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Cervical spinal cord deformation during simulated head-first impact injuries

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ABSTRACT

The relationship between bony spinal column and spinal cord injury during an injury event is not well understood. While several studies have measured spinal canal occlusion during axial impact, there has been limited work done to quantify the spinal cord compression or deformation during simulated injury. Because the cord is a viscoelastic solid it may provide resistance to bone fragments, ligaments or other elements that move into the canal and impinge it during column injury. This would differentiate the measurement of cord compression from the measurement of occlusion of an empty canal. In the present study, a novel method of visualizing and quantifying spinal cord deformation during dynamic head-first impact of *ex vivo* human cervical spine specimens ($N=6$) was developed. A radiodense, biofidelic surrogate spinal cord was imaged in the spinal canal using high speed cineradiography at 1000 frames per second. The dorsal–ventral diameter of the cord was measured at 1.5 mm increments along its length for each frame of the radiographic footage. The resulting cord deformations were used to determine the theoretical neurological outcome of the impact based on published *in vivo* ferret studies. The corresponding probability of recovery for the spinal cord deformations in these tests ranged between 8% for atlantoaxial dislocation injury and 95% for mid-cervical spine hyperextension injury (based on the ferret data). Clinically relevant spinal column fracture patterns were produced in this study.

1. Introduction

Spinal cord injuries (SCI) are devastating events that lead to paralysis, disability, lowered quality of life and medical costs. Spinal cord injury can be sustained during head-first impact associated with tackling head-first in football, being checked head-first into the boards in hockey, diving into water that is too shallow and head-to-roof impacts in automotive rollovers (Langer et al., 2008; Mcelhaney et al., 1979; Moffatt et al., 2003; Torg et al., 1990). In these instances the cervical spine is asked to halt the momentum of the following torso and fracture of the vertebrae can occur resulting in direct bony insult to the spinal cord, which can lead to paralysis. Both the degree of spinal cord deformation and the rate of cord deformation occurring transiently during the impact have been shown to be determinants of the ultimate functional outcome in ferret models (Kearney et al., 1988). Because of differences in physiology the ferret model results cannot be considered to be a direct analog to the human situation but the general trends of increased SCI severity with increased cord deformation and velocity of deformation may hold.

The relationship between vertebral motion or fracture and spinal cord deformation during a human injury event is not well established. A better understanding of this relationship could lead to improved animal models of SCI and to the development of new preventative devices. One frequent focus of previous work in this area has been the relationship between the maximum transient and subsequent post-injury spinal canal occlusion and cord compression. In the clinical setting, radiographic measurement of the post-injury canal dimensions (i.e. diameter, area or ratios) have been found to have no correlation with the neurological outcome (Keynan et al., 2006). The general hypothesis that post-injury, residual occlusion or compression is less than the true maximum has been borne out by many biomechanical studies. These studies have examined this by recording the recoiling action of bony fragments during burst fracture events (Chang et al., 1994; Panjabi et al., 1995; Raynak et al., 1998; Wilcox et al., 2002) or measuring pressure decreases after impact at the bone–cord interface (Pintar et al., 1995a, 1996; Tran et al., 1995) or with

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