Preinjury cervical alignment affecting spinal trauma

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Object. The authors tested the hypothesis that initial alignment of the head–neck complex affects cervical spine injury mechanism, trauma rating, injury classification based on stability, and fracture pattern.

Methods. Thirty intact human cadaveric head–neck complexes were prepared by fixing the thoracic end in polymethylmethacrylate. The cranium was unconstrained. The initial spinal alignment was described in terms of eccentricity, defined as the anteroposterior position of the occipital condyles with respect to the T-1 vertebral body. The specimens were subjected to impact loading delivered using an electrohydraulic testing device. Outcomes after injury were identified using radiography and computerized tomography. The mechanisms of injury were classified according to fracture pattern into compression–extension, compression–flexion, hyperflexion, and vertical compression. Trauma was graded according to the Abbreviated Injury Scale rating system. Based on clinical assessment, injuries were classified as stable or unstable. Injuries were also classified into bone fracture or nonfracture groups. Analysis of variance tests were used to determine the influence of eccentricity on spinal injury outcomes. Eccentricity significantly influenced the mechanism of injury (p < 0.0001), trauma rating (p < 0.005), and fracture (p < 0.0001) classification. Statistically significant differences, however, were not apparent when the classification of injury was based on stability considerations.

Conclusions. Spinal alignment is a strong determinant of the biomechanics of impact-induced cervical spine injury.

KEY WORDS • cervical spine • alignment • injury • impact

The characterization of the mechanics of injury in spinal trauma has been based on clinical, epidemiological, and laboratory studies, the latter prominently including cadaveric studies. The authors of clinical studies have reported the type and extent of these injuries and the treatment sequelae. The authors of epidemiological studies, on the other hand, have analyzed information on the incidence and source of injury by using databases such as the National Automotive Sampling System. In laboratory studies investigators have examined, to a different level of detail, the biomechanical parameters responsible for the traumatic injuries of the human cervical spine. These investigations, particularly those in human cadavers, significantly augment the outcomes from epidemiological data in several ways. For example, they can focus on replicating commonly encountered serious cervical spine injuries. They can also concentrate on critical factors or areas responsible for injury causation (that is, head impact–induced neck trauma) based on data obtained from epidemiological research.

The authors of clinical studies have attempted to underscore the importance of spinal alignment/orientation on the production of the cervical spine injury and associated biomechanical variables. For example, Portnoy, et al., classified cervical spine injuries based on x-ray films and inferred the effects of initial position and location of the external force to cause injury. The alignment of the cervical spinal column at the time of impact, however, could not be quantified because of the retrospective nature of the study. In football-related injuries, Torg, et al., studied photographic film of the event and other information; they indicated that vertebral trauma occurs secondary to impact loading on the head when the cervical column is aligned in a straightened position. Liu and Dai described this alignment by using a theoretical beam-column model in terms of the stiffest axis. Similar to the previous authors, no specific quantification of cervical column alignment at the time of head impact was recorded in either study, although this is of significant importance in fracture production and prediction.

Earlier, Culver, et al., demonstrated that head–neck position affects injury based on head impact tests in which 11 unembalmed cadaveric human specimens were used. In a series in which 12 intact human cadaveric heads were subjected to pendulum impact, Nusholtz, et al., suggested that there exists a relationship between initial head–neck position and injury, although no actual measurements of the position were made. Alem, et al., examined the effects of cervical lordosis (curvature) on human cadaveric neck injuries secondary to impact at the crown of the head. Different levels of tolerance were reported for prefixed and lordotic curvature–maintained spinal col-

Abbreviations used in this paper: AIS = Abbreviated Injury Scale; cAIS = categorical AIS; CT = computerized tomography; PMMA = polymethylmethacrylate; VB = vertebral body.
unms. The spinal alignment was not quantified and correlated with cervical injuries.

We have reported that the mechanisms of injuries are different between prefixed and preextended cadaveric spinal columns, although the preextension and -flexion data were not amenable to further analyses. Subsequently, we subject-ed 15 intact human cadaveric specimens to drop-weight injury and found cervical spine compression injuries to be more common in specimens with restrained than those with unrestrained spines. The effects of external restraint, which may have altered the orientation of the head–neck complex, were not quantified. Subsequent studies in which investigators evaluated inverted human cadaveric head–ligamentous cervical column–simulated torso drops, a mechanism classification was produced based on the eccentricity of the resulting force; the eccentricity defining the location of this force was not quantified. These authors have attempted to duplicate real-world traumatic injury caused by head impact. In addition, they have provided considerable evidence that the position/alignment of the head–neck complex influences the consequent injuries and their mechanisms. In none of these investigations, however, was the prealignment quantified. The present study was conducted to quantify the effects of alignment of the head–neck complex on cervical spine injuries. Because impact forces applied to the head during trauma are transmitted to the neck through the occipital condyles, their position can be used to advance our hypotheses. Specifically, the eccentricity of the cervical column measured as the anteroposterior position of the condyles with respect to the T-1 significantly influences the following injury outcomes: 1) types of injuries and injury mechanisms produced due to head impact; 2) AIS scores of cervical spine trauma; 3) differentiates between stable and unstable injuries of the cervical spine; and 4) differentiates between osseous and ligamentous trauma of the cervical spine.

