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Q1
Analysis of pedestrian-to-ground impact injury risk in vehicle-to-pedestrian collisions based on rotation angles

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A B S T R A C T

Introduction: Due to the diversity of pedestrian-to-ground impact (secondary impact) mechanisms, secondary impacts always result in more unpredictable injuries as compared to the vehicle-to-pedestrian collisions (primary impact). The purpose of this study is to investigate the effects of vehicle frontal structure, vehicle impact velocity, and pedestrian size and gait on pedestrian-to-ground impact injury risk. *Method:* A total of 600 simulations were performed using the MADYMO multi-body system and four different sizes of pedestrians and six types initial gait were considered and impacted by five vehicle types at five impact velocities, respectively. The pedestrian rotation angle ranges (PRARs) (***a***, ***b***, ***c***, ***d***) were defined to identify and classify the pedestrian rotation angles during the ground impact. *Results:* The PRARs ***a***, ***b***, and ***c*** were the ranges primarily observed during the pedestrian landing. The PRAR has a significant influence on pedestrian-to-ground impact injuries. However, there was no correlation between the vehicle velocity and head injury criterion (HIC) caused by the secondary impact. In low velocity collisions (20, 30 km/h), the severity of pedestrian head injury risk caused by the secondary impact was higher than that resulting from the primary impact. *Conclusions:* The PRARs defined in this study are highly correlated with the pedestrian-to-ground impact mechanism, and can be used to further analyze the pedestrian secondary impact and to predict the head injury risk. *Practical applications:* To reduce the pedestrian secondary impact injury risk, passive and active safety countermeasures should be considered together to prevent the pedestrian's head-to-ground impacts, particularly in the low-velocity collisions.

Q6
1. Introduction

The global status report on road safety 2015, which includes information from 180 countries, indicated that the total number of road traffic deaths remained plateaued at 1.25 million per year worldwide. The highest road traffic fatality rates were in the low-income countries (WHO, 2015). Pedestrian impacts were a significant proportion of road fatalities (Serre et al., 2007) and the majority of fatalities was caused by the head impacts (Fredriksson et al., 2001; Kong & Yang, 2010; Rosén & Sander, 2009; Rosen, Stigson, & Sander, 2011). Q8 Q7 Q9

In order to reduce the pedestrian mortality in traffic accidents, research efforts on pedestrian injury mechanisms have been conducted for decades, such as studies on injuries to the head (Bandak & Eppinger, 1994; Peng, Han, Chen, Yang, & Willinger, 2012), to the chest (Eppinger, Marcus, & Morgan, 1984; Han, Yang, Mizuno, & Matsui, 2012a; Lau & Viano, 1986), and to the lower limbs (Han et al., 2011, 2012b, 2012c; Mizuno & Ishikawa, 2005;). Such efforts put forward a lot of injury criteria (Hertz, 1993; Newman, Shewchenko, & Welbourne, 2000; Ommaya et al., 2002; Rosén, 2009). For decades, the studies of pedestrian safety have continued to focus on the injury risk prevention from the primary impacts. However, there are very few studies on the pedestrian ground impact injuries. Q10 Q11Q12 Q13

In the majority of vehicle-to-pedestrian accidents, pedestrians will eventually fall on the ground. Ashton and Mackay (1983) indicated that the pedestrian head injury severity caused by ground impact was higher than that resulting from vehicle impacts at low vehicle velocities. This is an earlier consideration for the secondary impact from the accident studies. Nowadays, with the development of automobile safety technology and the change of vehicle front end shapes, it is necessary to collect new accident statistics on the pedestrian secondary impacts. Otte and Pohlemann (2001) found that the road impact plays an important role on pedestrian injury in their analysis of 293 vehicle-to-pedestrian collisions. In their analyses, 65% of all pedestrians were injured by road impact, and 11.2% of the pedestrians suffered higher injury severity due to secondary impacts. Based on accident data, Badea-Romero and Lenard (2013) classified injuries in secondary impacts, and found that the head injuries in ground contact occur for pedestrian kinematics of Q14

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sideswipe, fender vault, and forward projection. Although none of these studies have detailed analysis of the pedestrian landing kinematics, the statistical results can be used to validate the simulations.

Some mathematical simulations have been performed to investigate Q15 the secondary impact injuries. Simms and Wood (2006a, 2006b) used the HIC36 and 3 ms acceleration to evaluate the head, pelvis, and chest injury risks, respectively; and found that the secondary impacts resulted in more unpredictable injuries as compared to the primary impacts. However, in the simulations, since only a single passenger car and a 50th pedestrian model were used without considering different pedestrian size and vehicle types, it was difficult to analyze the pedestrian landing mechanism comprehensively. Kendall, Meissner, and Crandall (2006) found that the injuries resulting from vehicle impacts consistently increased with vehicle velocity, while the head injury risk from a ground impact was correlated to a lesser extent with vehicle velocity. It can be seen that the study of pedestrian-to-ground landing kinematics is complex, and the mechanism of pedestrian landing injury is still unclear.

The pedestrian kinematics after the primary impact also has an effect on the secondary impact. Hamacher, Eckstein, and Paas (2012) analyzed the pedestrian trajectory height, throw distance, launch angle, and velocity after the primary impact; and found that the pedestrian launch angle and velocity as well as the pedestrian trajectory height were rather stable against variations of the initial posture and impact position, while the pedestrians' rotation was highly influenced by the leg and arm posture. While this study did a thorough analysis of post-crash pedestrian kinematics, a particular limitation of this study was a lack of analysis of pedestrian landing injuries. Therefore, it is difficult to understand the influence of each kinematic parameter on the severity level of pedestrian landing injury risk.

