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Exploring the mechanisms of vehicle front-end shape on pedestrian head injuries caused by ground impact

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ABSTRACT

In pedestrian–vehicle accidents, pedestrians typically suffer from secondary impact with the ground after the primary contact with vehicles. However, information about the fundamental mechanism of pedestrian head injury from ground impact remains minimal, thereby hindering further improvement in pedestrian safety. This study addresses this issue by using multi-body modeling and computation to investigate the influence of vehicle front-end shape on pedestrian safety. Accordingly, a simulation matrix is constructed to vary bonnet leading-edge height, bonnet length, bonnet angle, and windshield angle. Subsequently, a set of 315 pedestrian–vehicle crash simulations are conducted using the multi-body simulation software MADYMO. Three vehicle velocities, i.e., 20, 30, and 40 km/h, are set as the scenarios. Results show that the top governing factor is bonnet leading-edge height. The posture and head injury at the instant of head ground impact vary dramatically with increasing height because of the significant rise of the body bending point and the movement of the collision point. The bonnet angle is the second dominant factor that affects head–ground injury, followed by bonnet length and windshield angle. The results may elucidate one of the critical barriers to understanding head injury caused by ground impact and provide a solid theoretical guideline for considering pedestrian safety in vehicle design.

1. Introduction

Pedestrian safety remains a priority in vehicle design and pedestrian protection is a critical evaluation indicator in consumer and legislative tests (EEVC, 1998; Euro-NCAP, 2013). The global road safety report released by the World Health Organization in 2015 (WHO, 2015) indicated that approximately 1.25 million people had died from vehicle accidents, and nearly half of the fatalities were vulnerable road users (VRUs), including pedestrians (22%), cyclists (4%), and motorcyclists (23%). In China, approximately one quarter of the total road fatalities involve VRUs. Furthermore, a study on 328 fatal pedestrian cases found that head injury might lead to approximately 84% chance of death (including those with multiple death causation), thereby indicating that head injury was the dominant cause of pedestrian death (Belingardi and Chiandussi, 2011; Hefny et al., 2014).

Therefore, numerous efforts have been exerted to determine the mechanisms of various types of pedestrian injury to improve vehicle safety evaluation and design. Among the universal factors, such as vehicle velocity (Cuerden and Richards 2007; Poorfakhraei et al., 2014; Yan et al., 2015), pedestrian initial stance (Simms and Wood 2006; Elliott et al., 2012), protective effect of the helmet (Oida et al., 2015; Demarco et al., 2016), and impact location (Yang and Yao, 2005; Xu et al., 2015), vehicle front-end shapes have been studied extensively (Han et al., 2012; Lyons and Simms, 2012; Crocetta et al., 2015; Sankarasubramanian et al., 2015) because this factor can be optimized directly to help avoid collisions and reduce the possibility of serious injuries.

In general, head injuries stem from three major processes: the first contact between the lower limbs of the pedestrian and the bonnet, the second contact between the head/shoulder/pelvis of the pedestrian and the engine hood/windshield, and the final contact between the head/shoulder of the pedestrian and the ground (Roudsari et al., 2005). The pedestrian–vehicle interaction is highly dependent on vehicle profile, which has triggered many pioneering works. Yan et al. (Yan et al., 2015) found that the head injury criterion (HIC) in van collisions was 1.3–2.2 times that in small car and sedan collisions within a speed range of 38–60 km/h. The major difference was attributed to the front-ends of various vehicle types. The Total Human Model of Safety (Iwamoto et al., 2002) and four vehicle models with different front-ends were used to analyze the kinematic response of pedestrians, with HIC and rib deflection as injury indicators (Han et al., 2011). The results showed that a short vehicle engine hood and a large windshield area considerably reduced the risk of lethal damage. Furthermore, Lyons and

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Simms (Lyons and Simms, 2012) probed into the influence of windshield angle, stiffness characteristics, and friction coefficient on head injury risk during the primary impact between the head and the windshield. They found that increasing windshield angle reduced the peak value of head linear acceleration by 7% and head angular acceleration by 18%. Simultaneously, a large friction coefficient would generate high head acceleration. In addition, full-scale vehicle pedestrian impact tests with different vehicles were performed using both PMHS and the Polar-II dummy (Kerrigan et al., 2005; Subit et al., 2008; Kerrigan et al., 2012), verifying the effect of vehicle front-end on pedestrian head injury during contact with vehicle.

By contrast, limited research has focused on head injuries induced by ground impact because of the diverse kinematic processes and the complicated mechanism of impact with the ground. Kendall et al. (Kendall et al., 2006) compared injuries from head–engine hood and head–ground contact and found that the former was more severe at low speed, whereas both types of injury were extremely severe at high speed. They also pointed out that the secondary injury caused by the ground was always more severe in collisions with sport utility vehicles (SUVs). Hamacher et al. (Hamacher et al., 2012) found that direct head–ground contact tended to occur when a pedestrian was struck by a vehicle with a high leading edge and large bonnet and windshield angles. A simulative study was also conducted to determine the influence of vehicle front-end profile on secondary impact injury. The results showed that mid-size vehicles with a low leading edge and SUVs with a high leading edge could prevent direct contact between the head and the ground, whereas mid-size vehicles with a high leading edge and SUVs with a low leading edge always led to direct contact; the reasons for these findings remained unclear (Gupta and Yang, 2013). A series of studies that focused on secondary impact (head–ground) injury was conducted by Simms et al. In 2006, they found that the head impact point location and injury were predictable with the variation in pedestrian initial stance during the primary impact (head–vehicle contact) but unpredictable during the secondary impact (Simms and Wood, 2006). In 2011, Simms et al. (Simms et al., 2011) performed simulations to investigate the influence of bonnet leading edge. The results showed that vehicles with a high bonnet leading edge, such as SUVs, tended to cause the head to strike the ground first. Six circulatory impact mechanisms were suggested. To comprehensively study the head–ground impact phenomenon and validate the usability of the six impact mechanisms, Simms (Crocetta et al., 2015) adopted more representative vehicle types, a wider speed range, and more varied pedestrian initial stances.

