TRANSPORT
ISSN 1648-4142 / eISSN 1648-3480
2019 Volume 34 Issue 3: 394–403
https://doi.org/10.3846/transport.2019.10410

INVESTIGATION ON RISK PREDICTION OF PEDESTRIAN HEAD INJURY BY REAL-WORLD ACCIDENTS

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Received 25 May 2016; revised 22 July 2016, 11 March 2017; accepted 6 April 2017

Abstract. Head injury is the most common and fatal injury in car-pedestrian accidents. Due to the lack of human test data, real-world accident data is useful for the research on the mechanism and tolerance of head injuries. The objective of the present work is to investigate pedestrian head-brain injuries through real car-pedestrian accidents and evaluate the existed injury criteria. Seven car-to-pedestrian accidents in China were selected from the IVAC (Investigation of Vehicle Accident in Changsha) database. Accident reconstructions using multi-body models were conducted to determine the kinematic parameters associated with the injury and were used to measure head injury criteria. Kinematic parameters were input into a finite element model to run simulations on the head-brain and car interface to determine levels of brain tissue stress, strain, and brain tissue injury criteria. A binary logistic regression model was used to determine the probability of head injury risk associated with AIS3+ injuries (Abbreviated Injury Scale). The results showed that head injury criteria using kinematic parameters can effectively predict injury risk of a pedestrians' head skull. Regarding brain injuries, physical parameters like coup/countercoup pressure are more effective predictors. The results of this study can be used as the background knowledge for pedestrian friendly car design.

Keywords: head injury, traffic accident, pedestrian, injury criteria, logistic regression.

Introduction

Pedestrians are the most vulnerable road users in the worldwide. Recently in China, approximately a quarter of traffic accident deaths are pedestrians (TA 2014). Pedestrian head injuries are the most commonly occurrences in passenger family car to adult pedestrian accidents. They can lead to severe injuries and casualties in many cases. Preventing and minimizing head injuries has become a critical issue regarding a pedestrian friendly car design in respect to the existed head injury criteria. Thus, the most important is to establish robust injury criteria to comprehensively evaluate head injuries including both skull and brain structures. The previous studies related to head biomechanics have been worldwide carried out but injury criteria of brain remain controversial (Yanaoka *et al.* 2015). Due to the lack of human test data, real-world accident data is useful for head injury related studies.

Common head injuries in car-to-pedestrian collisions are skull fracture, laceration, cerebral injuries including contusion, concussion, intracranial hematoma and Diffuse Axonal Injury (DAI). Main causes of head injuries are the concentrated impact force, the load distribution in viscous material of the brain, and the inertial loading to the head/brain (Yang 2005). The skull fracture depends mainly on the impact velocity and region of the head and its contact area with the car. When the impact force exceeds the tolerance level, cranial bone fracture will occur. Subsequently, linear and angular accelerations of head are generated. These accelerations result in the relative movement between the skull and the brain. The brain injuries can be caused by high strain and strain rate due to this movement.

During the past decades, various head injury criteria have been developed to predict head injuries. The Wayne State University Tolerance Curve (WSUTC) has been used since the early 1960's. This criterion expresses the relationship between the linear acceleration and duration [ms] of the impacted head on head injury outcome (Lissner *et al.* 1960). Based on WSUTC, the US National Highway Traffic Safety Administration (NHTSA) proposed the Head Injury Criterion (HIC) in 1972. Then, HIC is widely used in industrial and research fields for risk prediction till now. However, HIC is only an empiric

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criterion considering the linear acceleration but the impact direction and the angular acceleration are neglected. Consequently, Newman (1986) proposed the Generalized Acceleration Model for Brain Injury Threshold (GAMBIT) that concerns the influences of both linear and angular accelerations. Considering the impact direction, Newman *et al.* (2000) proposed a new criterion called Head Impact Power (HIP). However, the aforementioned criteria are all based on kinematic parameters of head. All presents their limits to predict complex brain injuries. Recently, many researchers are dedicated to improve the existed criteria by considering physical parameters according to Finite Element (FE) simulations of biomechanical human models (Takhounts *et al.* 2003).

The purpose of present study is to investigate pedestrian head-brain injuries through real car-pedestrian accidents and evaluate the existed injury criteria through accidental reconstructions. First, Multi-Body System (MBS) reconstructions were implemented to determine head impact conditions. Then these impact conditions were applied as input parameters in the reconstructions with an FE human head model developed by Hunan University (HUHM-1). Then the existing head injury criteria calculated from MBS and FE HUHM-1 reconstructions were analysed using logistic regression method, in particular to evaluate their ability to predict brain injuries.

1. Method and material

1.1. Accident data

On-site investigation has been carried out in Changsha (China) since 2006 and an in-depth accident database has been developed since then by the Vehicle and Traffic Safety (VTS) research group of Hunan University. This database includes detailed accident information as measurements registered from accident scenes, interview of people involved in accidents and witnesses, as well as victim situations collected from emergency hospitals. In the current study, seven detailed cases with common family type cars to adult pedestrian were selected out from this database to implement accident reconstructions from MBS simulations to FE simulations with a biomechanical human head model. The selection of accidents was done according to the following requirements:

- the accident should be caused by a family type car commonly used in China;
- the pedestrian should be adult;
- the injury should be AIS1+ (Abbreviated Injury Scale);
- the documentation should include detailed sketch of the accident reports as showed in Figure 1a;
- the accidents should include detailed description of injuries, and on the car clear impact marks causing these injuries (Figure 1b).

