7

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Alignment Affects Cervical Spine Injury

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ABSTRACT

This study tested the hypothesis that the initial alignment of the head-neck complex affects the injury mechanism, trauma rating, injury classification based on stability, and fracture pathology. Intact human cadaver head-neck complexes were prepared by fixing the thoracic end. The cranium was unconstrained. Initial spinal alignment was described in terms of eccentricity. It was defined as the antero-posterior position of the occipital condyles with respect to the first thoracic vertebra. The specimens were subjected to impact loading using an electrohydraulic testing device. Injury outcomes were identified using radiography and computed tomography. The mechanisms of injury were classified according to pathology into compression-extension, compression-flexion, hyperflexion, and vertical compression. Trauma was graded according to the Abbreviated Injury Scale rating. Based on clinical assessment, injuries were classified as stable or unstable depending on the severity of trauma. Injuries were also classified into bony fracture or non-fracture groups. Analysis of variance procedures were used to determine the influence of eccentricity on injury outcomes in 30 specimens. Eccentricity significantly influenced the mechanism of injury ($p<0.0001$), trauma rating ($p<0.005$), and fracture ($p<0.0001$) classification. In contrast, statistically significant differences were not apparent when the classification of injury was based on stability considerations. Spinal alignment is a strong determinant of the biomechanics of impact-induced cervical spine injury.

INTRODUCTION

Clinical, epidemiological, and laboratory studies are used as models to understand the biomechanical characteristics of the human cervical spine. Traumatic injuries of the head-neck complex occur in motor vehicle crashes, falls, diving, and sporting events (Torg, 1991; Yoganandan et al., 1998). Clinical studies have reported the type and extent of these injuries, and the treatment sequelae (Clark et al. , 1998; White et al., 1990). Epidemiological studies, on the other hand, have analyzed information on the incidence and source of injury using databases such as the National Automotive Sampling System (NASS) (Yoganandan, et al., 1998). In contrast, laboratory investigations have examined, to a different level of detail, the biomechanical parameters responsible for the traumatic injuries of the human cervical spine (Winkelsteinl, 1998; Yoganandan, 1990). These investigations, particularly human cadaver studies, can combine the outcomes from clinical and epidemiological data in several ways. For example, they can focus on replicating commonly encountered serious cervical spine injuries (e.g., burst fracture) in a vehicular environment based on data obtained from clinical research. They can also concentrate on critical factors or areas responsible for injury causation (e.g., head impact-induced neck trauma) based on data ob.

Both clinical and laboratory-driven biomechanical studies have underscored the importance of spinal alignment/orientation on the production of the cervical spine injury and the associated biomechanical variables. For example, Portnoy et al. classified cervical spine injuries from x-rays, and inferred the effects of initial position and location of the external force to cause injury (Portnoy, 1972). However, the alignment of the cervical spinal column at the time of impact could not be quantified because of the retrospective nature of the study. In football-related injuries, using photographic film of the event and other information, Torg et al. indicated that vertebral trauma occurs secondary to impact loading on the head when the cervical column is aligned in a straightened position (Torg, 1987; Torg, 1990). Liu and Dai described this alignment using a theoretical beam-column model in terms of the stiffest axis (Liu, 1989). As before, no specific quantification of the alignment of the cervical column at the time of head impact was made in either study.

Culver et al. (1978), based on head impact tests using 11 unembalmed human cadavers, believed that head-neck position affects injury (Culver, 1978). From a series of pendulum impacts to the head of 12 intact human cadavers, Nusholtz et al. (1981) suggested that there exists a relationship between initial head-neck position and injury although no actual measurements were made of the position (Nusholtz, 1981). Alem et al. examined the effects of cervical lordosis (curvature) on human cadaver neck injuries secondary to impact at the crown of the head (Alem, 1984). Different tolerances were reported for pre-flexed and lordotic curvature maintained spinal columns. The spinal alignment was not quantified and correlated with cervical injuries. Based on human cadaver experiments, Maiman et al. (1991) reported that the mechanisms of injuries are different between pre-flexed and pre-extended spinal columns (Maiman, 1983). However, the pre-extension or pre-flexion data were not amenable for further analyses. Yoganandan et al. (1990) dropped 15 intact human cadavers and found cervical spine compression injuries to be more common in restrained than unrestrained cases (Yoganandan, 1986). The effects of external restraint that may have altered the orientation of the head-neck complex were not quantified. Although previous studies using inverted human cadaver head-ligamentous cervical column-simulated torso drops produced a mechanistic classification based on the eccentricity of the resulting force, the eccentricity defining the location of this force was not quantified (Winkelstein, 1997 & 1998).

