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Influence of the crash pulse shape on the peak loading and the injury tolerance levels of the neck in in vitro low-speed side-collisions

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Abstract

The aim of the present in vitro study was to investigate the effect of the crash pulse shape on the peak loading and the injury tolerance levels of the human neck. In a custom-made acceleration apparatus 12 human cadaveric cervical spine specimens, equipped with a dummy head, were subjected to a series of incremental side accelerations. While the duration of the acceleration pulse of the sled was kept constant at 120 ms, its shape was varied: Six specimens were loaded with a slowly increasing pulse, i.e. a low loading rate, the other six specimens with a fast increasing pulse, i.e. a high loading rate. The loading of the neck was quantified in terms of the peak linear and angular acceleration of the head, the peak shear force and bending moment of the lower neck and the peak translation between head and sled. The shape of the acceleration curve of the sled only seemed to influence the peak translation between head and sled but none of the other four parameters. The neck injury tolerance level for the angular acceleration of the head and for the bending moment of the lower neck was almost identical for both, the high and the low loading rate. In contrast, the injury tolerance level for the linear acceleration of the head and for the shear force of the lower neck was slightly higher for the low loading rate as compared to the high loading rate. For the translation between head and sled this difference was even statistically significant. Thus, if the shape of the crash pulse is not known, solely the peak bending moment of the lower neck and the peak angular acceleration of the head seem to be suitable predictors for the neck injury risk but not the peak shear force of the lower neck, the peak linear acceleration of the head and the translation between head and thorax.

Keywords: Neck injury; Whiplash trauma; Crash pulse; Injury criterion; Injury threshold

1. Introduction

The whiplash trauma of the cervical spine is still one of the most common injuries in traffic accidents. Whiplash injuries therefore continue to represent a substantial societal problem worldwide with associated costs, which are estimated at \$4.5–10 billion annually in the US (Tencer et al., 2003; Yoganandan et al., 1999, 2001), at €1 billion annually in Germany (Hell and Langwieder, 1998) and in average at over CAD\$3,800 per whiplash subject in Quebec (Spitzer et al., 1995).

In view of these enormous costs the development of new seats, head restraints and vehicles is of high importance. To determine their performance in protecting the occupant against whiplash, the use of injury criteria such as the neck displacement criterion (NDC) (Viano and Davidsson, 2002), the Nkm criterion (Schmitt et al., 2001), or the neck injury criterion (NIC) (Boström et al., 1996) has been proposed. These parameters are either directly or indirectly related to the loading of the neck: The NIC is calculated from the velocity and acceleration of the head relative to the first thoracic vertebra, the Nkm criterion is based on the upper neck flexion/extension moment and shear force and the NDC is based on the angular and linear displacement response of the occipital condyles with respect to the first thoracic vertebra.

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To determine human tolerance levels for these injury criteria, however, is difficult since the human tolerance to complex three-dimensional (3D) loading is not yet well characterised (Myers and Winkelstein, 1995) and the rate-dependence of the human tolerance to whiplash loading is still unknown. This rate-dependence is of special interest since the real crash pulse shapes are varying considerably from pulses with high to pulses with low loading rates (Krafft et al., 1998, 2002).

The aim of the present in vitro study therefore was to investigate the effect of the crash pulse shape on the peak loading and the injury tolerance levels of the human neck.

2. Materials and methods

Twelve fresh frozen human cadaveric cervical spine specimens including the occiput (C0) and the first thoracic vertebra (T1) were selected for this study. Exclusion criteria were spinal disorders except for minor degeneration. The age of the donors was 81 years in mean.

Before testing, the specimens were thawed at 4 °C and all soft tissue surrounding the discoligamentous spine was carefully removed. C0 and T1 were embedded in polymethylmethacrylate (PMMA) while the foramen magnum was aligned horizontally.

Then, the specimens were mounted to a custom-made acceleration apparatus, that is basically composed of a sled, a railtrack and a pneumatic acceleration unit (Kettler et al., 2004). Since the trunk of a vehicle passenger is known to move during a real-life crash, these movements had to be simulated in the present experiment. This was accomplished by the use of a pivot table, which was located between the sled and the lower end of the specimens and which was allowed to rotate passively about an axis perpendicular to the direction of the acceleration.

