GEOMETRICAL EFFECTS ON THE MECHANISM OF CERVICAL SPINE INJURY DUE TO HEAD IMPACT

Narayan Yoganandan, Frank A. Pintar
Thomas A. Gennarelli, Rolf H. Eppinger*, Liming M. Voo*

Department of Neurosurgery, Medical College of Wisconsin
and the Department of Veterans Affairs Medical Center

*Department of Transportation, NHTSA
Washington, DC

@University of Northern California
Petaluma, CA

ABSTRACT

Although considerable research has been conducted to reproduce common injuries such as wedge and burst fractures in a laboratory environment, there is a paucity of quantitative data relating the alignment of the cervical spine to the mechanism of injury and associated biomechanical variables. Consequently, this study was conducted to correlate spinal alignment with injury outcomes. Intact human cadaver head-neck complexes were subjected to dynamic loading using an electrohydraulic testing device. The cranium was unconstrained. The inferior end was fixed at the thoracic end. Spinal alignment was defined in terms of initial eccentricity. It was defined as the relationship of the occipital condyles with respect to the first thoracic
vertebra. The specimens were placed on an electrohydraulic testing device. They were impacted once on the superior end at velocities ranging from 2.5 to 8.0 m/s. Mechanisms of injury were identified using radiography and computed tomography images. Based on clinical assessment, injuries were classified as stable or unstable depending on the severity of trauma. In addition, injuries were graded according to the Abbreviated Injury Scale (AIS) rating. Trauma classifications were also based on fracture or non-fracture groups. Analysis of variance procedures were used to determine the influence of spinal geometry on injury outcomes. Of the 30 specimens, 17 were in the AIS ≥ 3 group and 13 were in the AIS < 3 group. Nineteen specimens had unstable injuries and the remaining structures were stable. Injury mechanisms were: three in compression-extension, five in compression-flexion, nine in hyperflexion, and 12 in vertical compression. Among the injured specimens, 19 had bony fractures with or without ligament injuries. Eccentricity significantly influenced the mechanism of injury (p<0.0001). Eccentricity also demonstrated significant differences between the two AIS groups (p<0.005). When the pathology was classified into fracture and non-fracture groups, eccentricity influenced the outcome of trauma (p<0.0001). In contrast, such statistically significant differences were not apparent when the classification of injury was based on stability considerations. Spinal alignment is a strong determinant on the injury biomechanics of the cervical spine due to dynamic compressive loading.

TRAUMATIC INJURIES to the human vertebral column often involve the cervical spine region. These injuries occur secondary to incidents such as motor vehicle crashes, falls, diving, and sports events (Yoganandan et al., 1998). The cervical spine is unique in terms of transmitting the external load from the head to the lower regions of the human torso. It is also unique because of its anatomical placement in the human body with relatively fewer supporting structures (Clark et al., 1998). In addition, the cervical spine supports the cranium with significant mass differences between the two structures. These factors, in association with the functional aspects of the cervical spine, render the structure to be a very important component in the human body. Trauma to this structure, as can be expected, has profound implications to the individual. Medical costs for incomplete paralysis and quadriplegia average more than $750,000 to $940,000 per patient, respectively (Miller et al., 1994). With an estimated annual occurrence of 10,000 spinal cord injuries with quadriplegia in the United States, this results in an annual cost of approximately $7.5 to $9.4 billion using the 1992 year as a basis (Winkelstein & Myers, 1998; Yoganandan et al., 1990).

Serious cervical spine injuries (Abbreviated Injury Scale, AIS ≥ 3) secondary to motor vehicle crashes occur due to the contact of the head with the vehicle structure; ejection may also play a role (AIS, 1990). In other words, these injuries are a by-product of impact loading to the cervical spine. It is therefore imperative to use impact loading as an input variable to determine the mechanisms of injury and associated biomechanical variables. Recognizing the importance and necessity of impact loading, several biomechanical studies have been undertaken by researchers. Studies have
included dynamic loading to segmented portions of the column, intact head-neck complexes including the simulation of torso structures, and intact human cadavers (Nightingale et al., 1997; Yoganandan et al., 1997; Yoganandan et al., 1989; Yoganandan et al., 1986). The importance of spinal alignment on the mechanisms of cervical spine injury has been emphasized in literature (Liu & Dai, 1989; Nusholtz et al., 1981; Pintar et al., 1995; Yoganandan et al., 1998).

