Kinematic responses and injuries of pedestrian in car-pedestrian collisions

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Abstract. How to protect pedestrians and reduce the collision injury has gradually become the new field of automotive safety research and focus in the world. Many engineering studies have appeared and their purpose is trying to reduce the pedestrian injuries caused by traffic accident. The physical model involving impactor model and full scale pedestrian model are costly when taking the impact test. This study constructs a vehicle-pedestrian collision model by using the MADYMO. To verify the accuracy of the proposed vehicle-pedestrian collision model, the experimental data are used in the pedestrian model test. The proposed model also will be applied to analyze the kinematic responses and injuries of pedestrian in collisions in this study. The modeled results can help assess the pedestrian friendliness of vehicles and assist in the future development of pedestrian friendliness vehicle technologies.

1. Introduction

Considering the traffic safety request for most people, automakers and related research institutions put a lot of manpower, material, and financial resources to develop and improve the car body structure and safety equipment, such as airbags, and energy absorbing steering columns. The purpose of these equipment are to reduce the severity of injury to the occupant during a crash. According to the statistics of fatal traffic accidents shows these safety structures and equipment have obvious protective effects on the passengers, so that the casualty rate of passengers in the vehicle's collision accident is greatly reduced. However, pedestrians hit by cars are still very serious [1]. For the traffic accident casualties, the number of pedestrian casualties are less than the number of casualties in the passengers and ranked second. Therefore, how to protect pedestrians and reduce the collision injury has gradually become the new field of automotive safety research and focus in the world.

According to statistical data, injury of pedestrian concentrates on some regions such as head, thorax, upper limbs, and lower limbs [2]. Injury distribution of each body region for fatalities and injuries has different severity level. To effectively reduce pedestrian fatalities and injuries, designing a pedestrian friendly vehicle and protection system in relation to considerations of pedestrian safety is a relevant and urgent task. Since the 1970s, many scientists in Europe, Japan or American have started researching to find out study for pedestrian protection. Many engineering studies have appeared and their purpose is trying to reduce the pedestrian injuries caused by traffic accident. The EEVC Pedestrian Working Groups (WGs 7, 10, 17) have worked to produce the test methods and criteria [3, 4].
To facilitate the evaluation and redesign the vehicle model for pedestrian protection, Working Group 17 of the European Enhance Vehicle Safety Committee (EEVC/WG17) has developed components system tests for evaluating the pedestrian friendliness vehicles, including full-scale dummy testing and impactor models testing [5]. These are the anthropomorphic test devices that simulate the dimensions, weight proportions and articulation of some testing human body parts or whole human body.

The physical model involving impactor model and full scale pedestrian model are costly when taking the impact test. Thus, to save money and time for taking impact test, computer simulation model is an effective, alternative way to replace the physical model. Nowadays, the impact between vehicle and pedestrian studies were simulated by computer program [6-9]. For instance there were some studies built model by MADYMO (Mathematical Dynamic Model) 2D and 3D. The data obtained was used to evaluate the kinematic in reconstructions of pedestrian crash and using its injury prediction ability to find impact area on vehicle.

To effectively assess pedestrian injuries resulting from impacts with vehicles, a computer simulation model must be developed for vehicle-pedestrian collision analysis. This study constructs a vehicle-pedestrian collision model by using the MADYMO. To verify the accuracy of the proposed vehicle-pedestrian collision model, the experimental data (Post-Mortem Human Subject (PMHS)) are used for the validation of pedestrian model [10]. These data provide the corridor trajectories for the head, pelvis, knee, and foot used to validate the pedestrian model. The proposed model also will be applied to analyze the kinematic responses and injuries of pedestrian in collisions in this study. The modeled results can help assess the pedestrian friendliness of vehicles and assist in the future development of pedestrian friendliness vehicle technologies.

2. Multi-body model

2.1 Pedestrian model
MADYMO offers a powerful and extensive human model database. A pedestrian model with a height of 175 cm and a weight of 77 kg was used in this study. In order to simultaneously get the femoral and tibial injury values at the same time, this study modified the original femoral and tibial models from a single ellipsoid to two same size of ellipsoids, and established a joint in between. The pedestrian model is described by 37 ellipsoids to replicate the human bodies. The ellipsoids of the model act as several individual body parts such as head, torso or upper leg, where the stiffness, shape, size, mass and inertia are predefined based on the MADYMO. 16 joints exists to connect these ellipsoids together. The contact response of the ellipsoids is measured by 24 accelerometers mounted in the ellipsoid surface. Seven chains connect all segments of pedestrian model. As mostly collision accident statistics show that pedestrians are in the process of walking and the vehicle impact on the side. In this study, the relative position between pedestrian and vehicle is set to the side impact mode.

2.2 Vehicle model
Figure 1 shows the frontal shape of the car model used in this study. Moreover, LEH denotes the height of the leading edge of the hood, BL represents the bumper lead (longitudinal distance from front of bumper to front of hood), BCH is the bumper center height, HL is hood length and α is hood angle. The vehicle model is constructed with multiple rigid ellipsoids representing the windshield, hood, hood front, bumper and tires, respectively.

