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The protective effect of a helmet in three bicycle accidents—A finite element study

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ABSTRACT

There is some controversy regarding the effectiveness of helmets in preventing head injuries among cyclists. Epidemiological, experimental and computer simulation studies have suggested that helmets do indeed have a protective effect, whereas other studies based on epidemiological data have argued that there is no evidence that the helmet protects the brain. The objective of this study was to evaluate the protective effect of a helmet in single bicycle accident reconstructions using detailed finite element simulations.

Strain in the brain tissue, which is associated with brain injuries, was reduced by up to 43% for the accident cases studied when a helmet was included. This resulted in a reduction of the risk of concussion of up to 54%. The stress to the skull bone went from fracture level of 80 MPa down to 13–16 MPa when a helmet was included and the skull fracture risk was reduced by up to 98% based on linear acceleration. Even with a 10% increased riding velocity for the helmeted impacts, to take into account possible increased risk taking, the risk of concussion was still reduced by up to 46% when compared with the unhelmeted impacts with original velocity. The results of this study show that the brain injury risk and risk of skull fracture could have been reduced in these three cases if a helmet had been worn.

1. Introduction

Cycling appears to be growing in popularity as a means of transportation (OECD/ITF, 2014; Pucher et al., 2011), which benefits both the environment and personal health. However, cyclists are also one of the most unprotected road user groups whereas the majority of the fatal and severe injuries in bicycle accidents are to the head (Amoros et al., 2011; Rizzi et al., 2013).

To date, the main form of safety protection for head injuries has been helmets. Nonetheless, there is some controversy regarding whether a bicycle helmet is an effective head injury protection for cyclists (e.g. Thompson et al., 1999; Curnow, 2003). Several studies, mainly epidemiological studies, have shown a protective effect of bicycle helmets (e.g. Amoros et al., 2012; Attewell et al., 2001; Povey et al., 1999; Thompson et al., 1999). While some studies, based on epidemiological data, claim less or no protection of the helmet (Curnow, 2007, 2003; Elvik, 2011). A limitation with epidemiological studies is the possible unreported cases with no head injury due to helmet wearing. There could also be co-founding factors that affect the results, e.g. the discussion about differences in risk-taking among cyclists wearing and those not wearing a helmet (Adams and Hillman, 2001; Bambach et al., 2013). Curnow (2007, 2003) argued also another limitation with previous epidemiological studies, specifically the fact that they have not explored the angular acceleration and brain injuries. Previous biomechanical studies have shown that the brain is more sensitive to rotational kinematics than linear kinematics (Gennarelli et al., 1972; Holbourn, 1943). However, the rotational effect on the head has been studied in an experimental study with and without a helmet (McIntosh et al., 2013), where a decrease of angular acceleration was seen when including the helmet. Still, one question that arises is how well these experiments mirror real bicycle accidents.

An alternative to epidemiological and experimental studies is computational studies, which are capable of reproducing real bicycle accidents. McNally and Whitehead (2013) simulated fictive accidents using rigid body models with and without a helmet to investigate the effect of the helmet and found a decreased acceleration of the head when including the helmet. However, rigid body models can only be used to study injuries with global injury criteria derived from kinematics, and not to study injuries on tissue level. This is a benefit with finite element (FE) models since they can include such details so that the effect on brain tissue level can be studied. A few studies have used FE head models to compare

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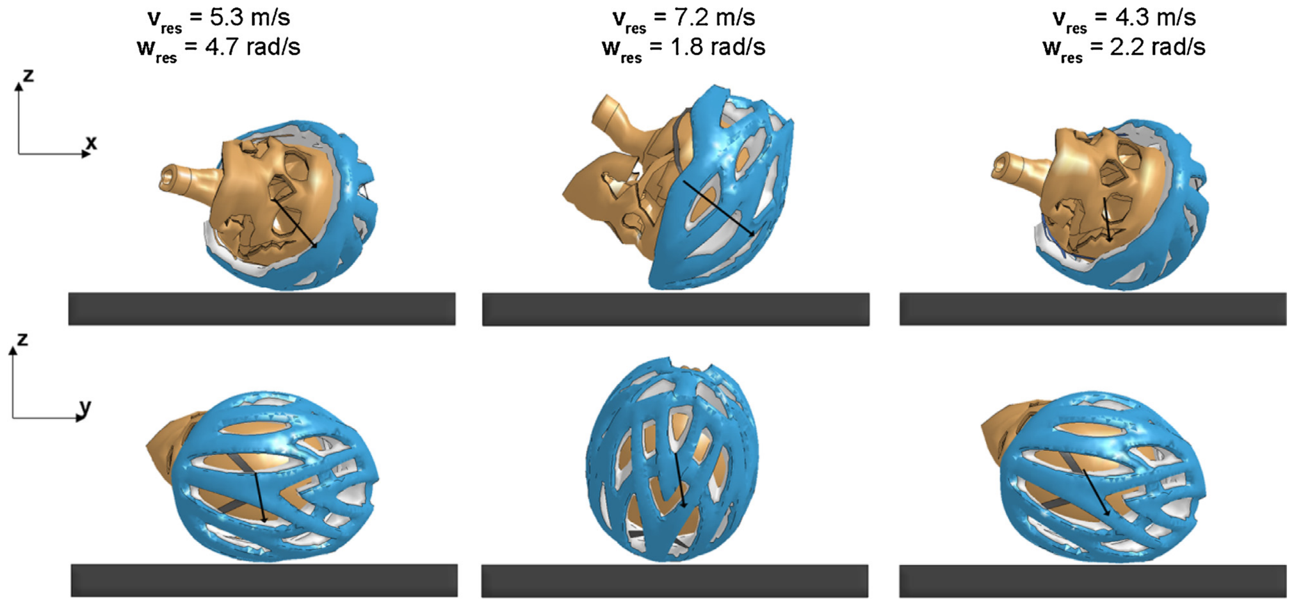

