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Cervical and thoracic spine injury from interactions with vehicle roofs in pure rollover crashes

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ABSTRACT

Around one third of serious injuries sustained by belted, non-ejected occupants in pure rollover crashes occur to the spine. Dynamic rollover crash test methodologies have been established in Australia and the United States, with the aims of understanding injury potential in rollovers and establishing the basis of an occupant rollover protection crashworthiness test protocol that could be adopted by consumer new car assessment programmes and government regulators internationally. However, for any proposed test protocol to be effective in reducing the high trauma burden resulting from rollover crashes, appropriate anthropomorphic devices that replicate real-world injury mechanisms and biomechanical loads are required. To date, consensus regarding the combination of anthropomorphic device and neck injury criteria for rollover crash tests has not been reached. The aim of the present study is to provide new information pertaining to the nature and mechanisms of spine injury in pure rollover crashes, and to assist in the assessment of spine injury potential in rollover crash tests. Real-world spine injury cases that resulted from pure rollover crashes in the United States between 2000 and 2009 are identified, and compared with cadaver experiments under vertical load by other authors. The analysis is restricted to contained, restrained occupants that were injured from contact with the vehicle roof structure during a pure rollover, and the role of roof intrusion in creating potential for spine injury is assessed. Recommendations for assessing the potential for spine injury in rollover occupant protection crash test protocols are made.

1. Introduction

Dynamic vehicle crash test protocols, such as those for frontal and side impact, underpin vehicle safety standards and new car assessment programmes internationally. However, to date no such dynamic rollover occupant protection (DROP) protocols have been formally established. Such a protocol is currently being sought in Australia (ATC, 2011) and is a "long term goal of NHTSA" (NHTSA, 2009a,b), and a number of dynamic test procedures and devices have been developed, e.g. the FMVSS 208 rollover dolly test, the controlled rollover impact system (Raddin et al., 2009) and the Jordan rollover system (Friedman et al., 2004). Aside from the possible application of a consumer new car assessment protocol (NCAP), a valid DROP protocol will be an important research tool for understanding injury potential in rollover crashes, developing occupant protection systems, and thereby assisting in reducing road trauma related to this crash mode. An important step in the development of a protocol is the identification of an anthropomorphic test device (ATD) capable of replicating the injury mechanisms, for which accurate real-world data of relevant injury mechanisms is required. This study aims to provide such information for spine injuries sustained in vehicle rollover crashes, and to compare the results with previous cadaver experiments under similar loading conditions. If it can be shown that cadaver spine injury pathology is clinically relevant to spine injury in rollovers, much further information to assess ATDs and establish injury assessment reference values (IARVs) for rollover crashes would be available (e.g. spine forces, moments, accelerations and impulses).

In a general sense, vertical compression loading of the spine can result from a load applied caudally via the head and/or cephalically via the torso. The former can result from a superior–inferior head impact and the latter can result from inertia of the torso loading the neck when the head stops relative to the body, such as diving into the ground. In the context of a vehicle occupant that interacts with the vehicle roof in a rollover crash, caudal impact loading (referred to in this paper as head impact loading) may result when a roof intrudes vertically against the occupants' head, and cephalic loading may result when an inverted occupant impacts the roof when the roof contacts the ground (often referred to as torso inertia or diving). Thus both head impact and torso inertia

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(or a combination of the two) may be relevant loading mechanisms to rollover occupants; clearly a head impact is involved in both mechanisms. Comparisons with cadavers under head impact or torso inertia experiments are made in the present study, thus a brief summary of spine injury mechanisms from these experiments follows.

The mechanisms of spine injury from head impact loading or torso inertia loading may be classified according to the presumed attitude of the (localised) spinal segment at the time of failure (Allen et al., 1982; Alem et al., 1984; Nightingale et al., 1997; Nusholtz et al., 1981, 1983; Nusholtz and Kaiker, 1986; Pintar et al., 1995; Yoganandan et al., 1986). Vertebral body fractures of an impaction or fragmentation type may result from the pure compression state of vertical compression. Fractures of the anterior aspect of the vertebral body and articular process/facet fractures may result from the compression associated with flexion bending, while ruptures of the posterior longitudinal ligaments may result from the tension associated with flexion bending. Fractures of the posterior structures (lamina, pedicle, articular process/facet and spinous process) may result from the compression associated with extension bending, while ruptures of the anterior longitudinal ligaments may result from the tension associated with extension bending. Fractures of the lateral aspects of the vertebral body and posterior structures (vertebral arch and transverse process) may result from the compression associated with lateral flexion bending. These local failure mechanisms are generally referred to as; compression–flexion, compression–extension, vertical compression and lateral flexion.

