resultant failure kinetics are negligible. The influence of the axial twist moment on failure kinetics in this loading mode is not well defined. However, the cervical damage patterns identified in these three experiments are not consistent with injuries historically classified as torsion injuries such as complete atlantoaxial dislocation or unilateral atlantoaxial facet dislocation.

As the sagittal plane flexion moment at failure increases, the axial failure load generally decreases. However, the sagittal plane extension moment at failure does not have an identified correlation with the axial failure load for the tests evaluated in this data set. The combined compressive axial load and moment for each test are plotted in Figure 6. Independent linear regressions were performed for tests with flexion and extension moments at the time of failure. Test 7 was included in both regressions because it was essentially a pure compressive load at failure. The coefficient of determination (R^2) for a linear combination of compression and extension was 0.001 and for combined compression and flexion was 0.44. A correlation with R^2 greater than zero indicates an improved definition of failure when compared to axial force alone. The trend line for tests including a flexion moment at failure results in a y-intercept of -4,525 N.

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As the eccentricity of the sagittal plane resultant load at failure increases in either the anterior or posterior direction, the resultant failure load generally decreases. The combination of sagittal plane resultant force and the eccentricity at which the force is applied for each test are plotted in Figure 7. Linear regressions were performed for anterior and posterior eccentric loads. Test 7 was included in both regressions because its eccentricity was approximately zero. The y-axis (resultant load) intercept was independently determined for both linear trend lines. Each linear regression resulted in a y-intercept of 4,675 N. This represents the approximate force tolerance if the load is applied through the center of the C7/T1 intervertebral disc for the current data set. The R^2 values for a linear combination of sagittal plane resultant force with anterior and posterior eccentricity are 0.56 and 0.29 respectively. These correlations are an improvement compared to the combination of axial force and sagittal plane moment.

For each of the PMHS tests evaluated, two injury metrics were calculated based on the axes intercepts determined from the linear regressions in Figures 6 and 7 and are reported in Table 1. The linear combination of compressive force and sagittal plane moment is a form of Nij but applied to the PMHS instead of the Hybrid III anthropomorphic test device. In the current study, the X and Y axes intercepts representing pure flexion and pure compression are 316 Nm and -4,525 N respectively. The average axial force at failure for Tests 7-12 is -3,827 +/- 950 N. The average combined axial force and flexion moment injury metric is 1.00 +/- 0.16. The standard deviation of the compressive load and flexion moment injury metric for the evaluated experiments was 16% of the metric mean value versus 25% for the axial force alone. A PMHS Nij was not derived for

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extension loading moments as a linear regression R^2 value approaching zero indicates that adding the extension moment to the compressive load does not better define the injury tolerance compared to compressive load alone.

The same analysis was conducted for combined sagittal plane resultant load and the eccentricity at which it was applied with respect to the center of the C7-T1 disc. The X and Y axes intercepts resulting from the regressions in Figure 7 and used to calculate an eccentricity based injury metric are approximately -38 mm (posterior eccentricity), 92 mm (anterior eccentricity) and 4,675 N. The actual eccentricities at failure did not exceed -14 mm in the posterior direction or 36 mm in the anterior direction. The average axial force at failure for Tests 1-7 is -3,863 +/- 1,280 N. The average combined sagittal plane resultant force and eccentricity injury metric for Tests 1-7 and 7-12 is 1.00 +/- 0.23 and 1.00 +/- 0.15 respectively. The calculated metric combining sagittal plane resultant load and eccentricity reduced the standard deviations' percentage of the metric mean from 25% and 33% for axial force alone to 15% and 23% for anterior and posterior eccentricity respectively. In addition to giving insight into the type of injury sustained, accounting for the eccentricity of the load decreased the scatter in the failure data when compared to the combination of axial force and sagittal plane moment and axial force alone.