In order to investigate the influence of vehicle shape and velocity on pedestrian-to-ground impact mechanisms, Simms et al. (2011) performed a series of simulations using MADYMO. They identified six configurations of pedestrian-to-ground impacts, found a correlation between bonnet leading edge height (BLEH) and HIC in the secondary impacts, and found that the body angle at the instant of ground contact was correlated with the HIC. Crocetta, Piantini, Pierini, and Simms (2015) identified six mechanisms of pedestrian-to-ground impact through analyzing 648 pedestrians-to-vehicle impact simulations using MADYMO: more parameters (such as vehicle shapes and a broader vehicle speed range and pedestrian initial stance) were covered. These two studies provided a good understanding of the injury risk of pedestrian secondary impact, and six kinds of landing kinematics were identified to analyze the risk of injury. However, the pedestrian landing kinematics are varied, and there are more than six types of kinematics. According to a video study (Han et al., 2017), the body region that made first contact with the ground can absorb impact energy in the fall and thereby may mitigate head injury severity. Hence, it is necessary to consider the pedestrian contact body region in addition to the landing mechanisms.

The aim of this current study was to understand the relationship between pedestrian landing mechanisms and injury risk based on the pedestrian rotation angle. Using rotation angle, the ground contact conditions of the head and other body regions can be expressed. A total of 600 MADYMO multi-body simulations were conducted with four different sizes of pedestrians and six initial gaits to evaluate pedestrian impacts by five vehicle types at five impact velocities. In this study, the landing kinematics was investigated with rotational angle. The relationship between pedestrian landing injuries and landing kinematics was illustrated. It was shown that the PRARs can be a good indicator of the secondary impact injury risk. The results of this study are useful to understand various injuries to pedestrian in secondary impacts and can elucidate the reasons why the secondary impact can lead to unpredictable injuries. The findings of this study can provide a theoretical guideline of pedestrian injuries resulting from ground contacts for the automobile industry and traffic management departments.

2. Methods

2.1. Pedestrian models

In order to cover a wide spectrum of vulnerable road user groups, four pedestrian models with different body sizes were developed using the multi-body system in MADYMO code, including 10-year-old children (10 YOC), a 5th percentile adult female, and 50th and 95th percentile adult males. The 50th percentile adult model was developed by Yang and Lovsund (1997), Yang, Lövsund, Cavallero, and Bonnoit Q16 (2000), and the validity of the model was verified by comparing the model responses with Postmortem Human Subject (PMHS) test results in terms of overall kinematic and dynamic responses of the body segments. The injury severities of the body parts were also well predicted. The 5th percentile adult female and 95th percentile adult male were scaled from the 50th percentile adult male (Yang et al., 2000).

Compared with adults, children have different anatomical structures and biological tissue characteristics. Furthermore, it is difficult to obtain a child model with accurate biomechanical characteristics. The scaling method for the 10 YOC was based on the study by Liu and Yang (2002). This method takes into account not only the differences in anatomical structures between children and adults, but also the biological tissues, such as the lateral flexion properties of various joints and the ligament elastic modulus. The validity of this method was well evaluated with two real-world accidents (Liu & Yang, 2002). The pedestrian models are shown in Table 1.

2.2. Vehicle models

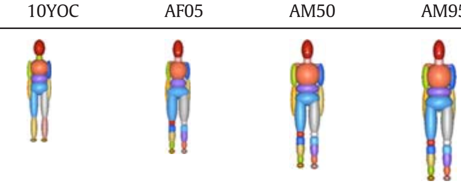
Five vehicle types (i.e., a Sedan, Minicar, SUV, MPV, and One-box) were developed based on the vehicle finite element model (Han et al., 2012a, 2012b, 2012c) as shown in Fig. 1, which covers a wide range of the classification of accident vehicles. The facet surface was generated from the corresponding finite element model with parameters of the bonnet length (BL), bonnet angle (BA), bonnet lead edge height (BLEH), ground clearance (GC), and windshield angle (WA) as shown in Table 2.

The contact stiffness characteristics were applied to all areas of the vehicle front-end structures where contact with a body part was expected, such as the bumper, hood, and windshield, which were simulated using the legform and headform impactors at impact velocities of 20, 30, 40, 50, 60 km/h, respectively (Han et al., 2012; Mizuno & Kajzer, 2000). The friction coefficient was defined as 0.2 for the contact between the body segments and the car (Wood & Simms, 2000). The road surface, on which the pedestrian finally landed, was modeled utilizing a rigid body with the friction coefficient of 0.58. The hysteresis slope was set to 10^8 for all vehicle contacts based on Crocetta et al. (2015).

2.3. Impact conditions

Previous studies primarily focused on the collision velocities below 40 km/h (Gupta & Yang, 2013; Simms et al., 2011; Tamura et al.,

Table 1
MADYMO pedestrian models.

	10YOC	AF05	AM50	AM95
				
Height (m)	1.38	1.53	1.75	1.90
CG height (m)	0.78	0.84	0.96	1.07
Weight (kg)	32.5	49.6	78.0	98.3

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