These studies have attempted to duplicate real-world trauma due to head impact. In addition, they have implied that the position/alignment of the head-neck influences the injuries produced and their mechanisms. However, in none of these investigations, was the position of the neck defined in order to quantify its effects on cervical spine injury. This study was conducted with a specific focus on the alignment of the head-neck complex. One way to define and quantify alignment is to use the anatomy of the structure under consideration. Since the impact force applied to the head in a traumatic environment is transmitted to the neck through the medium of the occipital condyles, the position of this component is used to advance the following hypotheses. Specifically, the eccentricity of the cervical column measured as the antero-posterior position of the condyles with respect to the first thoracic vertebra, significantly influences the following injury outcomes.

1) Types of injuries and injury mechanisms produced due to head impact;
2) Abbreviated injury classification (AIS) of cervical spine trauma;
3) Differentiates between stable and unstable injuries of the cervical spine; and
4) Differentiates between bony and ligamentous trauma of the cervical spine.

MATERIALS AND METHODS

Unembalmed human cadavers were selected through an evaluation of medical records and radiographic examinations. The subjects were free from bone disease, spinal disease, or metastasis. They were screened for human immunodeficiency virus, and Hepatitis A, B, and C. The head-neck complexes were isolated at the T2-T3 disc space. Radiographs were obtained in frontal and lateral projections. In addition, two-dimensional computed tomography (CT) 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 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 polymethylmethacrylate (PMMA) and the head was unconstrained at the superior end. The specimen was attached to a six-axis load cell and placed on the platform of a custom-designed electrohydraulic testing device. Approximately 15 degrees of head flexion was applied to remove lordosis. The alignment of the head-neck complex was described using the eccentricity parameter. The eccentricity of the structure was defined in terms of the antero-posterior 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 first thoracic vertebral body was defined to have zero eccentricity. The eccentricity was considered positive when the occipital condyles were positioned anterior to the first thoracic vertebral body. In contrast, the eccentricity was considered negative when the occipital condyles were positioned posterior to the first thoracic vertebral body (FIG. 1).

The piston of the electrohydraulic testing device impacted the most convex region on 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. The piston to the aluminum plate, which transmitted the force to the head, delivered impact loading. All specimens were impacted once. The direction of piston travel was vertical. The specimens were macroscopically examined and radiographs were obtained after impact loading. Computed tomography images were obtained in sagittal and axial planes. The following identifications were made to test the proposed hypotheses. Using x-ray and CT images, the mechanisms of injury to the cervical spine were classified into vertical compression, hyperflexion, compression-flexion, and compression-extension categories. Injuries were graded according to the Abbreviated Injury Scale (AIS, 1990). Injuries belonging to the $AIS < 3$ rating were considered to be in the categorical AIS 0 (CAT AIS 0) group. Injuries with higher severity ($AIS \geq 3$) were considered to be in the categorical AIS 1 (CAT AIS 1) group.

In addition, injuries were categorized as stable or unstable depending on the estimated severity of trauma. All 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 retropulsed into the spinal canal was considered a stable injury. In contrast, vertebral fracture with posterior soft tissue disruptions was considered to be unstable. Injuries were also classified as trauma related to bony fracture of the cervical vertebrae and trauma related to non-fracture (pure ligamentous type). Detailed statistical procedures were used to correlate eccentricity with biomechanical variables, i.e., mechanisms of injury, trauma rating (AIS), stability, and fracture classifications. Analysis of variance (ANOVA) procedures were used to determine the statistical significance of the results. A p-value of less than 0.05 was considered to be significant.