The data from selected cases for reconstruction are summarized in Table 1, including the most important information of age, height, weight, gender and injury description of the pedestrian, impact speed and type of the car as well as the scenarios description.

1.2. Accident reconstruction

MBS and FE simulations are combined to realistically reconstruct the accidents. MBS simulations are conducted using the MADYMO program (*https://tass.plm.automation.siemens.com/madymo*), in order to reproduce the pedestrian kinematics associated with the collision, such as impact velocity, impact location, angular velocity. Injury evaluation index as HIC, GAMBIT, HIP are also calculated through the simulation results. The head impact conditions derived from the MBS reconstructions are used as input data for FE reconstructions. A biofidelic human head model developed by Hunan University (HUHM-1) is used to in-depth investigate the injury mechanism and tolerance by correlating related physical parameters, such as coup/contrecoup pressures, Von Mises and shear stress.

1.2.1. MBS reconstruction models

The existing model of pedestrian developed by Yang *et al.* (2000) is used in the study. The model consists of 24 ellipsoids that represent the head, neck, chest, abdomen, hip, upper and lower extremities; these are connected by 18 joints. In each reconstruction, the pedestrian model is scaled according to the real height and weight of the victim (Table 1) using "gebod" code of MADYMO. The models of the cars involved in the accidents are developed according to their real 3D dimensions. The mechanical properties of the car models are defined based on stiffness properties acquired from European New Car Assessment Programme (Euro NCAP) sub-system tests (Martinez *et al.* 2007).

The initial posture and orientation of the pedestrian model are also adjusted according to recorded information in accidents. Typical car-pedestrian impact models are shown in Figure 2. Pedestrian walking speed ranges from 0 to 3 m/s to represent standing, walking, rapidly-walking and running status by interviews with peoples involved in accident and witnesses, and it will be finally determined through trial simulations. The initial speed of the car is calculated using both skid marks and throw out distance. Different friction coefficients are set based on weather conditions and road materials.

Pedestrian throw out distance, wrap around distance and impact marks from the real accidents are used to evaluate reconstruction results. When the error between the simulation and the accident data is less than 20%, the reconstruction results were accepted.

1.2.2. FE reconstruction models

The validated FE human head model (HUHM-1) is used in the current study (Figure 3) (Yang *et al.* 2005; Xu, Yang 2008). The whole model contains 6 components, 9890 nodes, 6487 solid elements and 7007 shell elements. The effective mass is 4.4 kg. The HUHM-1 model is not scaled to the actual size of the pedestrian involved in an accident because of the lack of exact head 3D dimensions in the

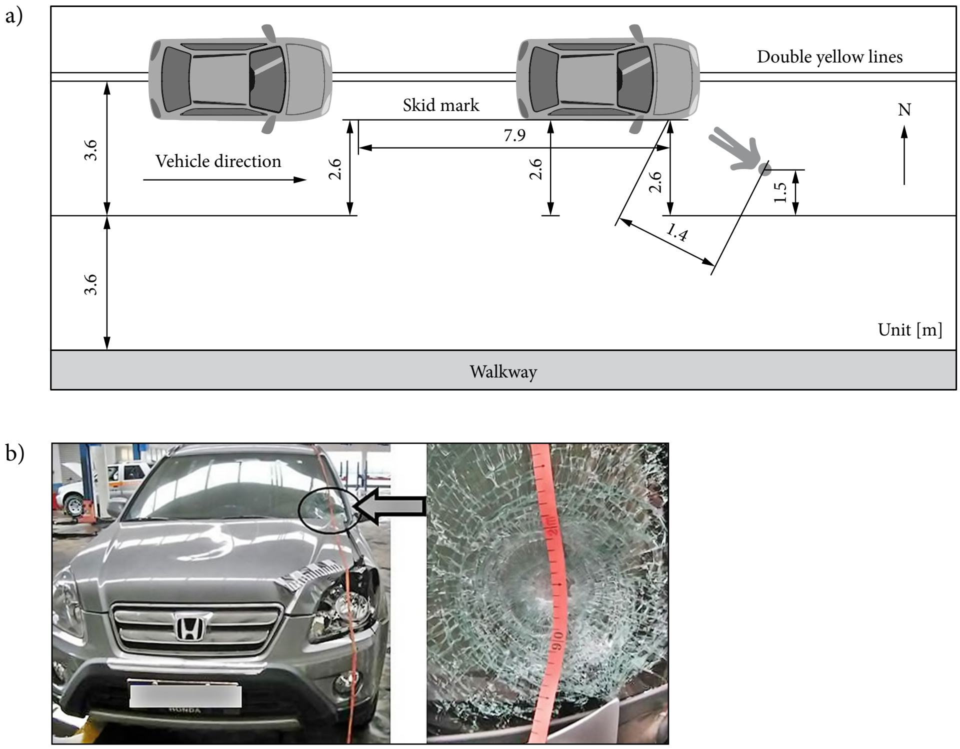

Figure 1. Accident data with detailed impact marks: a – sketch of the accident scene; b – photo of damages to the involved vehicle