A dummy head made of wood and brass was developed to represent the average human head with a mass of 4.5 kg (Clemens 1972) and a humanlike outer geometry. This dummy head was rigidly fixed to the PMMA block on C0 with its centre of gravity located analogous to that of the human head with respect to the cervical spine (Vital and Senegas, 1986). Before acceleration the dummy head was suspended using a thin cord connected at one side to the upper surface of the dummy head and at the other side to the frame of the sled, approximately 10 cm above the head (Fig. 1). By the use of this cord the specimens could be balanced in the upright, neutral position before acceleration. At the beginning of the acceleration, however, the cord was cut to allow the head to move completely unconstrained.

Each specimen was subjected to a series of incremental 90° side collisions from the right. The first impact was characterised by a peak acceleration of the sled of approximately 1 g. In each following impact this acceleration was increased by another 1 g. The experiment was stopped as soon as any structural failure became macroscopically visible with the naked eye. After structural injury had occurred, anteroposterior and lateral radiographs were taken for documentation purposes and to assess bony injuries, which were not visible from outside. While the duration of the acceleration pulse of the sled was kept constant at approximately 120 ms for all specimens, its shape was varied: Six specimens were loaded with slowly increasing pulse, i.e. with a low loading rate, the other six specimens with a fast increasing pulse, i.e. with a high loading rate (Fig. 2).

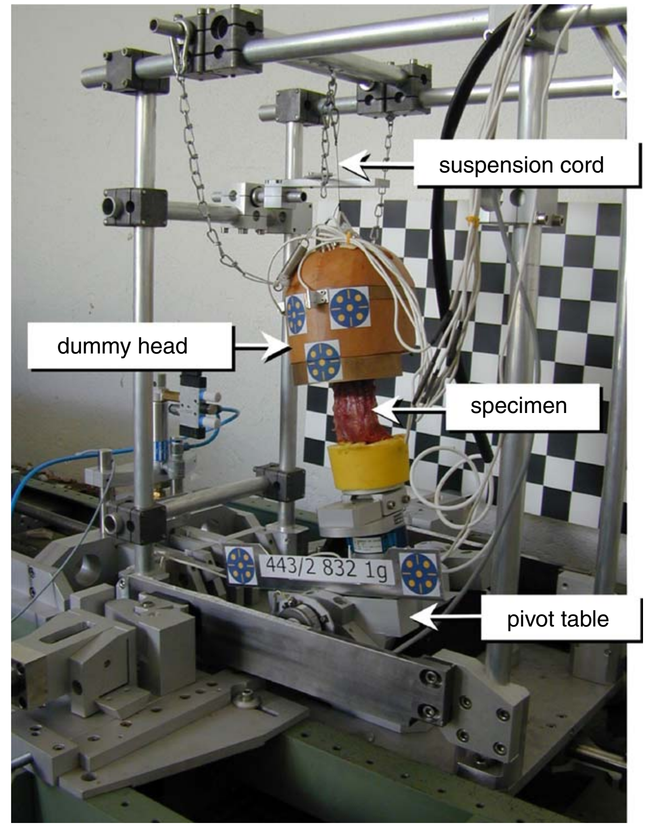

Fig. 1. In the custom-made pneumatic acceleration apparatus the lower end of the specimens was fixed to a pivot table. On the occipital bone a dummy head was mounted, which had to be balanced with a suspension cord. This cord was cut at the beginning of each impact.

The uniaxial acceleration of the sled (EGE-73AE1-100D1, measurement range ± 100 g, Entran Ludwigshafen, Germany), the 3D linear acceleration of the head centre of gravity (EGE-73AE1-100D1, measurement range ± 100 g, Entran Ludwigshafen, Germany) and the 3D forces and moments between neck and pivot platform (lower neck load cell 4894J, measurement range 452 Nm, respectively, 13345 N, Denton COE GmbH, Heidelberg, Germany) were recorded simulta-