Comparative analysis on traumatic brain injury risk due to primary and secondary impacts in a pedestrian sideswipe accident

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ABSTRACT

A series of pedestrian sideswipe impacts were computationally reconstructed; a fast-walking pedestrian was collided laterally with the side of a moving vehicle at 25 or 40 km/h, which resulted in rotating the pedestrian's body axially. Potential severity of traumatic brain injury (TBI) was assessed using linear and rotational acceleration pulses applied to the head and by measuring intracranial brain tissue deformation. We found that TBI risk due to secondary head strike with the ground can be much greater than that due to primary head strike with the vehicle. Further, an 'effective' head mass, m_{eff}, was computed based upon the impulse and vertical velocity change involved in the secondary head strike, which mostly exceeded the mass of the adult head-form impactor (4.5 kg) commonly used for a current regulatory impact test for pedestrian safety assessment. Our results demonstrated that an SUV is more aggressive than a sedan due to the differences in frontal shape. Additionally, it was highlighted that a striking vehicle velocity should be lower than 25 km/h at the moment of impact to exclude the potential risk of sustaining TBI, which would

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be mitigated by actively controlling m_{eff}, because m_{eff} is closely associated with a rotational acceleration pulse applied to the head involved in the final event of ground contact.

INTRODUCTION

Sideswipes occur when a pedestrian contacts the side of a moving vehicle, which twists or rotates the pedestrian's body axially. To our knowledge, however, mechanical responses or environments involving sideswipe accidents are still unknown, and there is a lack of specific, real-world accident data for reconstructing sideswipes at this moment. In the current study, therefore, a series of pedestrian impact simulations involved in sideswipe accidents were performed at the specific impact velocities, i.e., 25 and 40 km/h, and the potential severity of brain injury was assessed using pre-selected TBI predictors such as translational and rotational acceleration pulses applied to the head as well as the cumulative intracranial strains in the brain tissue. To further understand how vehicle safety should be designed and improved for vulnerable road users, the purpose of this study was set to compare the effects of different vehicle types and impact velocities on TBI in primary as well as secondary head strikes by accounting for the broad range of pedestrian sideswipe impact scenarios.

METHODS

Mathematical Models

A series of parametric studies involving a set of variables were conducted with full-scale vehicle finite element (FE) models of a Ford Explorer and a Ford Taurus (National Crash Analysis Center), and the 50th percentile American male pedestrian FE model with a detailed brain, THUMS ver. 3 (Toyota Central R&D Labs., Inc.). Material properties utilized in the human head model were already detailed elsewhere, and Table 1 briefly provides those assigned for the current brain FE model comprising three major parts, i.e., the cerebrum, cerebellum, and brainstem. The vehicle front profiles were characterized by features such as bonnet length, bonnet angle, bonnet leading edge (BLE) height, and windshield angle etc., the geometric dimensions of which are summarized in Table 2 and Fig. 1.

Initial Settings for Pedestrian Impact Simulations

Figure 2 shows baseline simulation setups. Impact simulations were performed for two initial vehicle velocities, 25 and 40 km/h, to cover the range of typical impact speeds in pedestrian accidents [1], while at the same time a transverse travelling speed of 2.7 m/s was given to the whole body of a struck pedestrian to replicate its fast walking or jogging state and to maintain its initial posture prior to impact. Since it is common in Japan that pedestrians are struck when they are crossing the road from right to left [2], the initial pedestrian position was assumed to be located at the front right side of the striking vehicle, 1,400 mm away from the center line, which replicated a purely sideswiping impact condition with no overlap at impact. A constant deceleration pulse of 0.7g was applied to the striking vehicles to simulate braking upon impact, similar to the approach adopted in previous studies [3–6]. The vehicle downward pitch during braking and 1.0g vertical gravity were also considered as done in our preceding works [3, 4]. Further, the following configurations (#1 – #5) were simulated as shown in Fig. 3 and summarized in Table 3:

#1 Facing at 60 degrees away from the vehicle (–60 degree).

#2 Facing at 30 degrees away from the vehicle (–30 degree).

#3 Facing sideways to the vehicle (0 degree; baseline model).

#4 Facing at 30 degrees toward the vehicle (+30 degree).

#5 Facing at 60 degrees toward the vehicle (+60 degree).

The global coordinate system used for the simulations is also shown in Fig. 2. For the striking vehicle, positive *x*-, *y*- and *z*-axes point to the backward, right and superior directions, respectively. The origin of the coordinate system for the *x*- and *y*-axes was defined in relation to the initial position of the center of gravity (CG) of the pedestrian's head. Additionally, zero in the *z*-axis was defined to be at the ground level. In the present study, the ground or road surface on which the impacted pedestrian finally landed was modelled using a rigid plane with a friction coefficient of 0.6, referring to a dry-asphalt surface, and a friction coefficient of 0.3 was used for vehicle-to-pedestrian contacts [6, 7]. The commercially available dynamic explicit FE code LS-DYNA ver. 971 R6.1.1 (Livermore Software Technology Corp.) was used throughout the study with a time step of 0.9×10^{-6} seconds.