Table 1. Car-to-pedestrian cases selected for accident reconstructions

Case number	Age [year]	Height [m]	Weight [kg]	Gender	Car	Velocity of the car [km/h]	Scenarios	Injury Description
Case 1	50	1.74	72	male	VW Jetta	27.0	side impact; standing	right temporal contusion (AIS4); right temporal cephalophyma (AIS4); right temporal epidural hematoma (AIS4)
Case 2	20	1.72	60	male	Honda Accord	22.0	side impact; running (Figure 2c)	scalp haematoma (AIS1)
Case 3	26	1.62	49	female	VW Jetta	30.2	side impact; walking (Figure 2a)	right side subarachnoid hemorrhage (AIS3); cerebral concussion (AIS2); scalp haematoma (AIS1)
Case 4	48	1.73	72	male	Mazda 6	43.6	rear impact; standing (Figure 2b)	coronal linear fracture (AIS2); subarachnoid hemorrhage (AIS3)
Case 5	61	1.55	46	female	VW Jetta	33.4	side impact; walking	cerebral concussion (AIS2)
Case 6	74	1.50	58	female	Lin Shuai	57.6	side impact; walking	right temporal contusion (AIS4); subarachnoid hemorrhage (AIS3); basilar fracture (AIS2); scalp laceration (AIS2)
Case 7	18	1.71	81	male	VW Jetta	28.6	side impact; standing	cerebral concussion (AIS2)

accident database and also such scaling is assumed not be influencing the results significant of current study.

In present study, an FE windshield model is developed using a pre-validated method (Sun *et al.* 2005). The model contains two coincident layers to simulate the glass and the PolyVinyl Butyral (PVB) layer, respectively. The glass layer is modelled by shell elements with stress failure limit. The PVB layer is modelled by membrane elements, using a hyper-elastic material. The bonnet model is developed based on the 3D dimension of the car involved in accident. The material characteristics are defined using these from validated Neon model (NHTSA 2006).

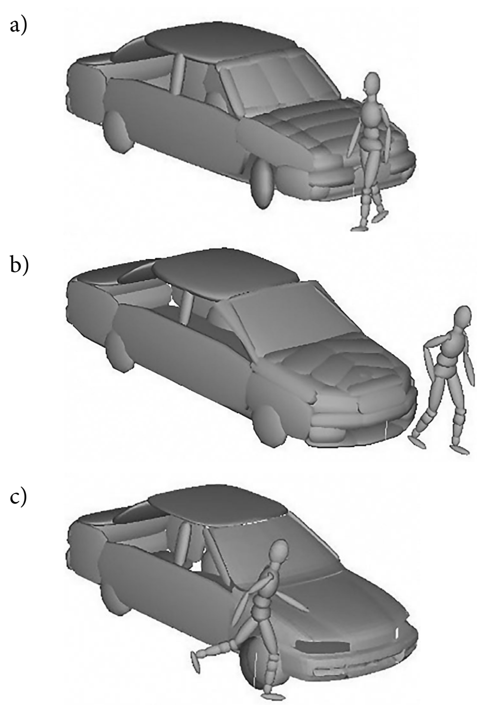

Figure 2. Typical MBS car-pedestrian impact models:
a – normal walking; b – standing and working; c – running

The initial impact conditions of FE reconstruction (Figure 4b) as initial head linear velocity, angular velocity, orientation and position, as well as the velocity and position of the car, were defined according to the corresponding values derived from MBS reconstruction (Figure 4a). The accuracy of FE reconstruction is evaluated by real accident information, such as windscreen damage, bonne deformation and pedestrian head injury.

1.3. Considered head injury criteria

a) HIC

HIC had been widely used in the requirements for crash safety evaluation all over the world (Henn 1998), as following:

$$HIC = \max_{(t_1,t_2)} \left((t_2 - t_1) \cdot \left(\frac{1}{t_2 - t_1} \cdot \int_{t_1}^{t_2} a(t)\,dt \right)^{2.5} \right), \qquad (1)$$

where: a is the resultant linear acceleration measured at the Center Of Gravity (COG) of the head [m/s^2]; t_1, t_2 are chosen in order to maximize the HIC value [ms].

b) GAMBIT

GAMBIT expresses the maximum linear and angular accelerations of the COG of the head as factors of head injuries (Newman 1986):

$$G(t) = \frac{a_m}{250} + \frac{\alpha_m}{10000} \le 1, \qquad (2)$$

where: a_m is the maximum linear acceleration of head [g]; α_m is the maximum angular acceleration [rad/s^2].

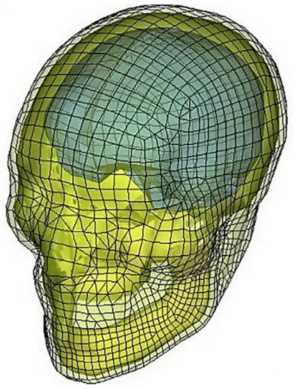

Figure 3. Hunan Head (HUHM-1) model

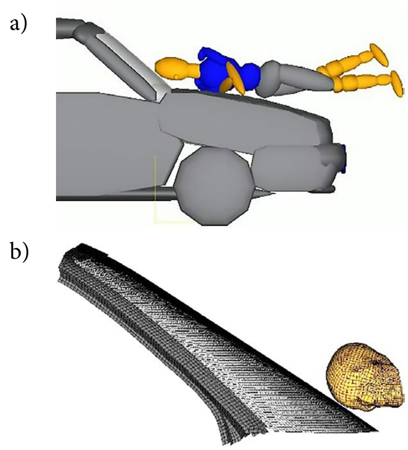

Figure 4. Pedestrian kinematics at the moment of the head impact to the windshield (a) and FE reconstruction of head injuries (b)