It is known that the cervical spine has a normal lordotic curvature. The transmission of the impact load delivered to the head occurs through the occipital condyles. With a preflexion of approximately 15 degrees, cervical vertebrae align in a columnar manner resulting in removal of the lordosis (Sherk et al., 1989; Yoganandan et al., 1998). Researchers have consistently indicated that impact loading to the straightened cervical column via the head produces clinical injuries such as burst and wedge fractures (Liu & Dai, 1989; Torg, 1991). Contact related injuries such as hyperflexion trauma occurs in a different alignment of the cervical spine although the impact loading is still delivered to the intervertebral column through the occipital condyles (Harris & Mirvis, 1996). When the occipital condyles are oriented/aligned forward to the preflexed column, a flexion type loading of the cervical spine is possible. Similarly, when they are aligned posteriorly, extension type loading can be expected (Maiman & Yoganandan, 1991). There is a paucity of quantitative data relating this initial preloading alignment of the occipital condyles of the cervical spinal column to injury type, severity, and mechanisms. Consequently, this study was conducted to determine the biomechanics of spinal injury and correlate the outcomes with the initial alignment variable expressed in terms of orientation of the occipital condyles.

MATERIALS AND METHODS

Unembalmed human cadaver head-neck complexes were used. Specimens were selected through an evaluation of medical records and radiographic examination to eliminate bone disease, spinal disease, or metastasis. The subject was screened for human immunodeficiency virus, and Hepatitis A, B, and C. Standard guidelines and laboratory practices were adopted in the biomechanical study. The demographics of the subjects were obtained. These included the documentation of age, height, weight, and sex. Following procurement and selection, the head-neck complexes were isolated by transecting at the second-third thoracic intervertebral disc space. Radiographs of the specimens were obtained in frontal and lateral projections. Two-dimensional computed tomography images were obtained in the axial and sagittal planes. The head-neck complexes were sealed in double plastic bags and kept frozen at -55 degrees Celsius. Storage of human cadaver material in this manner is routinely used in biomechanical investigations. These procedures do not alter the material characteristics of the bone and soft tissues including the ligament and cartilage. The specimens were stored in a humidity-controlled environment before testing.
The cranium and its contents were intact and unconstrained at the superior end. The inferior end of the preparation was fixed in polymethylmethacrylate (PMMA). The preparation was rigidly attached to the platform of a custom-designed electrohydraulic testing device via a load cell. All specimens had approximately 15 degrees of head flexion to remove the lordosis of the column. The piston of the electrohydraulic testing device was fixed with an aluminum plate covered with padding to serve as the impacting surface. Dynamic loading to the head was delivered with the actuator of the device at rates ranging from 2.5 to 8.0 m/s. All specimens were impacted once. The maximum piston excursions were set between 20 to 100 mm. The alignment orientation of the head-neck complex was defined in terms of the eccentricity parameter. The orientation of the occipital condyles with respect to the center of the first thoracic vertebral body was defined to have zero eccentricity. When the occipital condyles were oriented anterior to the first thoracic vertebral body, the eccentricity was defined to be positive. In contrast, when the occipital condyles were oriented posterior to the first thoracic vertebral body, the alignment was defined to be negative (Figure 1). Table 1 provides a summary of the test matrix. Depending on the initial alignment, the piston of the electrohydraulic testing device always impacted the highest point on the cranium applying contact induced axial load to the occipital condyles via the head. The direction of piston travel was always vertical. The distally transmitted force was documented by the six-axis load cell which was placed underneath the inferior end of the preparation.

