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Research paper

The relation between mechanical impact parameters and most frequent bicycle related head injuries

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ABSTRACT

The most frequent head injuries resulting from bicycle accidents include skull fracture acute subdural hematoma (ASDH), cerebral contusions, and diffuse axonal injury (DAI). This review includes epidemiological studies, cadaver experiments, *in vivo* imaging, image processing techniques, and computer reconstructions of cycling accidents used to estimate the mechanical parameters leading to specific head injuries.

The results of the head impact tests suggest the existence of an energy failure level for the skull fracture, specific for different impact regions (22–24 J for the frontal site and 5–15 J for temporal site). Typical linear patterns were described for frontal, parietal and occipital skull fracture. Temporal skull fracture described considerably higher variability. In term of contusion mechanogenesis, the experiments proved that relative brain–skull motion will not be prevented if the maximum frequency of the impact frequency spectrum stays below 150 Hz or below the frequency corresponding to the impedance peak of the head under investigation. The brain shift patterns in humans, both in dynamic and quasistatic situations were shown to be very complex, with maximum amplitudes localized at the level of the inferolateral aspects of the frontal and temporal lobes. The resulting brain maximum amplitudes differed when the head was subjected to a sagittal or lateral motion. Finally, the presented data support the existence of a critical elongation/stretch criterion for the occurrence of ASDH due to BV rupture, located around 5 mm elongation or 25% stretch limit. In addition, a tolerance level lying around 10,000 rad/s^2 for pulse durations below 10 ms was established for BV rupture, which seems to decrease with increasing pulse duration.

The described research indicates that injury specific tolerance criteria can provide a more accurate prediction for head injuries than the currently used HIC. Internal brain lesions are strongly related to rotational effects which are not appropriately accounted by the commonly accepted head injury criterion (HIC). The research summarized in this paper adds significantly to the creation of a fundamental knowledge for the improvement of

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bicycle helmets as well as other head protective measures. The described investigations and experimental results are of crucial importance also for forensic research.

1. Introduction

1.1. Epidemiological background

Head injury represents the leading cause of morbidity and mortality in adults up to the age of 45 (Jennett, 1996), in both industrialized and developing countries, accounting for up to half of the trauma deaths and the majority of cases of permanent disability (Kraus, 1993).

Injuries to the head are always caused by excessive impact loading and/or inertial loading to the head/brain. A published retrospective study reviewing 96 bicycle accidents (Depreitere et al. 2004b) indicated skull fracture, brain contusions, and acute subdural hematoma (ASDH) as three of the most frequent and most important head lesions to protect against during a bicycle accident, with incidences described as high as ~86% for skull fractures, ~73% for brain contusions, and ~43% for ASDH, from all identified head injuries, Despite the described incidences and the multitude of research performed so far in the field of head injury biomechanics, the exact mechanopathology and the relation between head impact characteristics and head injury type and severity are still a much debatable subject. Skull fractures depend strongly on the impact location on the skull and on the contact surface area as such, as well as the stiffness of the impacting surfaces and local bone characteristics. When the impact force exceeds a certain tolerance level, the cranial bone can deform until a certain limit. When the deformation goes above this limit skull fracture can occur. Underneath the skull fracture site the underlying brain tissue can be injured as it distorts under the deforming skull. Moreover, even in the absence of the skull fracture, the brain can be injured under the inertial loading developed in an angular and translational acceleration field. It is the resulting brain–skull relative motion that it is believed to be strongly related to the occurrence mechanism of cortical contusion, generalized diffuse injury, and concussion. In addition, the relative movement between skull and brain can cause the blood vessels to be stretched and rupture if a threshold is trespassed.

Nowadays, the efficiency of bicycle helmet designs in terms of head protection capacity and the risk for head injury is evaluated using Head Injury Criterion (HIC) The criterion summarizes the relationship between linear acceleration, impact duration, and the onset of skull fractures (Mellander, 1986). Because it excludes rotational aspects, the capacity of predicting other type of injuries than skull fracture has been criticized for a long time (Alvarez-Caldas et al., 2007; Depreitere, 2004a). This is supported by a more recent investigation performed by Verschueren (2009) which tried to establish a link between the kinematic impact parameters and the clinical observed head injuries, using computer reconstructions of bicycle accidents. The investigation identified no correlation between HIC and rotational parameters (angular acceleration and velocity), providing a bad prediction for other types of head injury. This indicates the need for injury specific tolerance criteria to be developed.

Despite extensive research performed in the field of head injury biomechanics, precise lesion-specific tolerance criteria for head injury in humans could not be established yet. Attempts have been made to develop injury specific tolerance criterion for DAI (Margulies and Thibault, 1992) and for ASDH related to BV rupture (Löwenhielm, 1978). These criteria have been investigated recently in our group (Verschueren, 2009) showing that the criterion proposed by Löwenhielm (1974, 1978) for ASDH due to bridging vein (BV) rupture gives a good prediction of this injury. However, the criterion for DAI as proposed by Margulies and Thibault (1992) was found to be inaccurate. In terms of contusion prediction the study of Verschueren (2009) found no differentiating criterion.

Based on all these observations, it is reasonable to consider that the mechanisms of specific head injuries are still too poorly understood to formulate clear and valid injury specific tolerance criteria. The current paper reviews more than 10 years of research work performed by our group in the field of head injury biomechanics and focused on three most frequent head injuries bicycle accidents related as previously described by Depreitere et al. (2004b).The research included epidemiological studies, cadaver experiments, and computer reconstructions of cycling accidents aiming to estimate the mechanical parameters of the impact (time history of forces, velocities, and accelerations). The fundamental knowledge gained on the magnitude and duration of head loads associated to most frequent head pathologies resulting from bicycle accidents will allow for an improved understanding of the mechanics of head injury essential for describing injury specific tolerance criteria and for enhanced protective measures to be developed (Depreitere et al., 2007). Nevertheless, understanding the relation between the impact mechanical parameters and resulting head lesions has an obvious potential for forensic research.

1.2. Head impact basic mechanical formulation

To understand how the external impact forces will act on and inside of the head during an impact, a simplified 2D mechanical analysis is provided. This mechanical interpretation is much simplified than what will describe a real bicycle accident. However, the goal of the simplified model is not to give an exact estimation of what the post impact motion of the head will be, but to show how different types of internal and external inertial forces acting on and inside of the head during an impact can be described by using basic mechanical formulation expressed in terms of forces and acceleration (Fig. 1).

During an impact the head is subjected to a time varying contact force $\mathbf{F}$ (F_x, F_y) and constant gravitation force (G). In a real situation the head will deform and eventually fracture, if