c) HIP

HIP also consider the head as a one-mass structure. In addition, head impact direction is deliberated (Newman *et al.* 2000):

$$HIP = \underbrace{C_1 \cdot a_x \cdot \int a_x dt + C_2 \cdot a_y \cdot \int a_y dt + C_3 \cdot a_z \cdot \int a_z dt}_{\text{linear contribution}} +$$
$$\underbrace{C_4 \cdot \alpha_x \cdot \int \alpha_x dt + C_5 \cdot \alpha_y \cdot \int \alpha_y dt + C_6 \cdot \alpha_z \cdot \int \alpha_z dt}_{\text{angular contribution}}, \qquad (3)$$

where: C_i coefficients are set as the mass or appropriate moments of inertia for the human head (i = 1, ..., 6); a_x, a_y, a_z are the components of linear acceleration along the three axes of the local coordinate system of the dummy head [m/s^2]; α_x, α_y, α_z are the components of angular acceleration around the three axes of the same system [rad/s^2].

d) SIMon criteria

Cumulative Strain Damage Measure (CSDM) is supposed to be correlated with neurological injury occurrences such as DAI. It measures the cumulative portion of the brain tissue experiencing tensile strains over a predefined critical level. Several critical levels are proposed in the current study. A level of 15% is chosen as it seems to show the best correlation with injuries regarding scaled animal test simulations (Takhounts *et al.* 2003).

Dilatation Damage Measure (DDM) is also supposed to be correlated with contusions. It involves localized regions where mechanical pressure exceeds threshold value that is able to cause tissue damage. A level of −100 kPa is chosen as it seems to show the best correlation with injuries regarding scaled animal test simulations (Takhounts *et al.* 2003).

e) Other criteria

A critical strain curve expressed in terms of the peak angular acceleration and change in angular velocity is used as a threshold corridor of brain injuries (Margulies, Thibault 1992; Yang 2005). It was suggested that the bridging vein could be ruptured when the head angular acceleration exceeds 4500 rad/s^2 and the change of the angular velocity is above 50 rad/s.

As head FE models are widely used recently, the physical parameters such as coup/contrecoup pressure, Von Mises and shear stress could be used to predict head injuries by reconstruction (Yao *et al.* 2008). Therefore, we decided also to use these criteria and make analysis of prediction for brain injury risk.

1.4. Statistical methods

Logistic regression is used widely in many fields (Dong *et al.* 2013; Dai *et al.* 2015), including the medical and social sciences. For example, the Trauma and Injury Severity Score (TRISS), which is widely used to predict mortality in injured patients, was originally developed by Boyd *et al.* (1987) using logistic regression. Logistic regression can be binomial, ordinal or multinomial. Binomial or binary logistic regression deals with situations in which the observed outcome for a dependent variable can have only two possible types (for example, "dead" vs. "alive" or "win" vs. "loss"). Multinomial logistic regression deals with situations where the outcome can have three or more possible types (e.g., "disease A" vs. "disease B" vs. "disease C") that are not ordered. Ordinal logistic regression deals with dependent variables that are ordered.

In the present study, binary logistic regression model was used to examine AIS3+ brain injury risk and its correlation to the calculated injury criteria (HIC, GAMBIT and HIP) and physical parameters (Simulated Injury Monitor (SIMon) criteria, coup/contrecoup pressure, Von Mises and shear stress). The brain injury probability of AIS3+ was defined as:

$$p(x) = \frac{1}{1 + e^{\alpha - \beta \cdot x}}, \quad (4)$$

where: $p(x)$ is the brain injury probability of AIS3+ for the given value x (such as HIC, shear stress etc.) of the injury predictor candidate; α and β parameters are determined using maximum likelihood method to maximize the function's fit to the data. Goodness-of-fit of the statistical model was examined by means of chi-squared χ^2. The probability value p is associated with χ^2. The relationship between injury and predictor variables is statistically significant when the probability value is at the level of $p \leq 0.05$. The α, β and their associated standard errors σ $(\alpha \pm \sigma, \beta \pm \sigma)$ were calculated by fitting the logistic regression model by maximum likelihood. When $x = \frac{\alpha}{\beta}$, $p(x)$ has a bending point with a maximum or minimum value for the slope and $p(x) = 50\%$ level. So the value of $\frac{\alpha}{\beta}$ gives the median of the distribution of MAIS3+ (Maximum AIS) over values of x. A bootstrap method was used to calculate the standard error σ of $\frac{\alpha}{\beta}, \left(\frac{\alpha}{\beta} \pm \sigma\right)$ for each injury parameter using MATLAB program (Zoubir, Boashash 1998). Total 1000 bootstrap samples were generated for each case.

2. Results

2.1. MBS reconstruction results

After several runs of each case, we could finally reconstruct each accident according to requirements for the current study as summarized in Tables 2 and 3. For all cases, the errors between the simulation and the accident are less than 20%, so the seven cases are well reconstructed.

