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Biomechanical modelling of impact-related fracture characteristics and injury patterns of the cervical spine associated with riding accidents

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ABSTRACT

Background: Horse-related injuries are manifold and can involve the upper and lower limbs, the trunk, spine or head. Cervical spine injuries are not among the most common injuries. However, they can be fatal and often result in neurological symptoms. This study investigated the influence of the posture of the cervical spine on the ultimate strength and the pattern of vertebrae failure with the aim to provide some guidance for protective clothing design.
Methods: Eighteen human cervical spines, each divided into two specimens (three vertebrae each), were subjected to a simulator test designed to mimic a spinal trauma in different postures of the specimen (neutral, flexion, extension). The stress-to-failure, the deformation at the time of fracture and the fracture patterns assessed based on CT scans were analysed.
Findings: Stress-to-failure of the superior specimens was lower for the flexion group compared to the others ($P = 0.027$). The superior specimens demonstrated higher stress-to-failure in comparison to the inferior specimens ($P < 0.001$). Compression in a neutral or flexed position generated mild or moderate fracture patterns. On the contrary, the placement of the spine in extension resulted in severe fractures mostly associated with narrowing of the spinal canal.
Interpretation: The results imply that a neutral cervical spine position during an impaction can be beneficial. In this position, the failure loads are high, and even if a vertebral fracture occurs, the generated injury patterns are expected to be mild or moderate.

1. Introduction

Horseback riding has been ranked as one of the most dangerous sporting activities with 93,000 accidents in Germany in the year 2000 alone (Federal Institute for Occupational Safety and Health (FIOSH), 2002). Accidents related to horses are more common not in competitive sport but rather during leisure riding (Carrillo et al., 2007; Puschel et al., 2012), but generally, little is known about the cause of an accident and the injury received.

In order to reduce the incidence of horse-related accidents, potential risk factors have to be identified. Questionnaires are the most frequently used tool to evaluate horse- and rider-related information, including the cause of an accident and injuries suffered (Ball et al., 2007; Meredith & Antoun, 2011; Puschel et al., 2012). Horse-related accidents can arise during handling of horses due to kicks and bites, while mounting, dismounting or riding as a consequence of falls of either the equestrian or the horse or both together. Accounting for more than 64%, falls from horses represent the most common sporting injury (Abu-Zidan & Rao, 2003; Cuenca et al., 2009; Hessler et al., 2012; Kiuru et al., 2002; Laurent et al., 2012; Sandiford et al., 2013; Ueeck et al., 2004). Injuries of the brain and skull (Ball et al., 2009; Cuenca et al., 2009; Ghosh et al., 2000; Kiuru et al., 2002; Rueda et al., 2010; Sandiford et al., 2013; Whitlock, 1999), facial (Eckert et al., 2011; Exadaktylos et al., 2002; Kiuru et al., 2002; Meredith & Antoun, 2011; Whitlock, 1999), spinal cord injuries (Andermahr et al., 2000; Ball et al., 2009; Eckert et al., 2011; Exadaktylos et al., 2002; Ghosh et al., 2000; Rueda et al., 2010; Whitlock, 1999), skeletal traumas (Ball et al., 2009; Cuenca et al., 2009; Ghosh et al., 2000) and soft tissue injuries (Campbell-Hewson et al., 1999; Exadaktylos et al., 2002) can occur. Physical handicaps after horse-related accidents are also documented on occasion (Ball et al., 2009; Dekker et al., 2004). In certain extreme circumstances, horse-related injuries can result in the death of the rider (Ball et al.,

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2007; Ghosh et al., 2000; Kiuru et al., 2002; Whitlock, 1999) most commonly due to severe head injuries (Griffen et al., 2002; Hessler et al., 2010; Jagodzinski & DeMuri, 2005).

Spinal fractures and spinal cord injuries are not the most common injury resulting from a horse-related accident reported with incidences of less than 10% (Andermahr et al., 2000; Silver, 2002; Ueeck et al., 2004). However, these injuries can result in paraplegia and tetraplegia (Lin et al., 2011). The thoracolumbar junction between T 11 and L 1 (61%–64%) is most commonly affected followed by fractures at the L 2 and L 3 level (22%) (Hessler et al., 2012; Siebenga et al., 2006). Fractures of the thoracic and lumbar spine outnumber those of the cervical spine (Kiuru et al., 2002; Siebenga et al., 2006; Silver, 2002). However, when they do occur, the consequences can be severe (Silver, 2002) with the possibility of neurologic functional impairment and even death.

Active (e.g., controlled downfall training sessions) and passive protective mechanisms (e.g., a helmet or a vest) were developed over the last years to face this issue and to reduce the risk of severe injuries due to an accidental impaction. Currently, no available protective systems protect the cervical spine from damage caused by a horse-related accident. A new approach could be inflatable collars of airbag-vests which might force the spine into a preferable posture. In order to improve protection systems, it is vital to assess injury patterns and the clinical outcome of equestrian accidents biomechanically. Therefore, the objective of this in vitro study was to reconstruct impact-related injury patterns of the cervical spine under consideration of three different postures of the middle and lower cervical spine during axial compression (neutral vs. extension vs. flexion).

2. Methods

2.1. Specimens

This study was performed according to the criteria of the Ethics Commission of the City of Hamburg. The human specimens were provided courtesy of the Institute of Legal Medicine of the UKE Hamburg University Medical Center.

