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Preliminary female cervical spine injury risk curves from PMHS tests

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ABSTRACT

The human cervical spine sustains compressive loading in automotive events and military operational activities, and the contact and noncontact loading are the two primary impact modes. Biomechanical and anatomical studies have shown differences between male and female cervical spines. Studies have been conducted to determine the human tolerance in terms of forces from postmortem human subject (PMHS) specimens from male and female spines; however, parametric risk curves specific to female spines are not available from contact loading to the head-neck complex under the axial mode. This study was conducted to develop female-spine based risk curves from PMHS tests. Data from experiments conducted by the authors using PMHS upright head-spines were combined with data from published studies using inverted head-spines. The ensemble consisted of 20 samples with ages ranging from 29 to 95 years. Except one, all specimens sustained neck injuries, consisting of fractures to cervical vertebrae, and disruptions to the intervertebral disc and facet joints, and ligaments. Parametric survival analysis was used to derive injury probability curves using the compressive force, uncensored for injury and right censored for noninjury data points. The specimen age was used as the covariate. Injury probability curves were derived using the best fit distribution, and the ± 95% confidence interval limits were obtained. Results indicated that age is a significant covariate for injury for the entire ensemble. Peak forces were extracted for 35, 45, and 63 (mean) years of age, the former two representing the young (military) and the latter, the automobile occupant populations. The forces of 1.2 kN and 2.9 kN were associated with 5% and 50% probability of injury at 35 years. These values at 45 years were 1.0 kN and 2.4 kN, and at 63 years, they were 0.7 kN and 1.7 kN. The normalized widths of the confidence intervals at these probability levels for the mean age were 0.74 and 0.48. The preliminary injury risk curves presented should be used with appropriate caution. This is the first study to develop risk curves for females of different ages using parametric survival analysis, and can be used to advance human safety, and design and develop manikins for military and other environments.

1. Introduction

The osteoligamentous structures of the spinal column sustain axial loads in various scenarios involving civilian and operational military activities. Injuries to the musculoskeletal systems occur to wounded warriors (Owens et al., 2008). Vertebral fractures are associated with the transmission of the compressive force to the cervical spine from contact loading to the head, although inertial loads from underbody body blast events can also result in such trauma (Bird et al., 2005; Blair et al., 2012; Mahoney et al., 2007; Possley et al., 2012b; Schoenfeld et al., 2012; Yoganandan et al., 2013). An airborne vehicle from an improvised explosive device may impart compressive loads to the head-neck complex of the restrained occupant within the vehicle, and this scenario may be similar to automotive events (Possley et al., 2012a).

Contact loading from the head to the cervical spine also occurs in automotive and athletic events (Nightingale et al., 2015). Biomechanical studies continue to be an area of research to determine tolerance and injury criteria (Yoganandan et al., 2015b). For example, failure tests have been done using isolated vertebrae, functional units, spine segments, entire cervical column with and without the intact or artificial head, and whole body studies (McElhaney et al., 1988, 1983; Nightingale et al., 1997; Yamada, 1970; Yoganandan et al., 1986, 1990). Studies have used different types of post mortem human subject (PMHS) models to apply head contact loads to the cervical spine. The PMHS head-spine preparations and whole body specimens have been mounted on the platform of a materials testing device or dropped using free fall techniques to apply dynamic compressive forces (Nightingale et al., 1996b; Pintar et al., 1995; Yoganandan et al., 1986, 1990).

Although such tests have produced quantifiable information including the peak forces and deflections, and correlated the

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biomechanical metrics with injury outcomes, female- and age-specific risk curves using parametric survival analysis have not been conducted. This is the aim of this study. Specifically, using PMHS force and age data, injury probability curves for females are derived in this paper so that the data may be used in military and other applications.

2. Methods

Three series of PMHS experiments were used. The first series consisted of tests with the impact loading delivered along the superior-to-inferior (SI) axis of the spine to the upright head-neck complex. Briefly, nine unembalmed female specimens were tested in this study. The ages ranged from 29 to 95 years, with a mean age of 62.2 years and standard deviation of 19.5 years. The specimens were fixed at the distal end of the spinal column (T1-T2) using polymethylmethacrylate (Pintar et al., 1995; Yoganandan et al., 1990). The cervical spines were aligned by attaching cables and pulleys to the anterior and posterior regions of the head via a halo ring. The preflexed spines removed the lordosis. A load cell was attached to the inferior end of the fixation. The preparation was fixed to the platform of an electrohydraulic testing device. The SI loading was delivered by the piston of the device such that it contacted the head within one centimeter of the vertex. Following the test, radiographs were taken, computed tomography images were obtained, and sequential anatomical sections were also obtained. Injuries and their mechanisms were assessed. A schematic of the test setup is shown in Fig. 1.