Injury Analysis

The potential risk of sustaining TBI was assessed using three selected parameters: Head Injury Criterion (HIC_{15}), resultant rotational acceleration of the head ($\ddot{\theta}_{max}$) and cumulative strain damage measure (CSDM). The CSDM, originally developed by Bandak and Eppinger [8], calculates the cumulative volume of the fraction of brain elements that experiences the maximum principal strain exceeding the specified damage tolerance level, i.e., a maximum principal strain of 0.15 in the cerebrum, cerebellum and brainstem tissues. Further, HIC_{15} (Eq. 1) and the maximum rotational acceleration of 3-ms pulse measured at the CG of the head ($\ddot{\theta}_{max}$, Eq. 2) were used to evaluate the risk of sustaining TBI during primary and secondary head strikes.

$$\mathrm{HIC}_{15} = \max \left[\frac{\int_{t_1}^{t_2} a\ (t)\ dt}{t_2 - t_1} \right]^{2.5} (t_2 - t_1) \tag{1}$$

$$\ddot{\theta}_{\max} = \max \left[\frac{\int_{t_3}^{t_4} \ddot{\theta}\ (t)\ dt}{t_4 - t_3} \right] \tag{2}$$

Here, linear acceleration, a (t) of Eq. 1, is expressed in g as a multiple of gravitational acceleration, and $\ddot{\theta}_{max}$ is the resultant rotational acceleration. Each time interval was designated as follows: $t_2 - t_1 \leq 15$ (ms) and $t_4 - t_3 = 3$ (ms), while t_1 and t_3 were determined to maximize the metrics for the primary and secondary impacts, respectively. In addition, SPSS ver. 23 (IBM) was used for comparative or statistical analysis, and significant difference was determined for $P < 0.05$ in the present study.

Effective Head Mass during Secondary Head Strike

During the ground impact phase, the impulse of the net external force applied to the head changes its momentum as previously shown in an impulse–momentum model (Eq. 3) of a walker's heel strike mechanics [9].

$$\int_{t_\mathrm{i}}^{t_\mathrm{f}} \left(F_\mathrm{z} - m_\mathrm{eff}\, g\right)\, dt = m_\mathrm{eff}\left(v_\mathrm{f} - v_\mathrm{i}\right) \tag{3}$$

where t_i and t_f are the beginning and end times of the impact phase, F_z is the vertical ground reaction force, m_eff is the effective mass of the head, g is the gravitational acceleration, and v_i and v_f are the vertical velocities of m_eff at t_i and t_f, respectively. In this study, m_eff was defined as the portion of the 'apparent' head mass during the $t_\mathrm{f} - t_\mathrm{i}$ ms period between pre- and post-head strikes, i.e., 12.9 ± 3.8 (mean ± SD) ms on average in the simulated cases (N = 20). Thus, m_eff would comprise the mass from the neck, torso or other body segments. More specifically, we computed m_eff during the secondary head strike as follows (Eq. 4):

$$m_\mathrm{eff} = \frac{\int_{t_\mathrm{i}}^{t_\mathrm{f}} F_\mathrm{z}\ dt}{\Delta v + g\Delta t} \tag{4}$$

RESULTS

Pedestrian Kinematics

In a low-velocity impact case (Fig. 4), the first contact between the hip and fender accelerated the pedestrian's lower body due to friction and resulted in a rotation over the window frame or A-pillar of the striking vehicle, which induced the large twisting moment about its longitudinal axis. In a high-velocity impact case, the first contact between the arms and side door/window accelerated the pedestrian's upper body and similarly caused a large rotation over the side of the striking vehicle. Figure 5 demonstrates a typical example of reaction forces of each body segment during SUV (sport utility vehicle)-to-pedestrian impacts. We should note that a contact force involved in the secondary head strike against ground was remarkably sharp, which typically ranged from 15 to 25 kN, and its duration time, a few milliseconds, was short compared to that of other body segments. In the reconstructed sideswipe accidents, the struck pedestrian was generally rotated away from the moving vehicle and then projected onto the ground, while the pedestrian fell to the ground comparatively close to the point of the first impact (Fig. 6).