Figure 1: Schematic of the experimental test setup. Illustrations on the left, middle, and right show the negative, zero, and positive eccentricities.
Table 1: Test Matrix

<table>
<thead>
<tr>
<th>Number of Specimens</th>
<th>Alignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>Positive eccentricity</td>
</tr>
<tr>
<td>8</td>
<td>Zero eccentricity</td>
</tr>
<tr>
<td>4</td>
<td>Negative eccentricity</td>
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Following impact, the specimens were macroscopically examined and radiographs were obtained. Computed tomography images were obtained in sagittal and axial planes, following which, in some specimens, cryomicrotome sections were taken. The mechanisms of injury to the cervical spine were identified using these images. Vertical compression, hyperflexion, compression-flexion, and compression-extension modalities were identified based on clinical classifications. In addition, injuries were classified as stable or unstable depending on the estimated severity of trauma. For this purpose, the following approach was adopted. All injuries were identified using pre and posttest images that included radiographs and CT scans. Injury identifications were commensurate with clinical assessments. Injuries potentially requiring conservative treatment were classified as stable. In contrast, injuries with spinal canal compromise and/or potential neurologic involvement requiring non-conservative treatment were considered unstable. For example, a simple compression fracture without bone retropulsing into the spinal canal was considered a stable injury. In contrast, vertebral fracture with posterior soft tissue disruptions was considered to be unstable. These injury classifications were done by our neurosurgical clinical faculty. Injuries were also classified as trauma related to bony fracture of the cervical vertebrae and trauma related to non-fracture (pure ligamentous-type). In addition, trauma was graded according to the AIS 1990 version (AIS, 1990).

STATISTICAL ANALYSIS

Detailed statistical procedures were adopted to correlate the alignment factor, i.e., eccentricity obtained during the test, with the biomechanical variables, i.e., various mechanisms of injury, AIS, and stability groups. Factorial analysis of variance (ANOVA) procedures were used to determine the statistical significance of the results. Discrete significant levels (p values) were obtained and reported in the following section.

RESULTS

Thirty head-neck complexes were included in the analysis. The demographics of the subjects are as follows. The mean age, height, and weight were 59 years, 172 cm, and 78 kg, respectively. Eighteen specimens were tested with positive, eight were tested with zero, and four were tested with negative eccentricities (Table 1). More specifically, the input eccentricities ranged from -0.5 to 10.2 cm for all preparations. Based on the mechanisms of injury, there were three specimens in the compression-extension category, five specimens in the compression-flexion category, nine
specimens in the hyperflexion category, and 12 specimens in the vertical compression category. One specimen did not sustain injury. There were 19 specimens with unstable injuries and the remaining cervical spine structures were considered stable. Among the injured specimens, 19 responded with bony fractures of the cervical spine vertebrae with or without associated ligamentous injuries. In contrast, the remaining specimens demonstrated pure ligamentous-type trauma. Seventeen specimens sustained serious cervical spine injuries (AIS ≥ 3), and the remaining 13 specimens sustained less serious injuries. Eccentricity significantly influenced the mechanism of injury (p<0.0001). The mean eccentricities for compression-extension, compression-flexion, hyperflexion, and vertical compression were -0.5, 2.3, 5.3, and 0.1 cm, respectively. Statistically significant differences were found between compression-extension and compression-flexion (p<0.05), compression-extension and hyperflexion (p<0.025), compression-extension and vertical compression (p<0.025), compression-flexion and vertical compression (p<0.001), and vertical compression and hyperflexion (p<0.0001) groups. The mean eccentricities were 4.1 cm (±0.11) in the AIS < 3 group, and 0.85 cm (±0.36) in the more severe group (AIS ≥ 3). Eccentricity also demonstrated significant differences between the two AIS groups (p<0.005). Likewise, eccentricity influenced the outcome of trauma when pathology was classified into fracture and non-fracture (p<0.0001) groups. The mean eccentricities in the fracture and non-fracture groups were 0.6 cm (±0.3) and 5.2 cm (±1.0), respectively. In contrast, such statistically significant differences were not apparent when the classification of injury was based on stability considerations.