Materials and Methods

Unembalmed human cadavers were selected by evaluating medical records and radiographic data. The mean age, height, and weight of the 30 specimens were 59 years, 172 cm, and 78 kg, respectively. There were 18 male (mean age 59 years, mean height 176 cm, and mean weight 80 kg) and 12 female specimens (mean age 60 years, mean height 165 cm, and mean weight 75 kg). The subjects were free of bone disease, spinal disease, or metastasis. They were screened for human immunodeficiency virus, and viral hepatitis Types A, B, and C. The head–neck complexes were isolated at the T2–3 intervertebral disc space. Radiographs were obtained in anterior and lateral projections. In addition, two-dimensional CT scans were obtained in the axial and sagittal planes. The head–neck complexes were sealed in double plastic bags and kept frozen at -55°C. Storage of human cadaveric materials in this manner does not alter the biomechanical characteristics of the bone and soft tissues including ligament and cartilage.

The inferior end of the specimen was fixed in PMMA, and the head was left unconstrained at the superior end. The specimen was attached to a six-axis load cell (Denton, Inc., Rochester Hills, MI) and placed on the platform of a custom-designed electrohydraulic testing device. Approximately 15° of head flexion was applied to remove lordosis (Fig. 1). The alignment of the head–neck complex was defined in terms of the anteroposterior position of the condyles with respect to the distal end of the preparation. Three types of eccentricities were defined. The position of the occipital condyles with respect to the center of the T-1 VB was defined as having zero eccentricity. The eccentricity was considered positive when the occipital condyles were positioned anterior to the T-1 VB.

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In contrast, the eccentricity was considered negative when the occipital condyles were positioned posterior to the T-1 VB (Fig. 1). Specimens were intentionally aligned at varying eccentricities. Because the majority of clinical injuries are compression–flexion related, a preference was given to positive eccentricity.

The piston of the electrohydraulic testing device impacted the most convex region of the cranium to apply a contact-induced axial load to the head. This was accomplished as follows. A padded aluminum plate was attached to the piston of the testing device to serve as the impacting surface. Impact loading was delivered by the piston to the aluminum plate, which then transmitted the force to the head. All specimens underwent a single impact force delivered using a direct vertical piston motion. The specimens were macroscopically and radiographically examined after impact loading. Computerized tomography scans were obtained in sagittal and axial planes. Based on imaging results, the mechanisms of injury were classified as vertical compression, hyperflexion, compression–flexion, and compression–extension. Injuries were graded according to the AIS. Injuries graded as an AIS score of less than 3 were considered to be in the categorical AIS 0 (cAIS 0) group. Higher severity injuries (those with an AIS score of ≥ 3) were considered to be in the categorical AIS 1 (cAIS 1) group. In addition, injuries were categorized as stable or unstable depending on the estimated severity of trauma as well as results of clinical assessments. Injuries likely not to require surgery were classified as stable; in contrast, those with spinal canal compromise and/or potential neurological involvement likely requiring surgery or rigid immobilization (such as a halo vest) were considered unstable. For example, a case of simple compression fracture in which no bone retrtoposes into the spinal canal and the posterior elements are intact was considered stable; in contrast, vertebral fracture with posterior ligament disruptions was considered unstable. We also divided the injuries into bone fracture and nonfracture (that is, ligament and/or disc injury).

Detailed statistical procedures were used to correlate eccentricity with the biomechanical variables (that is, mechanisms of injury, trauma rating (AIS), stability, and fracture classifications). Means of the eccentricity parameters were computed for all four selected groups of biomechanical variables. Analysis of variance was used to determine the statistical significance of the results. A factor analysis for each variable with respect to eccentricity was completed to determine interaction effects. The Fisher protected least significant difference test was used to obtain significant interactions between any two variables with a given factor.

Results

Thirty intact human cadaveric head–neck complex specimens were tested. The input eccentricities ranged from -0.5 to 10.2 cm for all specimens. More specifically, 18 specimens were tested with positive, eight were tested with zero, and four were tested with negative eccentricities.

Based on our criteria, three specimens suffered compression–extension injuries, five specimens compression–flexion, nine specimens hyperflexion, and 12 specimens vertical compression injuries. One specimen sustained no injury. Analysis of the data was conducted using 29 specimens. Seventeen specimens sustained serious cervical spine trauma (cAIS score of 1). The remaining specimens sustained less serious trauma (cAIS score of 0). There were 19 specimens with unstable injuries, and the other cervical spine structures were considered stable. Among those with injuries, 19 specimens sustained vertebral fractures with or without associated ligamentous injury. In contrast, the other specimens demonstrated ligamentous-type trauma (without bone fracture).