DISCUSSION

Catastrophic neck injury mechanics resulting from head first impacts are dominated by the axial compressive load. The location, magnitude and direction of the resultant load drives the moment response at the base of the neck. Compressive force

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tolerance of the cervical spine varies due to several factors including load application vector, head constraint and head and neck initial orientation. The current approach applied to a subset of studies lays the foundation to combine additional experimental data where cervical kinetics are well defined and may lead to further refinement of the tolerance of the cervical spine in compression. The combination of the resultant sagittal plane load with eccentricity shows promise at being a more sensitive predictor of catastrophic cervical spine tolerance in compressive loading modes. The current analysis needs to be expanded to include more PMHS tolerance data, such as Nightingale et al. (1997), to evaluate the robustness of the method across various applied loading vectors and cervical postures. Additionally, non-bony injuries, upper cervical spine injuries, female PMHS and the proposed injury metrics ability to delineate the presence and/or severity of injury needs further evaluation. Finally, with an expanded data set, the influence of donor age, gender and size can be investigated and taken in to account.

Previous researchers have similarly attempted to combine multiple PMHS compressive cervical spine test methodologies conducted by multiple investigating groups in an effort to refine the threshold for sustaining an injury. Viano and Parenteau (2008) have analyzed the combined whole body PMHS data sets of Culver et al. (1979), Nuscholtz et al. (1981, 1983), Alem et al. (1984), Yoganadan et al. (1986) and Sances et al. (1986) and found that in the absence of directly measured spinal kinetics, peak head velocity was an identifiable parameter across experimental methodologies and predictive of cervical injury during

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impacts to the apex of the head. The current study provides an approach for combining the results of studies that include lower neck kinetics with the goal of further refining the tolerance of cervical spine compressive injuries.

The center of the C7/T1 intervertebral disc appears to be an appropriate location for sagittal plane moments and applied load eccentricities to be calculated. Generally, the loads decrease with increased eccentricity in either direction from this location in the current study. Additional experiments added to the data set will determine if this trend continues. The current study derived a relationship between sagittal plane resultant force and eccentricity using linear regression, however, if more experimental data becomes available, various non-linear relationships can be evaluated. The coefficients of determination for the linear regressions of anterior oriented loads were greater than for posterior oriented loads. This may be due to the geometry of the vertebrae and the complexity of the interaction between facet joints during rearward extension or posterior oriented loading. Another potential explanation for the reduced correlation in posterior oriented loads is two potential outliers identified in a data set of seven experiments. Test ID #1 and #2 both have an eccentricity of approximately -14 mm but the sagittal plane resultant forces range from 1,548 N to 4,824 N. The removal of Test ID #1 from the linear regression would results in an R^2 close to zero. However, if Test ID #2 is treated as an outlier, removal would result in an improved R^2 of 0.57. Similarly, if Test ID #2 were removed from the axial compressive force and sagittal plane moment analysis, the R^2 improves to 0.34 and the y-intercept becomes -4,780 N, similar to the other regressions. There is not sufficient basis to remove either data point from consideration, however, this emphasizes the need for additional experimental data.

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As applied compressive loads decrease and approach non-injurious levels, pure eccentricity without compressive loads does not present a meaningful loading scenario. The relationship between resultant sagittal plane loads and eccentricity will only maintain meaning for non-trivial loads. In order to significantly load the cervical spine in compression, the loading vector needs to be in proximity to, and nearly parallel with, the cervical column. At large eccentricities or increasingly oblique loading vectors, the head will translate transverse to the cervical column minimizing compressive loading of the spine. Expansion of the current data set with loading conditions at increased eccentricities will aid in further defining the extent of application of combined force and eccentricity as an injury metric.

The majority of non-fatal cervical fractures, dislocations and subluxations are sustained in the lower (C3-C7) cervical spine. A robust lower neck compressive injury criterion that can ultimately be correlated with ATD response should better define the injury tolerance in these cases due to the proximity of the measured loads to the injury site. The Beam Criterion (BC) was proposed by Bass et al. (2006) for the lower human cervical spine in frontal collisions including significant tensile loading due to inertial loads from a head supported mass. Similar to Nij, BC is the linear combination of the axial force and sagittal plane moment measured at the center of the C7-T1 intervertebral disc. The derived constants for BC are 5,430 N for compression and 141 Nm for flexion. A BC of 1.0 corresponded to a 50% risk of AIS 2 or greater human cervical spine injury. In the current study, the compression and flexion intercepts are 4,525 N and 316 Nm respectively. Additionally, the force intercept

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derived in the eccentricity analysis was 4,675 N. This range of loading is consistent with the initial Nij compression intercept advocated by NHTSA (Eppinger et al., 1999) based on close to pure compression tests conducted by Pintar et al. (1990) which are not considered in this data set due to the lack of reported data other than force at failure. These intercepts are also consistent with results of Qingan et al. (1999) who impacted C2-C4 vertebral segments and found average peak compressive force for non-damaged segments of 4.11 +/- 0.11 kN and the average peak compressive force for damaged segments of 4.89 +/- 0.38 kN. The number of subjects in the current study serves as a limitation in drawing conclusions on a statistical basis, but the y-intercepts of the linear regressions are consistent with the findings of previous researchers. More experiments including a wider variety of injury outcomes need to be evaluated.