TBI Prediction and Effective Head Mass

As shown in Figs. 7–9, each of the TBI assessment parameters involving a primary head strike was relatively minor. However, TBI assessment parameters involving ground impact were considerably high and far exceeded each of the injury assessment reference values (Figs. 7 and 8), i.e., HIC_{15} score of 1,000 [10] and $\ddot{\theta}_{max}$ of 18 krad/s^2 [11]. It should be noted that the change in TBI predictors were almost consistent when represented as a function of striking vehicle type (Figs. 7a–9a). Nevertheless, the change in $\ddot{\theta}_{max}$ was different from that of the other metrics when represented as a function of striking vehicle velocity (Figs. 7b–9b), whereas the scores of HIC_{15} and CSDM seem to be correlated well with each other.

As for the ground impact event, by integrating the time history data of reaction forces in relation to each body segment (Fig. 5), cumulative impulses of the head, torso, upper and lower extremities were computed for the pre- as well as post-head strike phases. Because the mechanical interaction between the struck human body and striking vehicle was limited in the reconstructed accident cases, post-impact pedestrian kinematics just prior to landing onto the ground was apparently a free fall phenomenon from a certain height. Thus, the effective head mass (m_{eff}) during a secondary head strike was computed in each case as given in Eq. 4 [9] and resulted in 7.4 ± 4.5 (mean ± SD) kg on average. As demonstrated in Fig. 10, worthy of note is that m_{eff} is considerably variable depending on a pedestrian's landing style.

Statistical Analysis

We performed a MANOVA and compared each of the selected TBI predictors (Figs. 7–9). As for the primary impact case, there was no significant difference between the parameters (HIC$_{15}$, $\ddot{\theta}_{\max}$, and CSDM) with respect to a vehicle type nor an impact velocity. As for the ground impact case, however, it was found that resultant head rotational acceleration pulse, $\ddot{\theta}_{\max}$, was closely associated with a vehicle type ($P < 0.05$), i.e., an SUV is more significantly aggressive than a sedan (Fig. 8a). In addition, HIC$_{15}$ was significantly correlated well with an impact velocity ($P < 0.05$), i.e., TBI risk increases with an increase of the striking impact velocity (Fig. 7b). In regard to the body orientation angle, we also found statistical significances ($P < 0.05$) with respect to CSDM due to secondary head strike and post-impact thrown distance. Specifically, CSDM value involved in ground impact was significantly higher for 0 degree case (facing sideways to the vehicle) than –60 degree case (facing at 60 degrees away from the vehicle). In addition, longitudinal post-impact thrown distance was significantly higher for –30 degree case than +30 degree and +60 degree cases (facing at 30 and 60 degrees toward the vehicle). Furthermore, by using a multiple linear regression analysis, CSDM was found to be closely correlated well with the HIC_{15} score involving primary (P < 0.05) and secondary (P < 0.01) head strikes, respectively. We also found that an effective head mass, m_{eff}, was significantly associated with a head rotational acceleration pulse, $\ddot{\theta}_{max}$, (P < 0.05) rather than the HIC_{15} score computed purely based upon a translational acceleration pulse measured at the CG of the head. It should be noted that m_{eff} was obviously linked to resultant head impulse involved in a final event of ground contact.

DISCUSSION

Since we focused on a sideswipe accident in the present study, the translational impact energy was not completely transferred to the struck human body. However, the score of HIC_{15} or translational acceleration pulse was a more influential factor on the intracranial tissue deformation or CSDM (P < 0.01) when the struck pedestrian hit the ground. This is opposed to our instinctive insight, because mechanical interaction between the human body and striking vehicle was comparatively limited in sideswipe accidents. However, since the head of sideswiped pedestrian is likely to contact with the vehicular stiff components such as an A- or B-pillar and a roof edge, depending on the assigned pre-impact pedestrian's movement, increased impact velocity of the head in a horizontal direction may have contributed to the resultant severity of HIC_{15} score during secondary head strike.

There is still a room for discussion with respect to the tolerance limit for the human brain involved in a rapid head rotation. According to the data reported by

Ommaya et al., cerebral concussion occurs with 50% probability at a rotational acceleration of 1.8 krad/s^2 with the impact duration ranging from 0 to 20 ms, while much higher tolerance values up to 25 krad/s^2, which cause diffuse brain injury and subdural hematoma, may be possible for shorter durations [12]. As thresholds for more severe TBI such as diffuse axonal injury (DAI), Ommaya et al. additionally proposed 12.5 krad/s^2 for mild DAI, 15.5 krad/s^2 for moderate DAI, and 18 krad/s^2 for severe DAI, respectively [12]. Comparing the values obtained in the present study to these thresholds, it should be noted that average $\ddot{\theta}_{max}$ obviously exceeded the tolerance limit for DAI due to ground impact.

