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Development and validation of a pedestrian deformable finite element model [†]

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Abstract

Pedestrian protection has become an increasingly important consideration in vehicle crash safety. Pedestrian-vehicle crashes cause a significant number of pedestrian fatalities and injuries globally. Computer models are powerful tools for understanding how to reduce the severity of injuries in such crashes. Real-world studies of pedestrians provide an important source of information for evaluating pedestrian model dynamic performance and ability to reconstruct injury-causing events. This study describes the validation process of deformable pedestrian model using published post-mortem human subject (PMHS) trajectory and head resultant velocity corridors, and demonstrates its applicability to pedestrian - vehicle impact research. We implemented the deformable pedestrian model using LS-DYNA finite element code. Based on PMHS data, the pedestrian model is used to validate the displacement trajectories of the head, pelvis, knee and foot. The finite element pedestrian model thus obtained can help assess the friendliness of vehicles with pedestrians in traffic crashes and assist in the future development of pedestrian safety technologies.

Keywords: Pedestrian; Deformable model; Pedestrian-vehicle impact; LS-DYNA

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1. Introduction

Traffic accidents result in a significant number of pedestrian fatalities and injuries globally. Pedestrian protection is a significant component of traffic safety. According to a survey of 35 European countries during 2003, pedestrians represented an average of 25% of all road user fatalities. In Japan, pedestrian fatalities accounted for 28% of the road toll, and approximately 16% in Australia. These figures compare with 13% for the USA and 40-50% for India and Thailand [1]. Thus, pedestrian accidents contribute to a significant proportion of traffic crashes, especially in Asian countries. Another investigation has shown that road accidents involving pedestrians are common and over 9,500 pedestrians die every year on the United States' roads [2]. Approximately 11% of road accident fatalities during 2004/2005 were of pedestrians in the United States. The above figures demonstrate the urgent need for the automobile industry to consider pedestrian safety. To effectively reduce pedestrian fatalities and injuries, it is urgently necessary to design pedestrian-friendly vehicles and pedestrian protection systems.

A new EU regulation has been devised with the intention of protecting pedestrians in crashes involving automobiles. Today, vehicles are already being tested for their characteristics in accidents involving pedestrians as part of the EuroNCAP (European New Car Assessment Program), using impactors (leg, head) on the bumper beam and motor hood. For the development of pedestrian protection systems, the hood should be raised approximately 6 to 10 cm shortly before impact to limit the effects of impacts involving pedestrian head and car hoods [3, 4]. Also, substituting the bumper material for a softer material such as buffer rubber or plastics can reduce the incidence of

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serious leg injuries [5, 6]. A recent trend is the application of outer air bag systems in the A-pillar and leading edge [6, 7].

To assess the degree of pedestrian protection provided by a vehicle and protection system, it is necessary to develop an efficient evaluation and analysis methodology for assessing vehicles in terms of pedestrian protection. Recent developments in computer technology have allowed applied mathematicians, engineers, and scientists to solve previously intractable problems. Numerical simulations are valuable design tools for automotive engineers. Two methods are currently used to assess the pedestrian friendliness of vehicles via computer simulation: the impactor method [8, 9] and the full scale method [10, 11]. Therein, the second method only applied the rigid pedestrian model, and currently deformable models are being developed, such as the THUMS AM-50 pedestrian model [12]. However, most deformable models have not been validated and published.

Most current pedestrian protection devices are based on the friendliness evaluation of car-to-pedestrian results of the impactor method. However, this method cannot obtain a full assessment of pedestrian-car impacts, such as pedestrian head impacts on the windshield or the A-pillar, and in particular it does not mention the kinematic response of pedestrians in impact with cars. For effectiveness in pedestrian safety assessment, the full scale method can effectively satisfy very strict requirements in evaluating pedestrian injuries. However, the rigid model remains inadequate for evaluating pedestrian injuries. Although the full rigid model avoids the weaknesses of the impactor method, precise evaluation of pedestrian injuries such as those involving the thorax and pelvis requires using the deformable model. The deformable human model not only presents good dynamic response and impact behavior of the pedestrian model to the vehicle and deformable models, but also provides precise and visible assistance in injury assessment, i.e., the deformable pedestrian model is able to realistically simulate the local deformation in addition to global deformation as in the rigid model. It is easy to identify the location of serious injuries and the manner in which organs are injured, such as bones and joints in the pelvis and thorax of current model.

To effectively assess pedestrian injuries resulting from impacts with vehicles, a deformable pedestrian model must be developed for vehicle-pedestrian collision analysis. This study constructs a pedestrian numerical model by using the LS-DYNA finite element code, and it also details the method used to build the pedestrian finite element model. To verify the accuracy of the proposed deformable pedestrian model, the experimental data (Post-Mortem Human Subject-PMHS) [13] are used in the pedestrian model test. These data provide the corridor trajectories for the head, pelvis, knee, and foot used to validate the pedestrian model. The proposed model can be applied to analyze the dynamic responses and injuries of pedestrian in collisions. The modeled results can help assess the pedestrian friendliness of vehicles and assist in the future development of pedestrian friendly vehicle technologies.

2. Development of the pedestrian finite element model

The pedestrian model was developed based on the Eurosid-1 model, which is a deformable occupant model suitable for use in side impact analyses. However, the Eurosid-1 model is a seat model and some parts are considered for analyzing occupant injury in side impact. It was revised and improved (especially those associated with the lower torso) as follows: pelvis, hip joint, thigh, leg, ankle, and foot. Fig. 1 displays the pedestrian model in the present study after development and validation.

