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A study on correlation of pedestrian head injuries with physical parameters using in-depth traffic accident data and mathematical models

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ABSTRACT

The objective of the present study is to predict brain injuries and injury severities from realworld traffic accidents via in-depth investigation of head impact responses, injuries and brain injury tolerances. Firstly, a total of 43 passenger car versus adult pedestrian accidents were selected from two databases of the In-depth Investigation of Vehicle Accidents in Changsha of China (IVAC) and the German In-Depth Accident Study (GIDAS). In a previous study the 43 accidents were reconstructed by using the multi-body system (MBS) model (Peng et al., 2013a) for determining the initial conditions of the head-windscreen impact in each accident. Then, a study of the head injuries and injury mechanisms is carried out via 43 finite element (FE) modelings of a head strike to a windscreen, in which the boundary and loading conditions are defined according to results from accident reconstructions, including impact velocity, position and orientation of the head FE model. The brain dynamic responses were calculated for the physical parameters of the coup/countercoup pressure, von Mises and maximum shear stresses at the cerebrum, the callosum, the cerebellum and the brain stem. In addition, head injury criteria, including the cumulative strain damage measure (CSDM) (with tissue level strain threshold 0.20) and the dilatational damage measure (DDM), were developed in order to predict the diffuse axonal injury (DAI) and contusions, respectively. The correlations between calculated parameters and brain injuries were determined via comparing the simulation results with the observed injuries in accident data. The regression models were developed for predicting the injury risks in terms of the brain dynamic responses and the calculated CSDM and DDM values. The results indicate that the predicted values of 50% probability causing head injuries in the Abbreviated Injury Scale (AIS) 2+ correspond to coup pressure 167 kPa, countercoup pressure −117 kPa, von Mises 16.3 kPa and shear stress 7.9 kPa respectively, and causing AIS 3+ head injuries were 227 kPa, −169 kPa, 24.2 kPa and 12.2 kPa respectively. The results also suggest that a 50% probability of contusions corresponds to CSDM value of 48% at strain levels of 0.2, and the 50% probability of contusions corresponds to a DDM value of 6.7%.

1. Introduction

Pedestrians are regarded as an extremely vulnerable and high-risk group of road users since they are unprotected in vehicle impacts (Anderson et al., 1997; SDSBG, 2005; Oh et al., 2008; Kong and Yang, 2010; TABC, 2010; ITARDA, 2010). In vehicle-to-pedestrian accidents, the head is one of the most frequently injured body parts and may lead to disability or even death, which has been widely investigated during the past four decades in order to understand the injury mechanisms and to develope safety counter-measures (Ashton et al., 1977; Willinger et al., 1995; Otte and Pohlemann, 2001; Maki et al., 2003; Fildes et al., 2004; Yang, 2005; Mizuno, 2005; Neal-Sturgess et al., 2007; Khaykin and Larner, 2016; Li et al., 2017). To date it was identified that the head injuries mainly result from contacts with vehicle front parts and also from ground contact (Otte and Pohlemann, 2001; Peng et al., 2012; Shang et al., 2018). Furthermore, the automobile windscreen has been identified as one of the main sources for pedestrian head injuries. Otte (1999) reported that the windscreen was the most frequent vehicle

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source of head injury in an analysis of 543 cases and Mizuno (2005) reported that the windscreen glass was the leading source of head injury for adult pedestrians in the Summary Report of IHRA Pedestrian Safety Working Group activity. Margriet et al. (2011) also found that windscreen area was the main source of the head injury in vehicle-to-pedestrian collisions through analysis of accident data.

