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An investigation into axial impacts of the cervical spine using digital image correlation

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Abstract

BACKGROUND CONTEXT: High-energy impacts are commonly encountered during sports such as rugby union. Although catastrophic injuries resulting from such impacts are rare, the consequences can be devastating for all those involved. A greater level of understanding of cervical spine injury mechanisms is required, with the ultimate aim of minimizing such injuries.

PURPOSE: The present study aimed to provide a greater understanding of cervical spine injury mechanisms, by subjecting porcine spinal specimens to impact conditions based on those measured in vivo. The impacts were investigated using high-speed digital image correlation (DIC), a method not previously adopted for spinal impact research.

STUDY DESIGN: This was an in vitro biomechanical study.

METHODS: Eight porcine specimens were impacted using a custom-made rig. The cranial and caudal axial loads were measured at 1 MHz. Video data were captured with two cameras at 4 kHz, providing measurements of the three-dimensional deformation and surface strain field of the specimens using DIC.

RESULTS: The injuries induced on the specimens were similar to those observed clinically. The mean±standard deviation peak caudal load was 6.0±2.1 kN, which occurred 5.6±1.1 ms after impact. Damage observable with the video data occurred in six specimens, 5.4±1.1 ms after impact, and the peak surface strain at fracture initiation was 4.6±0.5%.

CONCLUSIONS: This study has provided an unprecedented insight into the injury mechanisms of the cervical spine during impact loading. The posture represents a key factor in injury initiation, with lordosis of the spine increasing the likelihood of injury.

Keywords: Impact; Spine; Injury; Digital image correlation; DIC; Axial

Introduction

Sports such as rugby union (rugby) routinely involve high-energy impact forces. On rare occasions, these impacts can result in catastrophic injuries to the cervical spine that have devastating consequences for all those involved. Although the risk of injury or fatality in rugby is comparable to similar activities involving contacts and to general employment-related incidents [1], it remains important to

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minimize such risks. It has been estimated that approximately 40% of serious cervical spine injuries in rugby occur during scrummaging [2], and the relatively controlled nature of the set-scrum (in which the eight forward players of each team bind together and then engage with one another under the referee's instruction) may offer the best potential to reduce risk through an improved understanding of injury mechanisms and appropriate guidelines to the governing bodies of the game.

Previous research investigating axial impacts and injury mechanisms in the cervical spine has focused on head constraint [3], the effect of the impact surface angle and padding [4,5], vertebral compression [6], horizontally positioned impacts [7], the effect of axial preload [8], and burst fracture injuries [9]. These studies have demonstrated the complex nature of spinal injuries and the variation of injury mechanism(s) under seemingly similar conditions. Assessments of the injury mechanisms due to axial loading encountered in rugby scrummaging have been reported as being due to hyperflexion and buckling [2,10,11]. However, care must be taken in classifying cervical spine injury mechanisms, as injury may have occurred because of more than one mechanism and before any outwardly observable change in head position [3,12]. It may, therefore, be necessary to focus on specific forms of impact situations in a highly controlled manner, to fully understand the likely injury mechanisms and how they may be avoided.

Catastrophic neck injury during scrummaging may occur as a result of a head impact to a front row player because of improper engagement between the front rows of the opposing teams or during the collapse of a scrum [2]. Should a head impact occur, severe pocketing will result as a player's head lodges in the shoulder and neck areas of the front row of the opposing team. Such conditions give rise to a cervical spine impact in which both the cranial and caudal regions are highly constrained.

The aim of the present study was to provide an increased understanding of the injury mechanisms associated with constrained axial impacts of the cervical spine. The testing conditions for the investigation were aimed at replicating the constraints of rugby scrummaging. Injury mechanisms were investigated using a combination of load measurement and high-speed imaging. Digital image correlation (DIC), which has not previously been used in spinal impact research, was used to investigate both movements and strain fields induced by the impact on a multilevel cervical spine specimen.

Methods

Eight porcine cervical spinal specimens (C2–C6) were harvested from pigs aged between 8 and 12 months at the time of slaughter, with an average mass of approximately 60 kg (Bartlett & Sons Ltd., Bath, UK). The specimens were dissected from longer sections of spine (C1–T2), all musculature was removed, but facet capsules and ligaments were left intact with the exception of the anterior longitudinal ligament. The anterior longitudinal ligament was removed to provide better visibility to the anterior aspect of the vertebral bodies, which was used to measure the surface strain field using DIC. Pilot holes were made in the lateral aspects of the vertebral bodies to accommodate steel eyelets for the application of the follower load. After the dissection, specimens were wrapped in paper towel, sprayed with 0.9% saline solution, triple sealed in plastic bags, and then stored at −24°C.

Before impact testing, micro–computed tomography scans were acquired for each specimen using a Nikon XT225 ST (Nikon Metrology UK, Hertfordshire, UK) and a Perkin Elmer PE1620 detector (PerkinElmer, Buckinghamshire, UK). A total of 2,160 projections were acquired for each specimen. Image reconstruction was performed with CT Pro 3D software (version 3.1.3; Nikon Metrology), resulting in a voxel resolution of 0.06 to 0.10 mm.

On the morning of testing, each specimen was left to thaw for 6 hours at room temperature (20±2°C) while still triple sealed in plastic bags. During the last hour of thawing, the specimens were removed from the plastic bags, eyelets were screwed into the vertebral bodies, and three self-tapping screws were driven into the cranial and caudal ends to aid stability when potted in using low melting point alloy (MCP75; Mining & Chemical Products Ltd., Northamptonshire, UK). Care was taken during potting to ensure that the C3–C4 disc was aligned with the horizontal plane, and the specimen was in the neutral position.

After potting, the posterior aspect of each specimen was covered with paper towel and sprayed with 0.9% saline solution, whereas the anterior aspect of the vertebral bodies was dried with paper towel and painted with white paint, followed by a speckle spray of black paint to provide a means to perform the DIC measurements. The specimen was then mounted in a custom-made impact fixture, and a follower load was applied to each side of the specimen using constant-force springs rated at 51 N (CFS5.2; MISUMI Europa GMBH, Schwalbach, Germany) via Bowden cables. This resulted in a follower load of 51 N on each side of the specimen, with a further 50 N applied to the cranial end of the specimen due to the weight of the impact plate. This preload magnitude is comparable to previous in vitro cervical spine studies that have replicated the weight of the head and the stiffening effect due to passive muscle activity [8,13,14].

The impact fixture (Fig. 1) comprised an impact plate linked to a frame via two double linear bearing units (Model LTDR25; AB SKF, SE-415 50 Göteborg, Sweden). The impact fixture held the caudal end of the specimen rigidly and allowed only vertical movement to the cranial end, which aimed to replicate the constrained nature of an improper scrummage engagement in which the torso is constrained and the head severely pocketed.

Impacts were applied to the impact plate via a falling mass of 12.86 kg constrained with a custom linear bearing assembly. A drop height of 250 mm was used to produce