Figure 5 showed all the impact points of head on the car. The AIS3+ injuries were found mainly around the edges of the windshield and near the A pillar. These parts are much stiffer than the other area on the windshield.

Table 2. Comparisons of throw out distance

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Accident [m]	5.9	2.4	7.5	8.2	10.6	11.0	6.3
Reconstruction [m]	5.4	2.7	7.9	8.0	10.9	11.3	5.8

Table 3. Comparisons of wrap around distance

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Accident [m]	2.05	2.3	1.92	2.04	1.66	1.96	1.82
Reconstruction [m]	2.1	2.24	1.94	2	1.65	1.93	1.85

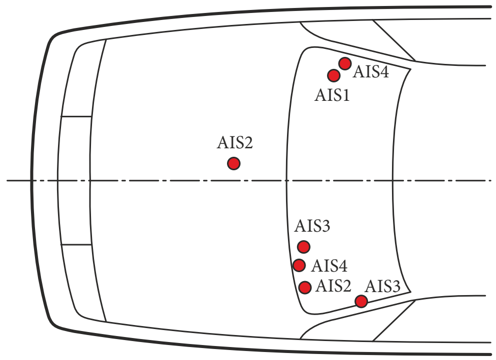

Figure 5. Head impact points and AIS codes on the car

Results regarding the injury related parameters calculated from MBS reconstructions of all cases are presented in Table 4. Brain injuries occurred when HIC is greater than the level of 463.3 and HIP is greater than the level of 26.7 while such level is not found in GAMBIT.

The correlation between head injury criteria, calculated from MBS reconstruction, and AIS3+ brain injury was examined using a logistic regression model as shown in Figures 6a–c. The *p*-value of HIC, GAMBIT and HIP are 0.140, 0.298 and 0.223, respectively. HIC exhibits the stronger correlation with AIS3+ brain injuries than other two criteria, however the *p*-value is still greater than 0.05. The values of α, β and $\frac{\alpha}{\beta}$ with their standard errors are presented in Table 5.

Table 4. MBS reconstruction results

Case number	HIC	GAMBIT	HIP [kW]	Maximum angular velocity [rad/s]	Maximum angular acceleration [rad/s^2]	MAIS
Case 1	1345.6	3.48	36.5	42.5	25686	4
Case 2	463.3	2.02	26.7	31.8	15300	1
Case 3	1500.1	3.53	48.2	57.1	28000	3
Case 4	2407.2	1.87	69.6	90.6	11794	3
Case 5	2081.3	1.84	64.4	39.6	9352	2
Case 6	5691.0	5.48	137.1	71.2	43874	4
Case 7	1281.2	4.02	42.5	50	30400	2

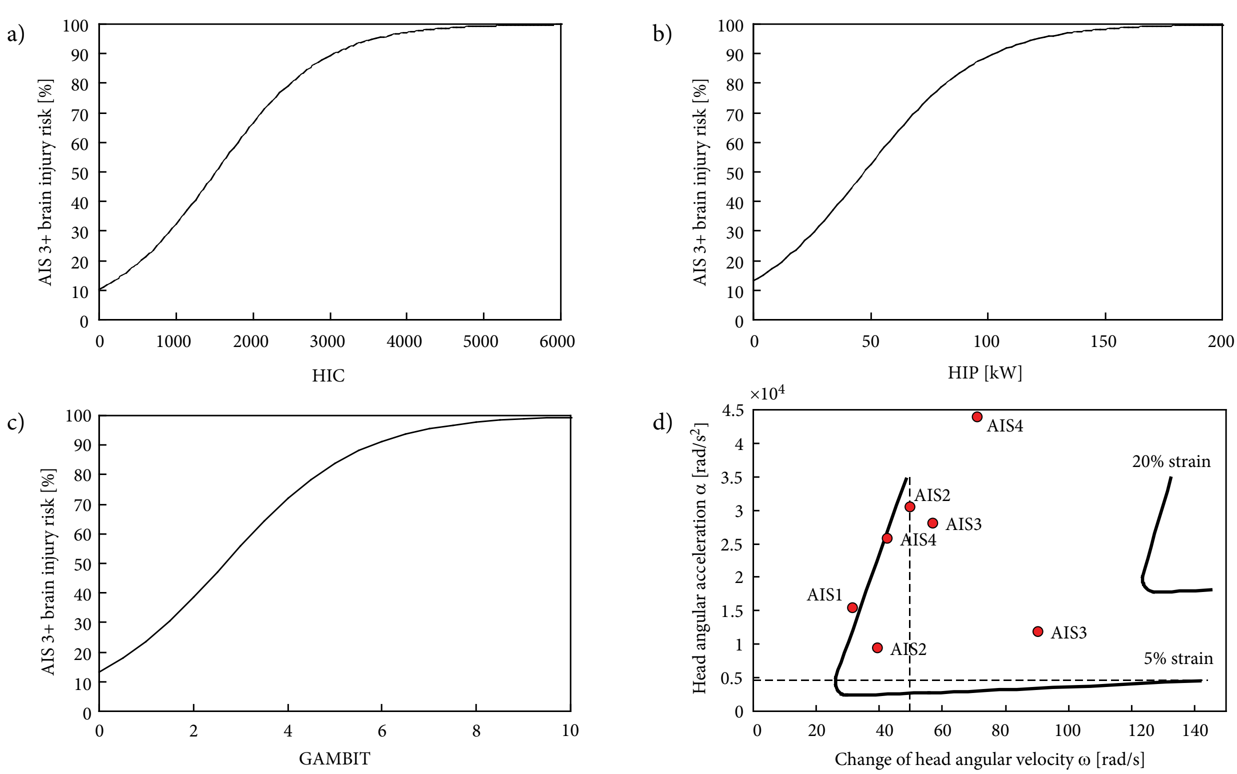

Figure 6. Logistic regression curves for: a – HIC versus AIS3+ brain injury risk; b – HIP versus AIS3+ brain injury risk; c – GAMBIT versus AIS3+ brain injury risk; d – the threshold corridor of angular velocity and acceleration