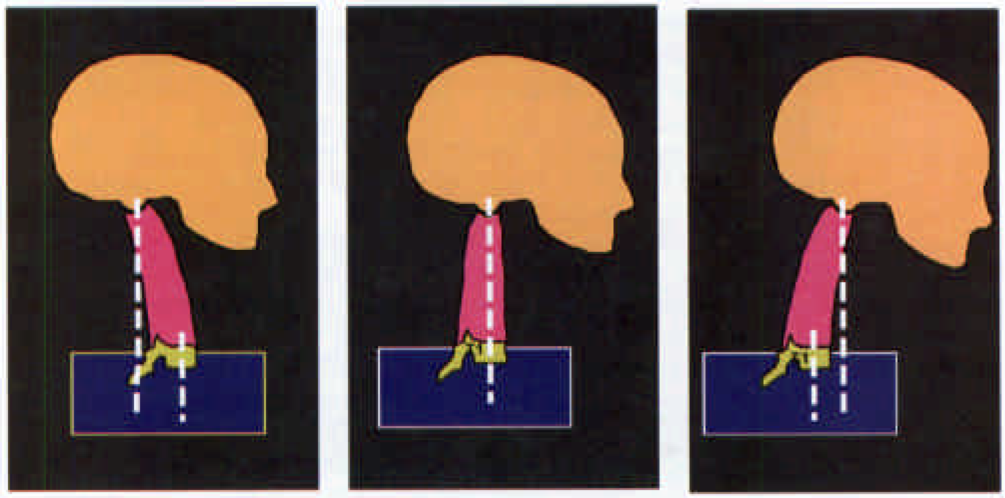

FIG. 1. Schematic of the experimental test setup. Illustrations on the left, middle, and right show the positive, negative, and zero eccentricities.

RESULTS

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. Seventeen specimens sustained serious cervical spine trauma (CAT AIS 1). Eccentricity significantly influenced the mechanism of injury (ANOVA result, $p<0.0001$). 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 ($p<0.05$) differences were found between compression-extension and compression-flexion, compression-extension and hyperflexion, compression-extension and vertical compression, compression-flexion and vertical compression, and vertical compression and hyperflexion groups. The mean eccentricities were 4.1 and 0.85 cm for the CAT AIS 0 and CAT AIS 1 groups. The difference in the eccentricity parameter was statistically significant. In contrast, such statistically significant differences were not apparent when the injury was classified into stable and unstable groups. However, the eccentricity significantly influenced the outcome of trauma when pathology was classified into fracture and non-fracture groups. The mean eccentricities in the fracture and non-fracture groups were 0.6 cm and 5.2 cm.

DISCUSSION

The study was based on the working hypothesis that alignment affects cervical spine injury. Because the external force applied to the head is transmitted to the cervical spine through the occipital condyles, this anatomical component was used to describe the alignment of the structure. In particular, the alignment of the head-neck complex was described in terms of an eccentricity variable relating the antero-posterior position of the occipital condyles with respect to the first thoracic vertebral body. Using this parameter, injury outcomes were statistically analyzed to test the hypothesis. A consistent experimental model was used in the study in order to produce clinical injuries. Similarly, traditional imaging modalities were used to classify cervical spine injuries following impact load application. The experimental model incorporated appropriate boundary and initial conditions. Unconstrained boundary conditions were used at the superior end for the application of the load. The inferior end was constrained in all degrees of freedom to measure the forces and moments sustained by the specimen.

These data which have been reported earlier will not be repeated here (Pintar, 1995 & 1998). The initial condition was such that the specimen was prepared and spinal alignment was described in terms of the eccentricity parameter. It was defined based on the antero-posterior position of the occipital condyles (FIG. 1). The eccentricity was measured in terms of the sagittal position of the occipital condyles with respect to the caudal end of the preparation. This procedure served to quantitatively define the initial condition and facilitated an analysis of the spinal alignment with biomechanical outcomes. Injuries, as discussed above, were documented using x-rays and CT images. These methodologies assisted in the identification of cervical spine trauma based on accepted mechanisms of injury and treatment (White, 1990; Maiman, 1991; Yoganandan, 1990). Furthermore, it was possible to quantitatively evaluate trauma outcomes with the eccentricity parameter. Cervical spine trauma was classified into less serious (CAT AIS 0) and serious (CAT AIS 1) trauma, bony fracture versus non-fracture (ligamentous injury), and stable versus unstable categories. All these variables were processed through detailed statistical analysis to test the proposed hypotheses.