Previous real-world crash studies have investigated risk factors for spine injury in vehicle rollovers, identifying roof intrusion, the number of quarter turns, far side seating position, vehicle type and occupant physiological characteristics as being associated with the incidence of spine injury (Funk et al., 2012; Hu et al., 2007; Mandell et al., 2010). However, these studies may not be directly relevant to a DROP protocol, since they included one or more of; unrestrained occupants, partially or fully ejected occupants, or rollovers with additional planar impact events. The aim of the present paper is to provide information regarding the nature and causes of spine injury for contained and restrained rollover occupants, to assist in the accurate assessment of spine injury in a DROP protocol.

2. Methods

2.1. Study design

In order to ensure that the spine injuries and mechanisms identified in the real-world study of vehicle rollover crashes are clinically relevant to a DROP protocol, the present study is restricted to contained and restrained occupants in pure rollover crashes. That is, non-ejected, seat-belted occupants in single-vehicle rollover crashes that did not involve planar impacts with fixed objects. Planar impacts with fixed objects or other vehicles might result in spine injury mechanisms that are not relevant to a DROP protocol, nor to the vertical impact cadaver experiments.

This study used a retrospective case–control design. The study population was contained, restrained occupants aged 16 years or older in pure rollover crashes, where the occupant impacted the vehicle roof structure. Occupants that impacted the roof structure were identified as those that sustained a head, face, spine or shoulder injury of any severity, and which had the roof structure coded as the injury source. Cases were occupants that impacted the roof structure and sustained one or more AIS2+ spine injury(s) (AIS2+ refers to AIS severity levels of 2–6, inclusive). Controls were occupants that impacted the roof structure and did not sustain AIS2+ spine injury (i.e. sustained an AIS1 spine injury and/or a head/face/shoulder injury of any severity). Limiting the case–control study population to occupants that impacted the roof structure poses the research question: given that an occupant impacts the roof structure in a vehicle rollover, what factors are associated with that occupant sustaining a spine injury?

2.2. Data

The study population was derived from the United States National Automotive Sampling System (NASS) Crashworthiness Data System (CDS). The CDS is a sample of around 5000 crashes per year involving passenger cars, light trucks, vans, and utility vehicles. In order to be selected in the sample, a crash must be police reported, must involve property damage and/or personal injury, and must involve at least one towed passenger car, light truck or van in transport on a traffic way. The CDS is a probability sample, stratified by geographic regions. Within each region a probability sample of police jurisdictions are selected, and crash cases are then stratified by crash type. National estimates may be produced from CDS data, however may differ from the true values because they are based on a probability sample of crashes and not a census of all crashes. In order to calculate national crash estimates, a weighting is provided for each crash. All analyses in the present paper use the weighting factors.

A previous study of the CDS data (Bambach et al., in press) identified contained, restrained occupants aged 16 years or older in pure rollover crashes during the years 2000–2009 (inclusive). Pure rollover crashes were identified as single-vehicle and single-event rollover crashes (i.e. no planar impacts with fixed objects or other vehicles occurred). The present study population was derived from this dataset, by identifying occupants that sustained one or more head, face, spine or shoulder injuries of any severity, and which had the roof structure coded as the injury source. The roof structure included the roof, windshield header and roof rail components. Occupants that impacted the roof structure and did not sustain an injury could not be identified in the data and were excluded from the study population. AIS2+ spine injuries were identified as the severity of spine injury relevant to the study, since spine fracture was the most frequent spine injury and spine fractures are coded in the AIS scheme as both severity levels of 2 and 3 (AAAM, 1998). The full case file for each occupant in the study population was reviewed using the CDS case viewer, AIS-coded injuries were extracted, the vehicle intrusion profile was reviewed and the maximum vertical roof structure intrusion above the occupants' seating position was extracted. The intrusion coded in the CDS is the residual (static) intrusion measured post-crash. The maximum of the roof structure component intrusion values was used since many occupants sustained multiple injuries attributed to different roof structure components.

The results of cadaver experiments subjected to superior–inferior head load by inverted drop tests or head impact devices were reviewed (Alem et al., 1984; Nusholtz et al., 1981, 1983; Nusholtz and Kaiker, 1986; Yoganandan et al., 1986). The injuries from 49 injured cadavers were coded according to the AIS (AAAM, 1998), and the injuries and study author descriptions were used to infer the injury mechanisms. A variety of initial conditions were assessed in the experiments by varying the initial orientations of the head and/or spine relative to the impact surface. These orientations were predominantly in the mid-sagittal plane, however in six tests initial orientations of the head around the posterior–anterior axis and the superior–inferior axis were varied by up to 15°.