The angular velocity and acceleration of head calculated from each case is presented in Figure 6d in order to analyse the critical strain level of the brain criterion. Based on the MBS reconstruction results, six cases including brain injury are within the area between 5% and 20% strain.

2.2. FE reconstruction results

Figure 7 shows an example of FE reconstruction results that windshield fracture features of the FE simulation is similar to the accidental car.

Physical parameters including coup pressure, contrecoup pressure, Von Mises and shear stress calculated from FE reconstruction are shown in Table 6 and Figure 8. Brain injuries occurred when coup pressure >122 kPa, contrecoup pressure <–140 kPa, Von Mises >–13.7 kPa and shear stress >7.9 kPa.

Table 7 shows all the coefficients of logistic regression for probability of AIS3+ brain injury based on results from FE reconstructions. Concerning the p-value, physical parameters exhibit the stronger correlation with AIS3+ brain injuries than the criteria based on kinematic parameters. Coup and contrecoup pressures exhibit the strongest correlation with AIS3+ brain injuries as their p-values are less than 0.05.

Figure 9 shows the SIMon criteria results, including CSDM and DDM, calculated from FE reconstruction results.

Table 5. Logistic regression coefficients and statistics for probability of AIS3+ brain injury (MBS results)

	$\alpha \pm \sigma$	$\beta \pm \sigma$	χ^2	p	$\frac{\alpha}{\beta} \pm \sigma$
HIC	2.169 ± 2.495	0.0014 ± 0.0015	2.175	0.140	1549.3 ± 833.5
GAMBIT	1.878 ± 2.349	0.7048 ± 0.7433	1.085	0.298	2.7 ± 2.9
HIP [kW]	1.885 ± 2.361	0.0398 ± 0.0447	1.488	0.223	47.4 ± 28.6

Table 6. FE reconstruction results

Case number	Coup pressure [kPa]	Contrecoup pressure [kPa]	Von Mises [kPa]	Shear stress [kPa]	CSDM [%]	DDM [%]	MAIS
Case 1	353	–271	26.9	15.5	2.0	11.0	4
Case 2	122	–140	13.7	7.9	5.6	2.0	1
Case 3	188	–195	15.7	9.0	3.1	1.1	3
Case 4	289	–262	33.3	19.2	13.3	13.0	3
Case 5	139	–181	16.3	9.4	1.6	2.7	2
Case 6	245	–236	25.6	14.8	12.2	12.5	4
Case 7	201	–197	22.1	12.8	2.0	9.2	2

Table 7. Logistic regression coefficients and statistics for probability of AIS3+ brain injury (FE results)

	$\alpha \pm \sigma$	$\beta \pm \sigma$	χ^2	p	$\frac{\alpha}{\beta} \pm \sigma$
Coup pressure [kPa]	10.6 ± 9.1	0.054 ± 0.047a	5.749	0.017	195.5 ± 25.8
Contrecoup pressure [kPa]	32.6 ± 48.5	–0.166 ± 0.250	6.290	0.012	–196.8 ± 14.6
Von Mises [kPa]	5.2 ± 3.9	0.257 ± 0.187	2.964	0.085	20.1 ± 8.3
Shear stress [kPa]	5.0 ± 3.8	0.436 ± 0.318	2.901	0.089	11.4 ± 5.1

a) b)

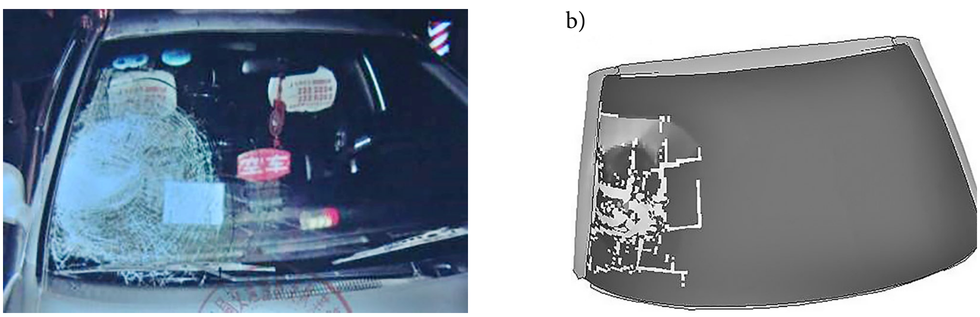

Figure 7. Comparision of fracture features of a car windshield in the accident and the FE reconstruction: a – accidental photo; b – FE simulation results