Currently available cervical spine compressive tolerance experiments that include lateral loading components are limited. In the few tests that include a lateral loading component, the lateral shear force and lateral bending moments contributed the least to the mechanical response at the time of initial failure. However, the lateral components increase the loading through the facet joints resulting in posterior loading and posterior element fractures. It is this loading through the facet joints that may also explain the fairly significant torsional moments at failure for the tests conducted by Toomey et al. (2009) as the facet joints are obliquely angled inferiorly as the joint extends posteriorly. The influence of these torsional moments on cervical tolerance is not currently well defined and inclusion of these data in a sagittal plane injury tolerance definition may partially explain the increased variance in the posterior vertebral loading injury metrics and requires further consideration.

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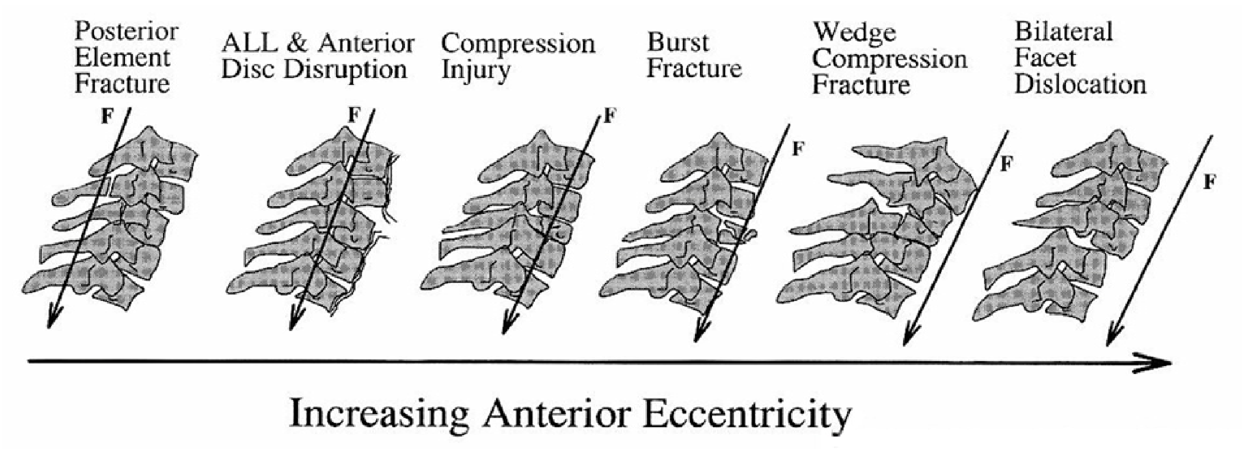

Figure 1– Influence of applied compressive force eccentricity on the mechanism of cervical injury (reprinted with permission from Winkelstein and Myers, The biomechanics of cervical spine injury and implications for injury prevention, *Medicine & Science in Sports & Exercise.* 1997;29 (7))

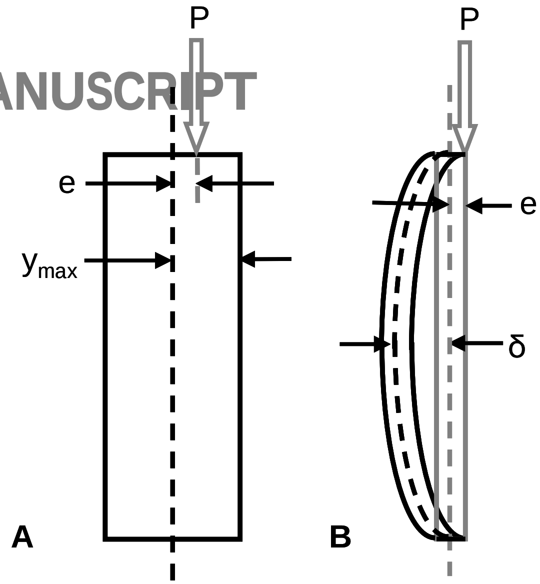

Figure 2– Generalized eccentric loading condition of a compressive strut (A) and a slender column (B).