However, current studies have not yet identified dominant factors, particularly for the effect of vehicle front-end shape on head injuries caused by secondary impact, and thus, the mechanism of head injuries remains unclear. To bridge this gap, the current work comprehensively conducts a simulative investigation on injuries caused by head–ground contact. In Section 2, simulative crash scenarios, including pedestrian and vehicle models, are established, and a parametric study matrix is designed. In Section 3, the rotation angle is suggested to be a dominant variable in head–ground contact description. In Section 4, comprehensive parametric discussions are presented to indicate the mechanism of head–ground impact injuries.

2. Methods

2.1. Human model

The 50th% mid-size male pedestrian model (Automotive 2013) was used in the impact with the parameterized vehicle models. The pedestrian model consisted of 52 rigid bodies presented in 7 configuration branches and an outer surface described by 64 ellipsoids and 2 planes. The model was verified on both segment and full-body levels with a volunteer and post-mortem human subject test data (Automotive 2013). The comparison between full-scale impact tests and computer simulations in terms of the kinematics of pedestrians, force during bonnet impact, and acceleration of body segments was evaluated and further validated the pedestrian model during the interaction with the vehicle (Yang et al., 2000). Moreover, to ensure the feasibility of pedestrian model after vehicle impact, Yao et al. (Yao et al., 2008) used the MADYMO pedestrian model to reconstruct 10 real accidents and found a good correspondence between simulations and collision data in terms of pedestrian wrap-around distance and pedestrian throw distance. However, the capability of the pedestrian model to predict injury from ground impact has not been verified. And it is a limitation of this study.

2.2. Vehicle models

The vehicle model was established based on an actual vehicle model, namely, the Toyota Camry. This basic vehicle model weighed 1800 kg and exhibited the following front-end dimensional parameters: a bonnet leading edge of 0.8 m, a bonnet length of 1.1 m, a bonnet angle of 10°, and a windshield angle of 25°. The loading and unloading curves of the vehicle materials were obtained from the European New Car Assessment Program subsystem tests (Martinez et al., 2007). In particular, the windshield was divided into three sections for modeling by considering the different stiffness levels of head impact locations on the windshield. The stiffness levels of the windshield sections were obtained from (Mizuno and Yonezawa 2001).

The contact type between pedestrian and vehicle was set as combined contact, and a friction coefficient of 0.3, which was verified in a previous research (Simms and Wood 2006), was set for pedestrian–vehicle contact. Pedestrian–road contact was set as slave contact, and only pedestrian contact characteristics were used. The friction coefficient of pedestrian–road contact was set as 0.58 based on the test results of (Wood et al., 2000).

2.3. Impact scenarios

The kinematic response of a pedestrian and the posture at pedestrian–ground impact would be extremely complicated and varied given the high flexibility of the human model, which was connected by 53 joints. Therefore, defining the impact scenarios with considerable influence on the simulation results is necessary. The human model in this study was deliberately arranged such that it would be struck by the vehicle exactly on its middle section. The pedestrian would remain standing until it was struck from the lateral side. Such scenario occurs frequently at a cross intersection on a road (Yan et al., 2011), as illustrated in Fig. 1. Since the simulations were analyzed individually, only single initial stance and single walking speed were considered in this study in order to attain a reasonable analysis time. Actually, the simulation result is sensitive to these two factors (Crocetta et al., 2015) and the pedestrian stance defined here is most common rather than most dangerous.

The impact velocities of 20, 30, and 40 km/h were selected to represent a wide range of typical pedestrian–vehicle impact speeds (Simms and Wood, 2009). When impact velocity exceeds 40 km/h, the pedestrian will suffer more seriously from the impact with the vehicle than from that with the ground (Feng et al., 2013), and death mainly results from head–vehicle contact instead of head–ground impact. In addition, a constant deceleration of 0.8 g was adopted for the brake effect by setting the friction coefficient of vehicle–road contact as 0.8, similar to the strategy used by (Xu et al., 2015; Xu et al., 2016).

2.4. Injury evaluation index

HIC is widely accepted for assessing the severity of head injuries. The HIC_{15} value of 700 represents a 5% risk of receiving a severe injury. Head injury from pedestrian ground impact in partial simulations are assessed using both HIC_{15} and averages angular acceleration. The comparison between these two injury evaluation indexes is shown in Fig. 2. It is interesting to find that HIC_{15} and averaged angular acceleration are well correlated, similar to the results in (Kerrigan et al., 2012). Therefore, choosing HIC_{15} to describe head injury is appropriate