DISCUSSION

Data obtained for this study have been collected over several years of head-neck biomechanics research. The testing incorporated a consistent experimental protocol. Initial results with regard to the strength parameters have been previously presented; for example, hyperflexion injury mechanism characteristics were published at the 1998 IRCOBI Conference (Pintar et al., 1998). However, detailed analysis regarding the effect of spinal alignment-geometry on cervical spine biomechanics with this large sample size encompassing compression-flexion, compression-extension, vertical compression, and hyperflexion injuries has never been reported. This was the aim of the present investigation.

It is important to simulate appropriate boundary and initial conditions in order to determine the impact characteristics and correlate the outcomes with the biomechanical variables. All human cadaver head-neck complexes were fixed at the upper thoracic level using polymethylmethacrylate. This served as the boundary condition at the distal end of the preparation. In contrast, the proximal end of the preparation was unconstrained and the dynamic load was applied to the intact head. With regard to the initial conditions, the cervical spinal column was prepared and the initial alignment was defined with respect to the position of the occipital condyles. This is because, as stated in the Introduction, occipital condyles act as the medium of transfer of the externally
applied load from the head to the cervical spine. This bony articulation region of the head-neck complex is always the principal load path to the vertebral column located caudally, and is independent of the regional location of the external impact input. Consequently, the alignment parameter was defined using the classical mechanics-based eccentricity variable. The eccentricity was measured as the sagittal position of the occipital condyles with respect to the caudal end of the preparation. The above procedure served to quantitatively define the initial condition and it facilitated an analysis of the alignment parameter with biomechanical outcomes. The resulting injuries were documented by procedures including conventional x-rays and computed tomography. This methodology facilitated the identification of cervical spine trauma based on accepted mechanisms of injury and treatment and furthermore, permitted an evaluation of this categorical variable with the geometrical alignment. In addition, the assessed trauma was graded into several groups. These included AIS < 3 versus AIS ≥ 3 classifications, fracture versus non-fracture, and stable versus unstable categories. All these variables were processed through detailed statistical analysis to determine the effects of geometry on cervical spine injury biomechanics.

Results of the present study indicated that the initial alignment of the applied load vector is a statistically significant factor that influenced injury severity, fracture classification, and mechanisms of injury. Several studies have been published on impact loading of the human cervical spine (Maiman & Yoganandan, 1991; McElhaney et al., 1983; Nightingale et al., 1997; Nusholtz et al., 1981; Pintar et al., 1998; Winkelstein & Myers, 1998; Yoganandan et al., 1998; Yoganandan et al., 1986; Yoganandan et al., 1990). For example, McElhaney et al., tested the cervical column from the base of skull to C6-T2 at rates ranging from 0.13 to 64 cm/sec (McElhaney et al., 1983). Injuries included compression, burst, and Jefferson (C1) fractures. However, the type of injury or injury mechanism was not statistically correlated with any input variable. In addition, the spinal alignment was not quantified. Similarly, in another study, Maiman et al., tested isolated, intact cervical (base of skull to T3) and intact head-neck complexes under dynamic rates. Compression-flexion, axial, and flexion-related injuries were produced. However, similar to the above-cited study by McElhaney et al., no statistical analyses of the data were done. Although the spinal alignment was controlled, no objective parameters were measured to correlate the experimental outcome with geometry. Yoganandan et al., dropped 16 whole-body intact human cadavers vertically (from 0.9 to 1.5 m) so that the impact load was delivered to the head-neck via contact (Yoganandan et al., 1986). Head restrained and head unrestrained conditions were included in the study. Although vertebral column injuries were produced, initial spinal alignment was not quantified. Vertical drops of isolated human head ligamentous cervical spine columns attached to a torso mass of 35 kg produced cervical injuries (Nightingale et al., 1997). Natural cervical spinal column lordosis was maintained in this previous study. However, initial spinal alignment was not quantified. In another series of experiments, Nusholtz and co-workers indicated that the line (axis) of the impact force and initial orientation of the structure, i.e., geometrical effects, contributes to cervical spine trauma (Nusholtz et al., 1981).
Because of the above findings, the present study was designed to examine the effect of spinal alignment on cervical spine injury biomechanics. Furthermore, because of the large sample size used, it was possible to evaluate experimental data in terms of alignment to statistical outcomes. These are the strengths of this investigation (limitations discussed later). Despite these strengths, as indicated above, detailed comparisons with other impact studies are not possible, primarily due to a lack of alignment control and/or quantification. The type of injuries produced in this present study correlate well with clinical literature (Clark et al., 1998; Harris & Mirvis, 1996; Sherk et al., 1989; Yoganandan et al., 1998); this provides a first level of confidence with the experimental model. Another agreement with the present research is that a previous study (although did not report the alignment on a case by case basis) indicated that moving the base of the specimen (base of skull to C6-T2 preparation) in the anterior or posterior direction results in varying mechanisms of injury (McElhaney et al., 1983). Enhanced anterior alignment factor (eccentricity) in this study changed the spectrum of the mechanism of injury from a compression mode to a hyperflexion mode.