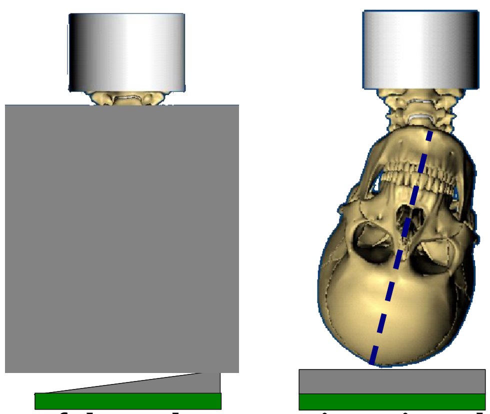

Figure 3 – Depiction of the neck postures investigated by Toomey et al. 2009 including a naturally lordotic spine impacting a laterally inclined (15 degrees) surface and a laterally pre-flexed cervical spine impacting a flat surface.

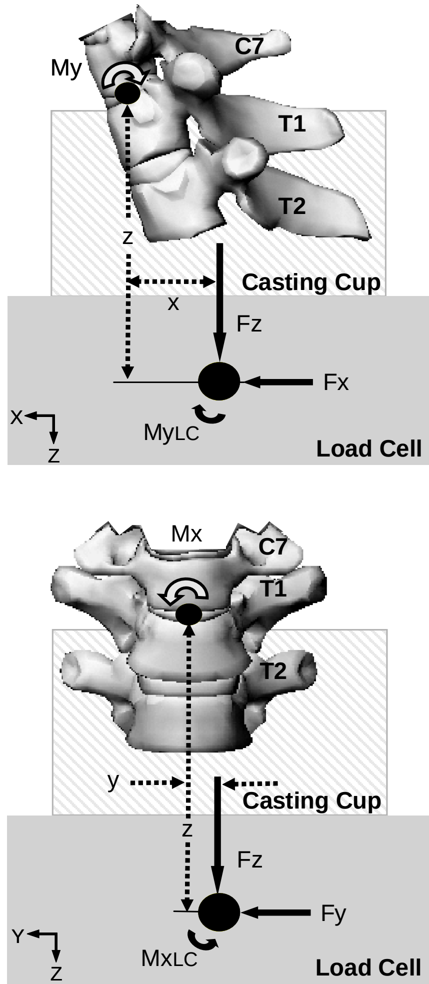

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Figure 4 – Depiction of the flexion/extension moment (My) and lateral bending (Mx) moment transformation from the load cell to the center of C7-T1 intervertebral disc defined by Equations 5 and 6. The SAE coordinate system has been adopted and the forces and moments depicted represent positive reaction loads.

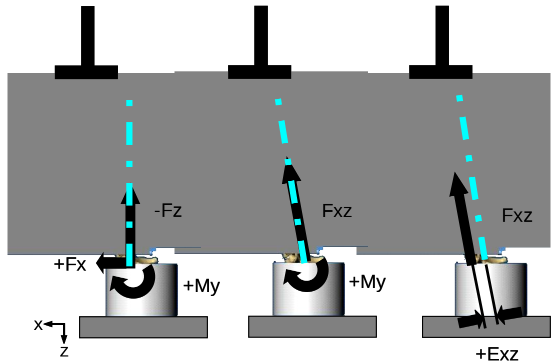

Figure 5 – Equivalent representations of a generalized two-dimensional loading scenario depicting the relationship between sagittal plane kinetics and resultant sagittal plane force eccentricity