Eighteen human spines including the first cervical vertebra to the second thoracic vertebra were used for preparation of the mechanical testing. The age of the specimens ranged between 16 and 45 years and included 9 samples from men and 9 from women. After extraction of the cervical spine from the human bodies, the specimens were covered with moisture fabric to prevent dehydration or humidity loss by sublimation and were then stored at −20 °C.

Prior to mechanical testing, all of the specimens were analysed using a CT scanner to ensure suitability for use in the study. They were examined for pathological defects or synostoses of vertebral bodies that would potentially influence the results. Furthermore, geometric parameters of the middle vertebra of each specimen (fourth or seventh cervical vertebra) such as the length, width and the height were determined, allowing for the calculation of the endplate area and the volume of the specimens (Avizo 5.0, VSG, Burlington, USA). By means of QCT scans (Toshiba Aquilion 32, Toshiba Medical Systems, Germany), the bone mineral density of the specimens in terms of K_2HPO_4 was also calculated.

Twelve hours prior to testing, the specimens were taken out of the freezer and slowly defrosted at room temperature. Muscular tissue was removed while the ligamental structures were preserved. During the preparation, the specimens were constantly hydrated with saline solution (0.9% NaCl). Each human spine was divided into two parts of 3 vertebral bodies: cervical vertebral level 3 to 5 (CV 3–CV 5) and cervical vertebral level 6 to the first thoracic vertebra (CV 6–TV 1). Based on the bone mineral density of the cancellous bone of the fourth or the seventh cervical vertebrae, respectively, the specimens were distributed into six groups each varying in terms of vertebral level (CV 3–CV 5 vs. CV 6–TV 1) and the position of the vertebrae while testing (neutral vs. extension vs. flexion). Neutral position of the cervical spine is preserving the normal, unloaded lordosis of the specimens.

2.2. Mechanical testing

The specimens, consisting of two functional spinal units, were fixed in holders allowing for the embedding of the endplate of the superior and inferior vertebra with polymethylmethacrylate (Ureol, Bodo Möller Chemie, Offenbach/Main, Germany). The specimens were always positioned centrally in the pot in order to minimise the risk of translational and rotational movements and to ensure an axial load application running perpendicular to the endplates of the middle vertebrae (Pintar et al., 1995). In the case of a neutral positioning, the plates of the embedding pots were oriented horizontally to the endplates (Fig. 1). In order to achieve a 10° extension or 10° flexion, modified holders with 5° tilt of the superior and inferior plate were used (Fig. 1). The chosen extension and flexion angles are in the same range as the physiological values of the intervertebral range of motion (IV-RoM) at the segment levels tested (3–20°) (Branney & Breen, 2014; White & Panjabi, 1990). Nevertheless, they represent a realistic example rather than a worst-case scenario. Potting occurred in a neutral posture, but mounting in the test rig resulted in extension or flexion during testing, respectively. The inferior pot of the embedded specimens was attached to a horizontal *x*–*y* table of a servohydraulic testing machine (MiniBionix II, MTS, Eden Prairie, MN, USA), whereas the superior pot was aligned and connected to the machine's actuator. The inferior embedding pot was connected to a low-friction *x*–*y* table, allowing translational movements in anterior–posterior and/or lateral direction. All tests were performed at room temperature. In order to simulate a horse-related trauma, a dynamic compression at the superior endplate was applied. Compression with maximum velocity of the servohydraulic testing machine ($v \approx 62{,}500$ N/s) was performed, until a 5% release in the applied force was detected. At this point, bony damage was considered to have occurred and the testing machine returned to the initial conditions as a precautionary measure in order to avoid additional damages to the vertebral structure due to further load application. However, due to a limited reaction speed of the servohydraulic testing machine after detection of a decrease in force – which is inherent to all mechanical testing – the specimens were very shortly exposed to further axial compression. The force-to-failure and the stress-to-failure (force-to-failure/area) and the displacement at the time of failure were defined as quantitative parameters for all experimental tests. Data sets were recorded continuously with a data acquisition rate of 512 Hz. The stiffness of the specimens, equivalent to the gradient in the force-displacement diagram, was determined using the linear correlation interval before the onset of fracture. Based on the applied impulse (integral of the force over the time) and the average impaction velocity, the mean energy at the time of the impaction was calculated. After mechanical testing, the specimens were analysed macroscopically and re-assessed by computed tomography, enabling the detection of spinal fractures, ligamentous injuries and a possible narrowing of the spinal canal. The existing fracture patterns were categorised using the classification of Wolter (1985, 1988). The chosen classification is based on the fracture pattern of the osteoligamentous columns and considers the severity of the spinal canal stenosis. Apart from ligamentous injuries, all other soft tissue disruptions that may lead to instability were ascertained. For the allocation of the correct fracture category, the injury patterns of the entire specimens (all three vertebrae) were considered.

2.3. Statistical analysis

For statistical analysis, the software package PASW Statistics 18 (IBM Corporation, Armonk, NY, USA) was used. According to the distribution of the data and the variation of their variances, parametric (one-way/two-way ANOVA, ANCOVA) or non-parametric tests (Mann–Whitney *U*-test, Kruskal–Wallis test) with a type I error probability of $\alpha = 0.05$