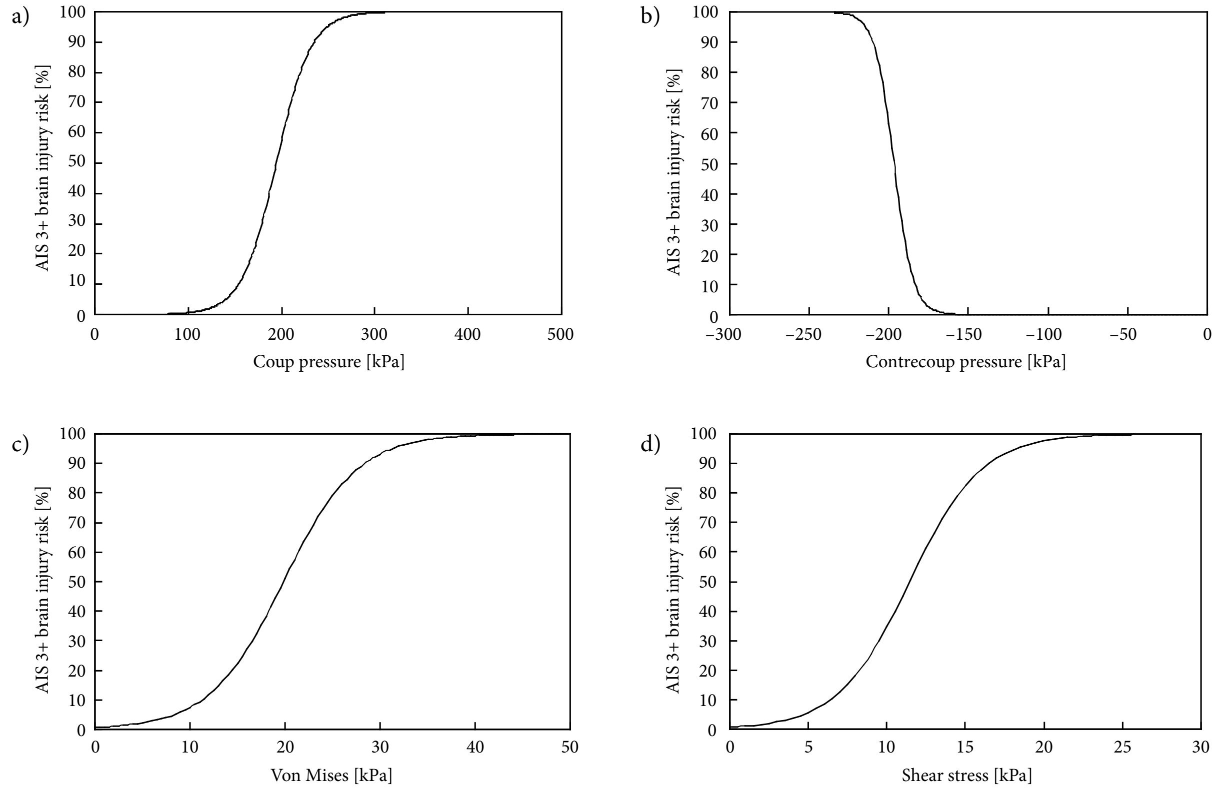

Figure 8. Logistic regression curves for: a – coup pressure versus AIS3+ brain injury risk; b – contrecoup pressure versus AIS3+ brain injury risk; c – Von Mises versus AIS3+ brain injury risk; d – shear stress versus AIS3+ brain injury risk

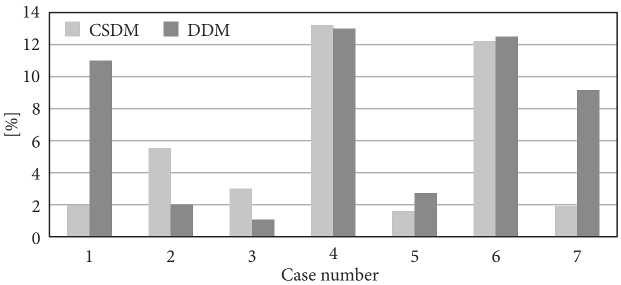

Figure 9. SIMon criterion results (CSDM, DDM)

3. Discussion

Head injury mechanisms are complex especially when considering brain injuries. Up to now, the brain injury mechanisms and tolerances remain controversial. In the current study, we investigate pedestrian head-brain injuries through real car-pedestrian accidental reconstructions and evaluate the existed injury criteria by the logistic regression model.

The correlations of all the criterion parameters with AIS3+ brain injury risk were examined using the logistic regression model, as shown in Figures 7 and 8. For each injury related parameter, there is a critical value for x, where $P(x)$ is 50% and where the injury risk shows a maximum increase.

MBS reconstruction results showed that when HIC value reached 1549.3 (Table 5), the pedestrian was likely to suffer AIS3+ head injury with 50% probability. Based on EEVC WG17 (EEVC 1998) HIC value 1000 is used as the tolerance level representing 20% probability of head injury, while in the current study the probability of AIS3+ when HIC = 1000 was 32% (Figure 6a). HIC exhibited a strong correlation with head injuries but the severity of brain injuries was not well predicted via HIC. For example, the AIS code was 4 while HIC was 1345.6 in case 1, but in case 5, HIC exceeded 2000 while the AIS code was only 2 (Table 4). These indicated that HIC was not of significant correlation to the brain injuries.