Fig. 1. Initial position of the head/helmet model in the three different cases, from left to right Case 4, 15 and 58. The arrows indicate the impact direction and the resultant velocity is shown at the top of the figure. In all three cases, the victim hit their head against concrete. All three victims sustained skull fracture and intracranial bleedings.

the differences between wearing and not wearing a helmet (Ito et al., 2014; Fahlstedt et al., 2014). The study by Ito et al. (2014) showed a decrease in the level of tissue deformation when including a helmet, but the study was limited to only one impact against a vehicle. While, several studies have shown that single accidents are more common than accidents involving a vehicle (Amoros et al., 2012; Rizzi et al., 2013; Scholten et al., 2015). Fahlstedt et al. (2014) used a FE head model to study the protective effect of three different helmet designs for twenty different fictive impacts against the ground. The results from their study showed that in impact situations, a helmet could reduce the risk of skull fractures and brain tissue deformation from a few percent to 77% depending on the impact configuration. Since it has been demonstrated that the protective properties are dependent on the impact condition, the question remains how well the helmet protects the head in real accident situations. To the authors' knowledge, no previous study based on FE simulations and real accident data has been published. Therefore, the objective of this study was to simulate three bicycle accidents using three separate conditions in each accident: no helmet, helmet and helmet with 10% increase in impact velocity. Detailed finite element simulations were used to compare the risk of concussion and skull fracture by evaluating the first principal strain of the brain tissue and von Mises stress of the skull bone.

2. Methods

The three accident reconstructions used in this study were based on real accident data collected by KU Leuven (Depreitere et al., 2004). The group from KU Leuven collected 86 cases in total, where 86% of the victims had suffered skull fracture and 73% cerebral contusions. Among the chosen cases all had skull fractures and cerebral contusion. The three accidents were single accidents in which the cyclists lost control of the bicycle, fell and impacted the head. Further details about the accidents and injuries can be found in the publication by Fahlstedt et al. (2015). The victims were not wearing a helmet at the time of the accident.

The FE simulations were performed only for the head impact with and without a helmet where the model consisted of the head and a simplified model of the neck. The head velocity just before impact was taken from rigid body simulations (Verschueren, 2009). The initial impact location was assumed to be where the swelling of the scalp was. This information was then applied to a detailed FE head model developed at KTH Royal Institute of Technology (Kleiven, 2007). The model has been compared with several cadaver experiments and has been used for accident reconstructions (Giordano and Kleiven, 2014; Kleiven, 2007, 2006). More details about the head model can be found in previous publications (Fahlstedt et al., 2015; Kleiven, 2007).

The helmet model used in this study was developed based on a helmet available on the market. The helmet model included the outer shell, the expanded polystyrene (EPS) liner and the head retention system. The model was evaluated against four experimental tests from an experimental test rig developed at KTH Royal Institute of Technology (Aare and Halldin, 2003). The comparison showed a correlation of the ratio of peak values of 92% between the experimental tests and simulations and 82% for the ratio of timing of peak values. A further description of the helmet model is presented in Appendix A.

The impact situations for the three accident reconstructions are presented in Fig. 1 with a resultant velocity ranging from 4.3 m/s to 7.2 m/s. The resultant linear impact velocity was also increased by 10% to evaluate the effect of a possible increased riding velocity among helmet users. Fyhri and Phillips (2013) found in their study that helmet wearers decrease their riding velocity when the helmet was taken off, in some cases by as much as almost 10%.

All simulations were performed using the software LS Dyna (version 971 revision 5.1.1). In all simulations the ground was assumed to be a rigid surface. The friction coefficient between the helmet and the scalp was set to 0.5, as was the friction coefficient between the helmet/scalp and ground. A sensitivity study of the friction coefficient both between the scalp/helmet-ground and the helmet-scalp was performed by altering the friction coefficient ±0.2.

The difference between the helmeted and unhelmeted simulations was evaluated for the effect on the brain tissue and skull bone. Several experimental studies (Bain and Meaney, 2000; Morrison et al., 2003) as well as a previous study with the FE head model used in this study (Kleiven, 2007) have shown that brain injuries correlate well to first principal Green–Lagrange strain. Thus, the first principal Green–Lagrange strain (the peak value of the brain tissue strain per element) was used to evaluate the effect on the