Human cadaver head-neck complexes were used in the study. This excludes the role of active spinal musculature. Therefore, any restraining or stabilizing action by the muscles that connect the skull and cervical spine during the loading process is not included in the analysis. Although this appears to be a limitation, cervical musculature is reported to have minimal effects, particularly when the dynamic loading is compressive in nature (Nightingale, 1997). This is because of the short time (a few milliseconds) in which impact-induced injuries occur to the cervical spine. The results from this study are, therefore, realistic. Clinically pertinent injuries such as burst and wedge fractures reproduced in this study provide an additional rationale for using the intact cadaver head-neck experimental model (Yoganandan, 1998; Sherk, 1989). Another potential limitation of the present model lies in the use of the isolated head-neck complexes that were fixed at the inferior end using PMMA. In the real world, the boundary condition at the distal end of the neck is not completely constrained as the thoracic structure articulates with the lower cervical spine in the cephalad direction and continues with the dorsal spine and rib cage in the caudal direction. However, the additional constraint added in the present experiment may not be unrealistic as the ribs (particularly at the upper thoracic levels) add considerable rigidity to the human torso. In fact, Nightingale et al., in their inverted cadaver head-cervical spine impacts, simulated the torso by attaching a 16 kg rigid mass to the base of the column (Nightingale, 1997). McElhaney et al.(1983) also fixed the cervical spine specimens at the inferior end, a boundary condition similar to the one used in the present model (Mcelhaney et al., 1983).

Impact loading of the cervical spinal column is an area of focus to many researchers (Winkelstein, 1998; Nightingale, 1997; Nusholtz, 1981; Yoganandan, 1986; Pintar, 1998; Maiman, 1991). As indicated in the Introduction, these researchers have attempted to reproduce clinical injuries of the cervical column. In addition, they have implied the position of the neck to affect the injury outcome. For example, et al., suggested that the position of the neck affects the injury mechanism (Culver et al., 1978). Nusholtz et al., suggested that the line of impact force and initial orientation of the spine influence the type of response and damage to the cervical spine (Nusholtz et al., 1981). However, to the best of our knowledge, published studies are not available that quantify the effects of initial spinal alignment on injury outcomes. Because of the above, the present study was designed to examine the effect of spinal alignment on injury biomechanics. Furthermore, because of the large sample size used, it was possible to statistically analyze the results. These are the strengths of this investigation.

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 (Sherk, 1989; Harris, 1996); this provides a first level of confidence with the experimental model. Another agreement with the present research is that a previous study (although the alignment was not reported) 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, 1983). Enhanced anterior eccentricity in this study 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 classification. However, it did not differentiate the stability characteristics of the injured spine, i.e., between stable and unstable patterns. A likely explanation for the lack of success stems from the definition. Two- and three-column concepts, and the potential for neurologic involvement are used to define instability. 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, 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 the two- and three-column concepts. The clinical emphasis that forms the basis for the definition may account for the observed statistical insignificance for the (in)stability parameter. It should be noted that in the present study, the assessment of instability was based on pre- and post-test films; a similar procedure is commonly adopted in a clinical setting. Therefore, the assessment of (in)stability is realistic. However, these results indicate 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. As indicated earlier, other factors such as neurologic function influence the decision. Thus, the null hypothesis, with regard to the effects of spinal alignment (as defined by eccentricity) on (in)stability, was not proven in this study.

The effects of initial spinal alignment were investigated on the impact biomechanics of the human cervical spine. The position of the occipital condyles with respect to the inferior end of the head-neck complex, termed as the eccentricity parameter, was used to describe spinal alignment. Thirty human cadaver head-neck complexes were used. Impact loading was applied to the cranium using an electrohydraulic testing device. The resulting pathology was assessed using pre- and post-test radiography and CT. Injuries were graded according to AIS rating. They were classified into stable and unstable groups. In addition, 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 the eccentricity is a statistically significant factor that influences the mechanism of injury, trauma rating (AIS), and fracture/non-fracture classifications. However, this variable did not influence the spinal stability classification.

These results underscore the importance and relevance of initial spinal alignment on head impact-induced cervical spine injury.

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