Newman (1986) indicated that when $G(t)$ value reached 1, slight head injury probably occurred. Table 5 showed the critical values of 50% probability of AIS3+ head injury was 2.7. In addition, this information can be used as additional criterion of GAMBIT.

Newman *et al.* (2000) proposed that when HIP reached 12.8 kW, cerebral concussion (AIS = 2) would be generated with 50% probability. In his study, SubDural Hematomas (SDH) was likely to happen with 50% probability when HIP reached 50 kW. In present study, the critical value for HIP was 47.4 kW (Table 5). Cerebral concussion occurred in case 3, 5, 7 while the HIP was 48.2, 64.4, 42.5 kW, respectively (Table 4). All these values exceeded the proposed tolerance of 12.8 kW. Marjoux *et al.* (2008) proposed a HIP tolerance of 48 kW for severe head injuries. These values are closer to these of current study. Due to detailed formulation considering both linear and angular acceleration and impact direction calculated from MBS reconstructions, then HIP presented a good prediction probability studying case of head injuries.

Threshold corridors of head injuries concerning of the peak angular acceleration and change in angular velocity also showed good probability for predicting brain injuries, as showed in Figure 7d. However, it does not show significant correlation of AIS severity to threshold levels.

As the former criteria are based on the kinematic parameters, physical parameters such as stress and pressure in present study exhibited stronger correlation to brain injuries (Table 7). In this study, the critical value of coup pressure is 195.5 ± 25.8 kPa and the critical value of contrecoup pressure is –196.8 ± 14.6 kPa (Table 7). Ward *et al.* (1980) proposed based on the experimental study a coup pressure tolerance of 235 kPa and contrecoup pressure tolerance of –186 kPa for serious brain injuries. Later Baumgartner (2001) based on FE model proposed pressure level of 200 kPa as an indicator of brain contusion, oedema and haematoma (Takhounts *et al.* 2003). Also Yao *et al.* (2008) suggested a coup pressure tolerance of 256 ± 76 kPa and a contrecoup pressure tolerance of –152 ± 25 kPa for AIS3+ brain injury. The critical values of these two pressure parameters between all these studies are comparable within a standard error. The differences may occur due to various FE head models.

In present study, the critical value of Von Mises is 20.1 ± 8.3 kPa and the critical value of shear stress is 11.4 ± 5.1 kPa (Table 7). Currently Yao *et al.* (2008) proposed a Von Mises tolerance of 14.8 ± 4.5 kPa and a shear stress tolerance of 7.9 ± 1.6 kPa for AIS3+ brain injury. Based on the reconstruction results of head to head collisions in professional American football games Zhang *et al.* (2004) proposed a shear stress of 7.8 kPa as the tolerance level for a 50% probability to sustain a mild brain injury. The results from present study are at higher level than other reports but comparable within a standard error.

Takhounts *et al.* (2003) proposed that slight DAI was likely to happen when CSDM reached 5.5% while serious DAI might occur when CSDM reached 22.7%. Cerebral concussion is considered to be the slight injury form of DAI. In present study, cerebral concussion is registered in case 3, 5, 7 while the CSDM are 3.1, 1.6, 2.0%, respectively (Table 6). The results show weak correlation between CSDM and cerebral concussion.

In the present study DDM is used to predict contusions. Contusions were registered in case 1 and 7 while the DDM were 11.0 and 12.5. Takhounts *et al.* (2003) proposed that 50% probability of contusions was correspond to a DDM of 7.2%. Comparing results from our study with previous results the DDM showed better capability to predict cerebral injuries than CSDM. It was also confirmed by Marjoux *et al.* (2008) who pointed that CSDM showed bad correlation with DAI due to the simple geometry and fewer elements of head model. In order to get the relationship between CSDM and DAI, detailed and accurate FE head model is needed. In addition, only 7 accident reconstructions were carried out due to the limited number of accident cases that are suitable for reconstructions. To improve the precision of calculated results, more accident reconstructions are needed in the future study.

Pedestrian safety is still a hot topic now. Although the injury risk prediction criterion is not effective enough, we could improve the vehicle design and set road speed limit to minimize the injury risk of pedestrian. The existing requirement tests for pedestrian safety have been widely applied all over the world. Even pedestrian airbags have been used in the new generation cars. Advanced Driver Assistant System seems to be the best solution for pedestrian safety, however we need steady improvement to the techniques.

Conclusions

MBS pedestrian and car models were effective in reproduction of the overall kinematics of a pedestrian in vehicle collisions. The head impact conditions at the moment of head impact against the bonnet and windshield can be calculated with accident reconstructions and used as input for injury reconstructions using head FE models.

Head injury criteria using kinematic parameters such as HIC and HIP can effectively predict head injury risk but still weak to predict detailed brain injuries. Physical parameters from FE reconstruction including coup/contrecoup pressure, Von Mises and shear stress are important predictors of brain injury risk. The critical values of these parameters, correlated to AIS3+ brain injuries with 50% probability, were determined for that confirmed findings from other studies.

The logistic regression model could be used to predict brain injury and help design pedestrian friendly car structure via FE head-car model simulations.

Acknowledgements

This study was supported by National Natural Science Foundation, China (51205117, 51405150) and Research Foundation of State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, China (51475003).

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