The extent of the eccentricity significantly influenced the mechanism of injury (p < 0.0001, analysis of variance) (Table 1). The mean eccentricities for compression–extension, compression–flexion, hyperflexion, and vertical com-
expression were \(-0.5, 2.3, 5.3, \) and 0.1 cm, respectively (Fig. 2). Statistical differences were found between vertical compression and hyperflexion \((p < 0.0001)\); compression-extension and hyperflexion \((p = 0.0002)\); compression-extension and compression-flexion \((p = 0.069)\); compression-flexion and vertical compression \((p = 0.0537)\); compression-flexion and hyperflexion \((p = 0.0121)\); and compression-extension and vertical compression groups \((p = 0.6356)\). The mean eccentricities were 4.1 and 0.85 cm for the cAIS 0 and cAIS 1 groups (Fig. 3 left). The difference in the eccentricity parameter was statistically significant \((p = 0.0041)\). In contrast, such statistically significant differences \((p = 0.4)\) were not apparent when the injury was classified into stable and unstable groups (Fig. 3 center). The eccentricity, however, significantly \((p < 0.0001)\) influenced the outcome of trauma when the lesion was classified into fracture and nonfracture groups. The mean eccentricities in the fracture and nonfracture groups were 0.6 and 5.2 cm, respectively (Fig. 3 right). Examples of some of these injuries and injury classifications are shown (Fig. 4).

**Discussion**

This study was based on the working hypothesis that alignment affects cervical spine injury. Because external forces applied to the head are transmitted to the cervical spine through the occipital condyles, this structure was used to describe the alignment of the column. In particular, the alignment of the head–neck complex was described in terms of the eccentricity relating the anteroposterior (sagittal) position of the occipital condyles to the T-1 VB. Using this parameter, injury outcomes were statistically analyzed to test the specific hypothesis stated earlier. Clinically pertinent injuries such as burst and wedge fractures reproduced in this study provided an additional rationale for using the intact cadaveric head–neck experimental model.3,27

We have previously used this experimental model to produce clinically relevant injuries as well as the injury classification scheme. The experimental model incorporated appropriate boundary and initial conditions. Unconstrained boundary conditions were used at the proximal end for the application of the load. The inferior end was constrained in all degrees of freedom to allow measurement of the forces and moments sustained by the specimen. This methodology as well as the results obtained in similar studies are reported elsewhere.15,16 This methodology served to define the initial condition quantitatively and facilitated an analysis of spinal alignment with biomechanical outcomes rather than relying solely on qualitative measures, such as radiography.

The aforementioned injuries were documented using x-ray films and CT scans. These modalities allowed identification of cervical spine trauma based on accepted mechanisms of injury and treatment, whereas biomechanical measures, including the eccentricity, allowed quantification of relevant outcomes of the induced trauma.11,22,26

In addition to the injury classifications related to mechanisms, fractures, and stability, another variable, the AIS score, was used in this study to evaluate the effects of preinjury alignment. In the AIS injury severity is scored using a numerical code (a value of 0 representing no injury and 3 representing serious injury). This variable, which was developed by physicians for the Association for the Advancement of Automotive Medicine, is particularly applicable to the present study because a significant majority of impact-induced cervical spine injuries are vehicle related. The AIS is a commonly used standard instrument for analyzing trauma and measuring outcomes. For example, an external injury such as a scalp laceration indicating the location of an impact load is statistically more likely to be responsible for cervical spine injury of 3 on the AIS rather than a score of 1 on the AIS. Documentation of these data may assist in correlating cases of “internal” cervical trauma and external signs of contact with the region within a vehicle responsible for causing the injury. Furthermore, the AIS score has been used by the United States Department of Transportation in its databases (National Automotive Sampling System and Fatal-
ity Analysis and Reporting System) since 1985; thus, it is incorporated in most epidemiological and economic analyses, and the correlation of our alignment parameter with this widely used variable will foster further research in the area of injury assessment. Therefore, it was deemed important to include the AIS in the present study. This was accomplished by classifying the cervical spine trauma into less serious (cAIS 0) and serious trauma (cAIS 1), bone fracture or nonfracture (ligamentous injury), and stable and unstable categories. All these variables were analyzed statistically to test the hypotheses.