Results from this investigation did not reveal statistically significant differences between stable and unstable patterns of injury with regard to the spinal alignment parameter. A likely explanation for this stems from the definition of injury itself. Instability is defined in clinical literature in many ways. This includes two- and three-column concepts, and the potential for neurologic involvement (Clark et al., 1998; Denis, 1983; Denis, 1984; Holdsworth, 1963; Maiman & Yoganandan, 1991). For example, in the two-column concept, the spine is divided into anterior and posterior segments (Holdsworth, 1963). The anterior column consists of the anterior longitudinal ligament, vertebral body, disc, and posterior longitudinal ligament. The posterior column consists of the posterior elements. In the three-column concept however, the spine is divided into three regions (Denis, 1983; Denis, 1984). Together, the anterior and middle columns of the three-column concept are the same as the anterior column of the two-column concept. The posterior column remains the same in both the two- and three-column concepts. Given this somewhat subjective premise, it may be reasonable to anticipate, a priori, the observed insignificance for the stability parameter in the statistical analysis of data. It should be noted however, that in the present study, the assessment of instability was made by our clinical faculty and it was based on pre and posttest films (radiographs and computed tomography sections); a similar procedure is commonly adopted in a clinical setting. These results indicate that alignment may not be the most efficacious variable to influence the decision with regard to clinical instability of the cervical spine. As indicated earlier, other factors such as neurologic function have influence on the decision.

The present dynamic model used human cadaver materials. This excludes the role of active spinal musculature. Consequently, any restraining or stabilizing action by the head-neck musculature during the loading process is not included in the analysis. The experimental model accounted for the passive musculature by suitably aligning the
head-neck complex. It has been reported that the effect of cervical musculature is minimal when the impact loading is compressive in nature (Nightingale et al., 1997). Therefore, from this viewpoint, the results from this study are realistic. Clinically pertinent injuries such as burst and wedge fractures primarily concentrated at one motion segment level reproduced in this study, provide an additional rationale for using the intact cadaver head-neck experimental model.

In summary, this study investigated the effects of spinal alignment on the biomechanics of the cervical spine. The attitude of occipital condyles with respect to the inferior end of the head-neck complex was characterized using the spinal alignment factor. Thirty human cadaver head-neck complexes were used in the study. Dynamic loading was applied to the cranium using an electrohydraulic testing device. The resulting pathology was assessed using pre and posttest radiography and computed tomography scans. Injuries were graded according to AIS rating. They were classified into stable and unstable groups. In addition, the pathology was classified into fracture and non-fracture types. The resulting mechanisms of injury were divided into compression-flexion, compression-extension, vertical compression, and hyperflexion trauma. Results indicated that spinal alignment is a statistically significant factor that influences the mechanism of injury, AIS rating, and fracture/non-fracture classifications. However, this geometrical condition did not influence the spinal stability classification. These studies underscore the importance of obtaining initial geometrical characteristics to understand cervical spine biomechanics.

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REFERENCES