Common head injuries in vehicle-to-pedestrian collisions are skull fracture, laceration, cerebral injuries including contusion, concussion, intracranial hematoma, and diffuse axonal injury (DAI). Therefore, preventing and minimizing head injuries has become a critical issue and it is fundamental to understand the mechanisms of these injuries. Various studies have been made in this field, but the injury mechanism and the tolerance thresholds of the brain remain controversial. Nowadays, more numerical models with higher biofidelity have been developed, which provide an efficient way to study the head injuries. Finite Element Methods (FEM) has been considered the best tool for investigating human head response under controlled impact conditions. Ward and Thompson (1975) presented a detailed finite element brain model which provides the important internal structural characteristics and surface geometry of the human brain and insight in brain dynamics. In order to study the human head response to impact loading, the head FE model was developed by Khalil and Hubbard (1977) and they found that the load spatial distribution has sufficient influence on skull strains. Willinger et al. (1995) developed a three-dimensional finite element model to distinguish the risk of focal lesion or sub-dural hematoma from diffuse axonal injury risks. Zhang et al. (2001) developed the human head FE model to investigate internal responses of the brain and improve head injury protection. Head Finite Element models were created using different head sizes and various element mesh densities and the frontal impacts towards padded surfaces were analyzed by Kleiven and von Holst (2002). The simulation results suggested that the size dependence of the intracranial stresses associated with injury is not predicted by the HIC and head size should be considered for new head injury criteria. A head finite element model was used by Zong et al. (2006) in order to predict the stress levels inside a head subjected to impact loading in a virtual environment. The human body head model (HBM-head) was developed by Yang et al. (2007, 2008) for investigations of head injuries in traffic accident. Different types of head injuries (skull fracture, focal brain injury, DAI, contusions, focal lesions) can be evaluated by using head response parameters such as head injury criterion (HIC), head impact power (HIP), skull von Mises stress, intracranial pressure, brain principal shear strain, cumulative strain damage measure (CSDM) and dilatational damage measure (DDM) (Takhounts et al., 2003; Zhang et al., 2004; Yang et al., 2008; Marjoux et al., 2008). There are a bunch of studies on the FE modeling head injuries in different crash events, but very few simulation studies on pedestrian head injuries in connection with in-depth analysis of accident data due to difficulty for acquisition of detailed data about road, vehicle, and injuries etc., and only relying on simulation results would make it difficult to establish a meaningful injury criterion. On the other hand there is still needs of additional study on pedestrian head injuries for improving vehicle safety performance. This research has main contributions to the better understanding the pedestrian head injuries by establishing the correlation of the head injuries with calculated physical parameter based on the real-world accident data from head to windscreen impact. The established predictors and the tolerance thresholds in this study can be applied to evaluate the effectiveness of improved protective measures by calculating the degradation of these injury parameter values.

In this study, the head to windscreen collisions were reconstructed by using FE models based on real-world pedestrian accidents. A total of 43 passenger car versus adult pedestrian accidents were selected from the two databases which have been established in China and Germany respectively. The objective is to analyze brain responses and determine brain injury tolerances, which can be used to develop head injury criterion and predict brain injuries.

2. Method and materials

This is a continuous study on the pedestrian head injuries and injury mechanisms from vehicle collisions by using a comprehensive methodology, in which a few approaches were used including the in depth analysis of the selected 43 accident data, the analysis of the kinematics via the multi-body system (MBS) accident reconstructions of the car to pedestrian impact, the reconstructions of the head-windscreen impact in each accident via a human head FE model, and a statistical analysis of brain injury risks via logistic regression models. The brain dynamic responses were calculated for the injury related physical parameters from stress and strain responses within the head FE model. In addition, head injury criteria and tolerance thresholds were developed in order to predict brain injuries with suggested injury predictors.

2.1. Source of accident data and the accident reconstructions

2.1.1. Accident data

In this study, all data used in modeling are from the In-depth Investigation of Vehicle Accidents in Changsha (IVAC) (Kong and Yang, 2010; Nie et al., 2015) and the German In-Depth Accident Study (GIDAS) (Otte et al., 2003) database.

A total of 43 pedestrian cases are selected from the IVAC and the GIDAS databases, of which 15 cases are from IVAC and 28 from GIDAS. These selected samples should meet the following conditions: (1) the victim's height should range from 150-to-185 cm and weight more than 50 kg according to actual adult human parameters; (2) the pedestrian head often doesn't impact with the windscreen at a low-speed collision and its injury severity is minor correspondingly. This study aimed at the head-to-windscreen impact, so the impact speed should over 20 km/h to ensure the head impacts with windscreen; (3) the impact locations between pedestrian body segments and accident car should be clearly identified; (4) the victim injury causations could be identified; and (5) the head injury severities could be determined based on the hospital diagnostic records and with AIS coding (AAAM, 2005). These requirements will ensure the validity of this study. The vital data for accident and injury reconstructions of these 43 cases are listed in Appendix Tables A1 and A2.

2.1.2. The MBS Accident reconstructions

The multi-body system (MBS) accident reconstructions were carried out based on accident information documented for each accident case (Peng et al., 2013a). The subjects for this study are adult pedestrians, the constraint condition was set according to the actual adult anthropometry parameters. In all traffic accident reconstructions, the pedestrian model were scaled according to the height and weight of the victims to ensure the reliability of pedestrian responses. The baseline pedestrian model is a 50th percentile male adult and it was scaled using the GEBOD module in MADYMO according to the gender, height and weight of the pedestrian victims, the car model was developed according to the dimensions of the accident car using ellipsoids coupled with facet elements. The contact stiffness of vehicle front components was obtained according to Martinez et al. (2007). The initial posture and orientation of the pedestrian model were set up based on the interrogation records, as well as the pedestrian injuries and contact locations between the car front and injured pedestrian body segments. The impact speed of the car to pedestrian was defined based on the results from real-world accident investigation.

2.2. Reconstructions of head injuries in windshield collisions

The head injury reconstructions were carried out by using a head FE model (Yang et al., 2007, 2008), in which the boundary and loading conditions are defined according to results from MBS accident reconstructions, including impact velocity, position and orientation of the head FE model. The brain injury parameters were obtained from

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