There are limitations to our methods, however. For example, cadaveric head–neck complexes cannot include active spinal musculature. The line of action of spinal musculature is not all coincident and is dependent on the loading mode. Therefore, any muscle-related restraining or stabilizing action by those connecting the skull and cervical spine during the impact loading process is not included in the analysis. This has the potential to affect the results and makes direct correlation with in vivo conditions difficult. Although this appears to be a limitation, cervical musculature is reported to have minimal effects, particularly when the dynamic loading is compressive in nature and because of the short duration (a few milliseconds) in which impact-induced injuries occur to the cervical spine. The results obtained in this study are, therefore, realistic. It should, however, be emphasized that under loading situations in which the effects of musculature are critical, the results of this study should be interpreted with caution.

Another potential limitation is that we investigated only axial impact–induced injuries by using isolated head–neck complexes that were PMMA fixed at the inferior end. In vivo, the distal end of the neck is not completely constrained because the thoracic spine articulates with the lower cervical spine in the cephalad direction and continues with the lumbar spine and rib cage in the caudal direction. The additional constraint of the PMMA, however, may not be important because the ribs (particularly at the upper thoracic levels) add considerable rigidity to the human torso and reduce spinal motion. In fact, in their study of inverted cadaveric head–cervical spine impact, Nightingale, et al., simulated the torso by attaching a 16-kg rigid mass to the base of the column. McElhaney, et al., also fixed the cervical spine specimens at the inferior end, a boundary condition similar to that used in the present model.

Impact loading applied to the cervical spinal column is studied by many researchers. As already indica-

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<tr>
<th>Variables</th>
<th>Eccentricity (cm)</th>
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<tr>
<td>compression–extension vs. compression-flexion</td>
<td>−0.5/2.3*</td>
</tr>
<tr>
<td>compression–extension vs. hyperflexion</td>
<td>−0.5/5.3*</td>
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<tr>
<td>compression–extension vs. vertical compression</td>
<td>−0.5/0.1*</td>
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<tr>
<td>compression–flexion vs. hyperflexion</td>
<td>2.3/5.3</td>
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<tr>
<td>compression–flexion vs. vertical compression</td>
<td>2.3/0.1*</td>
</tr>
<tr>
<td>hyperflexion vs. vertical compression</td>
<td>5.3/0.1*</td>
</tr>
<tr>
<td>injury severity—cAIS 0 vs. injury severity—cAIS 1</td>
<td>4.1/0.85*</td>
</tr>
<tr>
<td>stable vs. unstable</td>
<td>1.6/2.6</td>
</tr>
<tr>
<td>fracture (osseous trauma) vs. nonfracture (ligamentous trauma)</td>
<td>0.6/5.2*</td>
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* Statistically significantly intergroup difference ($p < 0.05$).
ed, these researchers have attempted to reproduce clinical injuries of the cervical column. In addition, they have suggested that neck position affects the injury-related outcome.\(^4\,^1^4\) To the best of our knowledge, however, there are no available published studies in which the authors quantify the effects of initial spinal alignment on injury-related outcomes. Furthermore, because of the large sample size used, it was possible to analyze the results statistically. These are the strengths of this investigation.

The type of injuries produced in this present study correlate well with those reported in the clinical literature;\(^7\,^1^8\) this provides a first level of confidence with the experimental model. Another factor in agreement with present findings is that the authors of a previous study (although not reporting on alignment) 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.\(^1^2\) Enhanced anterior eccentricity in this study (Fig. 4) changed the spectrum of the mechanism of injury from a vertical compression mode to a hyperflexion mode.

The eccentricity of the applied load vector was found to be a statistically significant variable that influenced the mechanisms of injury, severity of injury, and fracture clas-
sification. It did not, however, differentiate between stability and instability, using traditional clinical definitions of two column failure or canal compression.5,6,8,22 The clinical emphasis of these definitions may account for the observed statistical insignificance for the stability/instability parameter. It should be noted that in the present study the assessment of instability was based on pre- and post-test x-ray films; a similar procedure is commonly adopted in a clinical setting. Therefore, the assessment of stability/instability is realistic. Analysis of our results, however, indicates that an estimation of the initial spinal alignment may not be the most efficacious variable to influence the decision with regard to clinical instability of the cervical spine. Thus, the hypothesis with regard to the effects of spinal alignment (as defined by eccentricity) on stability/instability was not proven in this study, which may reflect the imprecision of how instability is defined clinically.

The results of our studies, among the first to quantify the effects of initial spinal alignment on fractures produced by impact, clearly indicate the role of eccentricity in affecting mechanism of injury, trauma rating, and fracture type. The large number of specimens used allows statistical analysis of the data, often unusual in biomechanical research. In the meantime, the results of this study have value in injury prevention and kinematics as well as assessing effects of directional loads on the traumatized spine.

References


Manuscript received December 6, 2000. Accepted in final form February 19, 2002. This study was supported in part by Department of Transportation National Highway Traffic Safety Administration Grant No. DTHJ22-93-Y-17028 and the Department of Veterans Affairs Medical Research.

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