2.3 Vehicle-pedestrian collision model
Figure 2 displays the vehicle-pedestrian collision model in present study. A vehicle impacts the left side of pedestrian with a velocity of 40 km/hr. In this model, the friction coefficients between foot and ground is 0.67, the friction coefficients between pedestrian model and car is 0.25 and the friction coefficients between car and ground is 0.8.
3. Analysis of pedestrian collision trajectory

Figure 3 presents a simulated impact sequence in a vehicle-pedestrian collision simulation model at an impact speed of 40 km/h. As figure 3 presented, the shank hit against the bumper and the thigh also hit the edge of the hood at 20 ms. The shank and thigh is still in contact with the vehicle at 40 ms. The pelvis shows a clockwise rotation owing to step forward with left thigh. The wrist contacted with the hood at 60 ms, and the pelvic parts also began to collide with the hood. The shank part from the bumper with the curvature action, then the thigh has left the front of the bumper and turned on the hood surface at 80 ms. The thigh with the body away from the vehicle, but the pelvis, arm maintain contact with hood surface at 100 ms. The left hand arm completely contact with the hood at 120 ms, the torso also began to hit the hood. The head hit the windshield at 140 ms, the torso also collided with the hood.

The vehicle-pedestrian collision model was validated using post-mortem human subject (PMHS) corridor for the head, pelvis, knee and foot [10]. Figure 4 to figure 7 list the head, pelvis, knee, and foot trajectories of pedestrian. The head displacement separates a little from the limitation, particularly at the end of the curve (figure 4). Because the slope angle of hood surface is 12° relative to the ground that will force the pelvis moves upward when it contacts and slides on the hood. The increase in upward pelvis movement is accumulated during the sliding process so that according to the pelvis...
curve, the final position is higher than the upper limitation of PMHS data. Because of the relation between the pelvis and the head, together with upward movement of the pelvis, the head displacement also exceeds the upper limitation. The pelvis and knee trajectories fall entirely within the corridor (figure 5, 6). The good agreement of knee displacement with experimental data clearly indicates that the hip joint in the pedestrian model is very suitable for free impact. The end of the foot trajectory curve does not fall within the PMHS corridor owing to the deformation of the leg upon impact with the bumper (figure 7). It is presumed that the ankle is made up of multiple ellipsoids in the pedestrian model. The thighs and calves are also joined by two ellipsoids, and more than one set of joints. It is more likely to make the pedestrian model have excessive bending, resulting in an ankle trajectory moving to the left of the situation.

**Figure 4.** Head trajectory of pedestrian model together with PMHS corridor.

**Figure 5.** Pelvis trajectory of pedestrian model together with PMHS corridor.

**Figure 6.** Knee trajectory of pedestrian model together with PMHS corridor.

**Figure 7.** Foot trajectory of pedestrian model together with PMHS corridor.

### 4. Injury analysis of pedestrian

In the MADYMO simulation analysis, the head, pelvis, thigh and shank were used to analyze the pedestrian injuries. In the injury of various parts of the human body, the head HIC value of 1255 exceeds the safety threshold of 1000. To translate HIC value into AIS severity scores, an AIS 4 head injury was produced. It may cause skull rupture and nerve damage which can lead to the risk of death. The pelvic injury reached 623.75 N which is lower than the criteria of pelvic fracture. Femoral and tibial injury is a common injury in pedestrian suffering impacts with vehicles. These injury are evaluated based on femur and tibia fracture resulting from bending moment of the femur on impact with the bumper and the resultant acceleration of tibia. The bending moment of the femur is 392.67N.m, and the tibia acceleration is 216.5 g. Limitations to avoid serious femur and tibia injury
are 200N.m for bending moment and 150g for tibia acceleration, respectively. The maximum bending moment and acceleration values for the femur and tibia exceed the threshold value. These results demonstrate that the femur and tibia suffers fracture on impact with the bumper.

In order to confirm the rigid multi-body model for the injury analysis, the injury results of are compared with the numerical simulation results of Rooij [8]. The injury data are shown in Table 1. According to the analysis model of Rooij and the injury model in this study, it can be found that the difference of analysis results are less than 15%. The frontal shape of the finite element vehicle model is more fine than that of the rigid multi-body model. It is the reason why Rooij result causes a high injury value of femur. The analysis of the head and pelvic injury values are converted to the AIS, as shown in Table 2. The table indicate that two models of the head and the pelvis of the AIS are in the same injury level.

| Table 1. Injury risk comparison between the Rooij and present study. |
|----------------|----------------|----------------|
|                | Rooij [8]      | Present study  |
| Head Injury (HIC) | 1420           | 1255           |
| Pelvis Injury (N)  | 675            | 623.75         |
| Femur Injury (N.m) | 99.56          | 94.95          |
| Tibia Injury (g)   | 237            | 216.5          |

| Table 2. The head and the pelvis of the AIS |
|----------------|----------------|----------------|
|                | Rooij [8]      | Present study  |
| Head           | AIS 4 ~ AIS 5  | AIS 4 ~ AIS 5  |
| Pelvis         | AIS 0 ~ AIS 1  | AIS 0 ~ AIS 1  |

5. Conclusion
In this study, a vehicle-pedestrian collision model was constructed by using the MADYMO to analyze the kinematic responses and injuries of pedestrian. The current study shows the vehicle-pedestrian collision model has a reasonable correlation with Post-Mortem Human Subject experimental data. And the model is more visible in assessing injuries of pedestrian. The modeled results can help assess the pedestrian friendliness of vehicles and assist in the future development of pedestrian friendliness vehicle technologies.

6. References
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