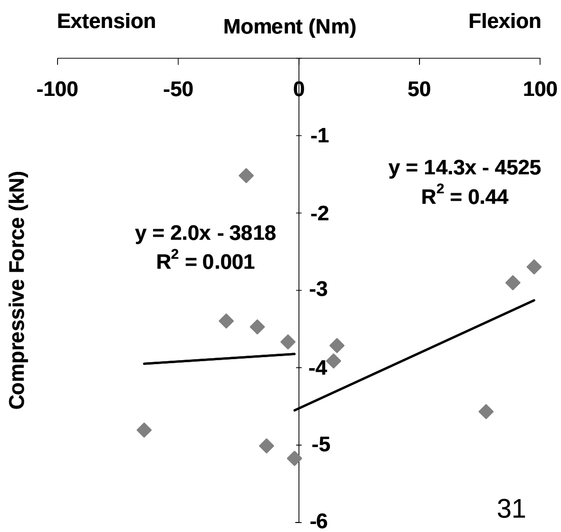

Figure 6 – Relationship between compressive force and sagittal plane moment at the center of the C7/T1 intervertebral disc at the point of PMHS cervical failure including linear regressions for both flexion and extension moments.

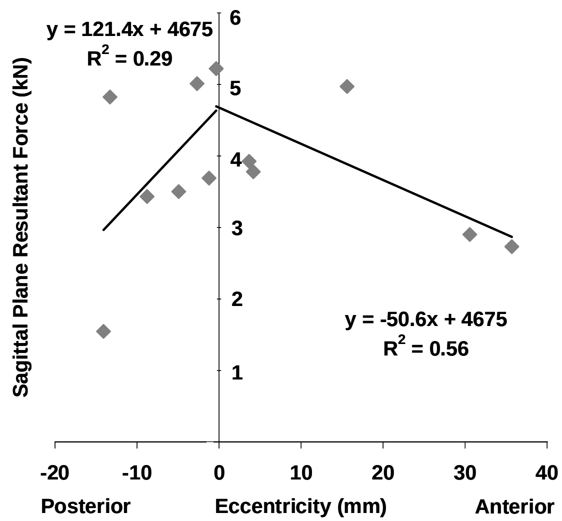

Figure 7 – Relationship between sagittal plane resultant force and its applied eccentricity from the center of C7/T1 intervertebral disc at the point of PMHS cervical failure including linear regressions for both anterior and posterior loading.

Table 1 –Kinetics at the center of the C7/T1 intervertebral disc at the time of documented cervical damage

Test ID	Age	Test Condition	Fx (N)	Fy (N)	Fz (N)	Fxz (N)	Mx (Nm)	My (Nm)	Mz (Nm)	Exz (mm)	Fz-My Metric	Fxz-Exz Metric	Cervical Damage
1*	55	Config 1	305	-70	-1518	1548	-7.2	-21.8	-21.4	-14.1	-	0.70	C5 lamina/pedical/upper & lower facets, C6 lamina/pedicle frx, C1 unilateral mass frx
2	59	-5 cm	424	-	-4805	4824	-	-64.1	-	-13.3	-	1.38	C3-C4 ALL and C4, C5 spinous proc frx

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3*	77	Config 2	500	2	-3396	3433	-31	-30.1	-44.5	-8.8	-	0.96	C3-C4 ALL, C4 spinous proc frx, C4 ant sup tear drop frx
4*	88	Config 2	454	-104	-3472	3502	-9.9	-17.2	-39.3	-4.9	-	0.88	C5 inf facet, C6 pedicle/lamina frxs
5	50	0 cm	-74	-	-5010	5011	-	-13.4	-	-2.7	-	1.14	C6 body wedge frx
6	76	5 cm	429	-	-3666	3690	-	-4.5	-	-1.2	-	0.82	C4 burst frx w. C3-C4 pos lig rupture
7	50	0 cm	715	-	-5172	5221	-	-1.8	-	-0.3	1.14	1.13	C3 body ant-sup chip frx
8	48	0 cm	313	-	-3912	3925	-	14.4	-	3.7	0.91	0.88	C3 body vertical frx w. lamina frx
9	59	0 cm	699	-	-	3778	-	15.8	-	4.2	0.87	0.85	C4 / C7

					3713								bodies comp frxs
10	67	5 cm	1960	-	- 4567	4970	-	77.6	-	15.6	1.26	1.23	C4 frx ant body
11	66	0 cm	40	-	- 2901	2902	-	88.7	-	30.6	0.92	0.95	C5 body comp frx
12	54	5 cm	436	-	- 2697	2732	-	97.5	-	35.7	0.90	0.97	C7 body mild comp

*Indicates Test from Toomey et al. (2009). The remainder of tests from Pintar et al. (1995).

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