The second series of experiments, also consisting of head impact tests, used the inverted head-cervical column PMHS model (Saari et al., 2013). Briefly, six human cadaver osteoligamentous occiput to T2 spines were prepared such that the T1-T2 levels were fixed such that the C7-T1 intervertebral joint was unconstrained. There were 6 females.

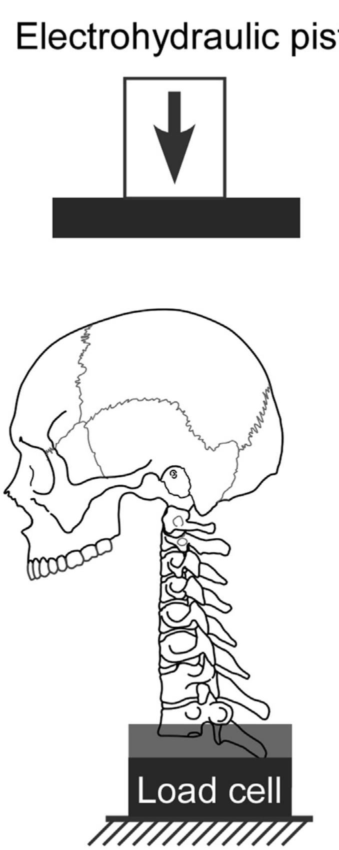

Fig. 1. Schematic of the test setup of the specimen showing the load cell at the distal end of the head-spine preparation. The piston of the electrohydraulic testing device delivered the head contact loading.

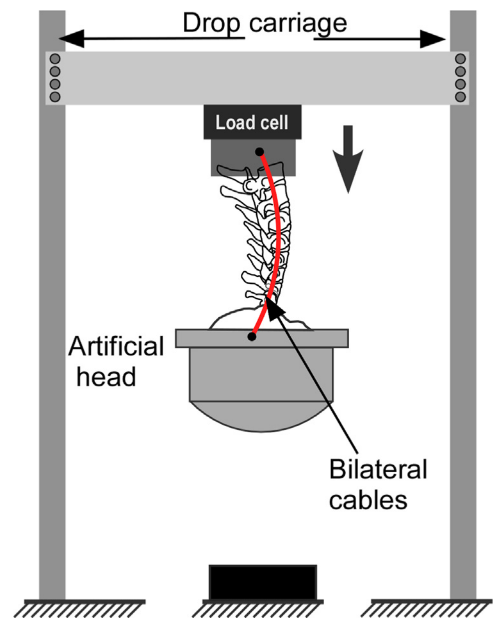

Fig. 2. Schematic of the test setup of the inverted PMHS specimen attached to an artificial head. The bilateral cables from C2 to the distal end were used in some preparations.

Ages ranged from 65 to 94 years with a mean of 72.7 ± 6.6 years. A custom artificial head was attached to the occiput. The C4-C5 intervertebral disc was maintained horizontal in the lordosis posture. The specimens were attached to the drop-test carriage carrying a simulated torso mass of 15 kg. A schematic of the setup is shown in Fig. 2. A load cell attached to the inferior end of the column was used to record neck loads. In some specimens a bilateral cable was used to simulate the follower load.

The third series of experiments also used the inverted head-cervical column PMHS model to apply head contact dynamic loading to the spine (Nightingale et al., 1997, 1996a, 1996b). A schematic of the test setup is shown in Fig. 3. Briefly, human cadaver osteoligamentous head to T3–4 spines were prepared such that the two inferior vertebrae were fixed such that the C7-T1 intervertebral joint was aligned at 25 degrees with respect to the horizontal. There were five female specimens in this group of tests. Ages ranged from 35 to 75 years with a mean of 53.6 ± 16.0 years. The impact load to the specimen was delivered using the free-fall drop technique. The intact PMHS head-T1 specimens were fixed at the distal end of the spinal column. The maintenance of the anterior orientation of the C7-T1 joint preserved the lordosis. A simulated torso mass of 16 kg was added to the carriage of the drop-testing device, and this process was similar to the previous series of tests. A six-axis load cell was attached to the inferior end to record neck loads.

The statistical analysis was performed using the R software (Team, 2014). Data were treated as censored observations based on the outcome of the experiments. The force from each test was used as the predictor variable, and the specimen age was treated as a covariate. The selection of the optimal distribution was based on the corrected Akaike information criterion (Petitjean et al., 2015; Yoganandan et al., 2014, 2016a). The Kolmogorov-Smirnov statistic was used to check the validity of the optimal distribution. The plus and minus 95% confidence intervals was computed for the selected distribution, and the Normalized Confidence Interval Size (NCIS) was also determined. It was defined as the ratio of the width of the confidence interval (CI) to the magnitude of the force at a specific risk level (Yoganandan et al., 2015a, 2014). In the following equation, UL and LL represent the upper and lower bounds of the confidence interval, and μ represents the mean value of the force.