We also calculated m_{eff} at the moment of ground impact based on the head impulse and the instantaneous velocity change in a vertical direction (Eq. 4); several portions of the human body including the neck, torso and upper as well as lower extremities contributed to the magnitude of m_{eff}, depending on a landing style of the struck pedestrian. As a result, m_{eff} was found to be closely associated with a rotational acceleration pulse of the head (P < 0.05) and mostly exceeded the mass of the adult head-form impactor (4.5 kg) commonly used for a current regulatory impact test for pedestrian safety assessment. Thus, our results highlight that ground impact is constantly much more severe and at higher risk for sustaining a TBI, and the key would be to control the landing style of the struck pedestrian even in a low-speed impact case of 25 km/h or below so that m_{eff} or the resultant head impulse can be minimized before his/her head hits the ground.

In conclusion, a series of sideswipe pedestrian accidents were computationally reconstructed. We demonstrated that an SUV is more aggressive than a sedan, suggesting that an improvement of vehicle frontal shape will be required to attain the reduction of TBI risk. Additionally, our results highlight that a striking vehicle velocity should be lower than 25 km/h at the moment of impact to exclude the potential risk of sustaining TBI, because low-speed (25 km/h) impact cases are not necessarily safe considering a final event of ground contact. We also found that m_{eff} during ground impact was fairly comparable with the resultant magnitude of head impulse and could be more than double the mass of the human head depending on a pedestrian’s landing style.

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NOMENCLATURE

HIC_{15}	Head injury criterion
$\ddot{\theta}_{max}$	Head rotational acceleration pulse measured at CG of the head
CSDM	Cumulative strain damage measure
m_{eff}	Effective head mass

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Figure Captions List

Fig. 1	Geometric dimensions characterizing vehicle front profiles.
Fig. 2	Initial setups for pedestrian impact simulations (baseline models). Striking velocity was set at 25 or 40 km/h, while a constant deceleration pulse was given at 0.7g at the moment of impact.
Fig. 3	Initial configurations for an SUV-to-pedestrian impact simulation.
Fig. 4	Pedestrian kinematics obtained in low-speed SUV impact cases (25 km/h). Facing angle was set to –60 (left) and +60 (right) degrees, respectively.
Fig. 5	Typical examples of time history of reaction forces of each body segment during vehicle-to-pedestrian impacts (UprEx: upper extremity; LwrEx: lower extremity).
Fig. 6	Comparison of post-impact thrown distance of struck pedestrian (* P < 0.05 vs. sedan in transverse direction).
Fig. 7	Comparison of the score of head injury criterion, HIC_{15} (* P < 0.05 vs. 40 km/h in ground impact).
Fig. 8	Comparison of resultant head rotational acceleration pulse, $\ddot{\theta}_{max}$ (* P < 0.05 vs. sedan in ground impact).
Fig. 9	Comparison of cumulative strain damage measure (CSDM).
Fig. 10	Comparison of effective head mass (m_{eff}) due to ground impact.

Table Caption List

Table 1: Material properties assigned for the brain FE model.

	Density (kg/m^3)	Shear modulus (kPa)		Decay constant (s^{-1})
Cerebrum	1000	G_0	10.0	100
		G_∞	5.0	
Cerebellum	1000	G_0	12.5	100
		G_∞	6.1	
Brainstem	1000	G_0	22.5	100
		G_∞	4.5	

Table 2: Geometric dimensions of vehicle front profiles.

Vehicle type	Bonnet length (mm)	Bonnet angle (deg)	BLE height (mm)	Ground clearance (mm)	Windshield angle (deg)
SUV	990	8	940	290	40
Sedan	1020	10	650	180	28

SUV: sport utility vehicle (Ford Explorer); Sedan: conventional car (Ford Taurus); BLE: bonnet leading edge.

Table 3: Vehicle-to-pedestrian impact configurations simulated in the present study.

Case No.	Vehicle type	ΔV (km/h)	Body orientation (deg)
suv25–00	SUV	25	0
suv40–00	SUV	40	0
suv25–30	SUV	25	–30
suv40–30	SUV	40	–30
suv25–60	SUV	25	–60
suv40–60	SUV	40	–60
suv25+30	SUV	25	+30
suv40+30	SUV	40	+30
suv25+60	SUV	25	+60
suv40+60	SUV	40	+60
sdn25–00	Sedan	25	0
sdn40–00	Sedan	40	0
sdn25–30	Sedan	25	–30
sdn40–30	Sedan	40	–30
sdn25–60	Sedan	25	–60
sdn40–60	Sedan	40	–60
sdn25+30	Sedan	25	+30
sdn40+30	Sedan	40	+30
sdn25+60	Sedan	25	+60
sdn40+60	Sedan	40	+60

SUV: sport utility vehicle (Ford Explorer); Sedan: conventional car (Ford Taurus). When a body orientation angle is positive, pedestrian is set to be toward the striking vehicle. When a body orientation angle is negative, pedestrian is set to be facing away from the striking vehicle.