- Number of nodes: 55,000
- Number of materials: 80
- Number of shell elements: 46,000
- Number of solid elements: 100,000
- Number of beam elements: 100

The deformable model is extremely useful for analyzing pedestrian injuries. Based on the force of the

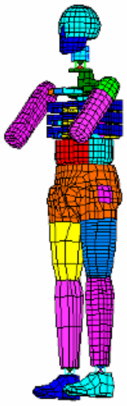


Fig. 1. Pedestrian model.

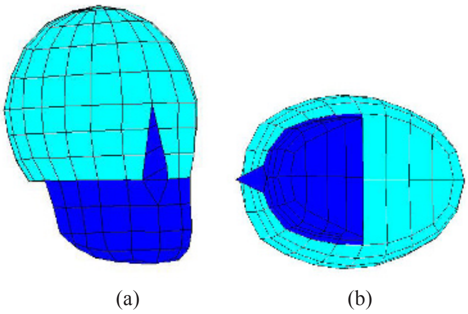

(a) (b)

Fig. 2. Head of pedestrian model: (a) ISO view, (b) Bottom view.

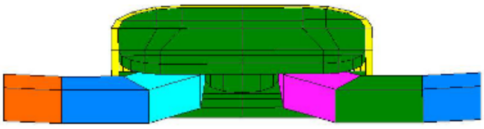


Fig. 3. Clavicle of pedestrian model.

contact and the model deformation associated with an impact with a car, the injuries are compared, the vehicle pedestrian friendliness is assessed, and guidance is provided for the future development of pedestrian safety technologies. The pedestrian finite element model is detailed further as follows.

2.1 Head

The head of the model consists of an aluminum skull covered with PVC skin. The skin is modeled using solid elements, the inner nodes supported by rigid body skull. Fig. 2 illustrates the head model.

2.2 Clavicle

The Eurosid-1 clavicle is designed to realistically represent the shoulder or arm rotation that occurs during a side impact. The model describes the interaction between the clavicle and the shoulder box, which is important to support for vertical clavicle loading. Owing to the shoulder deformation will influences the kinematic response of the pedestrian model during the pedestrian-car impacts. In this pedestrian model, the clavicle includes an additional deformable element on both sides to facilitate shoulder deformation on impact. Fig. 3 illustrates the clavicle.

2.3 Arms

The arm on the impact side is described using finite elements that contain the PVC skin and nylon plate. Fig. 4 shows the arm model. The joints connecting the arm to the clavicles are revolute joints.

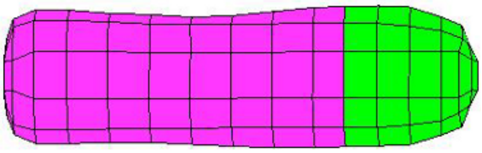


Fig. 4. Arm of pedestrian model.

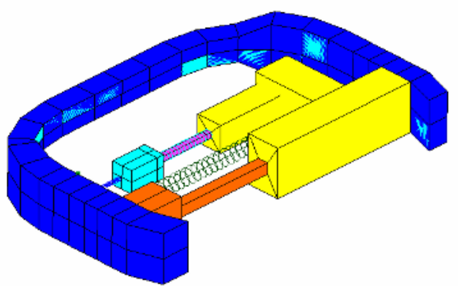


Fig. 5. Rib module of pedestrian model.

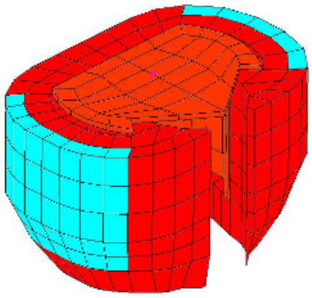


Fig. 6. Abdomen of pedestrian model.

2.4 Thorax

The Eurosid-1 thorax comprises three identical rib modules. Fig. 5 shows the model. The inner spring-damper assembly of each rib model is built from multibody entities. Moreover, the outer components--steel strip, foam and foam skin--are modeled with finite elements.

2.5 Abdomen

Deformable materials are used to model the abdomen flesh, load cells and abdomen drum. The abdomen drum is connected to the rigid body modeled spine. Fig. 6 illustrates the abdomen model. The waist joint has a very unusual design; the joint flexibility is defined by the Young's Modulus of the elastic mate-

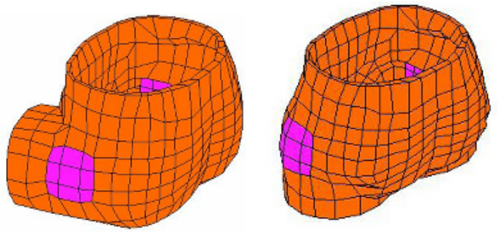

(a) (b)

Fig. 7. Pelvis models (a) seat model (b) pedestrian model.

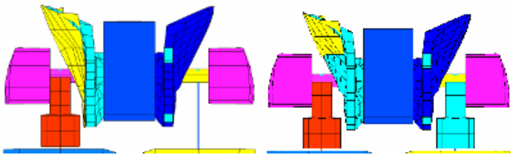

(a) (b)

Fig. 8. Hip joint structures (a) seat model (b) pedestrian model.

rial. Thus, in the pedestrian model the joint was softened by reducing the Young's Modulus of the material.

2.6 Pelvis

The sacrum block, iliac wings, pelvis plugs and outer flesh are modeled using finite elements to represent the complex deformation of the pelvis. After changing the seat model to a standing model, the pelvis foam became unreasonable for connecting with thigh model (see Fig. 7) because its shape was only suitable for the seat model. In this investigation, the pelvis foam was rebuilt with the same size as the original model, with the inside geometric of the foam model being kept intact and the outside surface being changed using the standing model, as shown in Fig. 7. Material, property and contact types resemble the original model. The nodes connection to the thigh coincided with the thigh nodes to be more suitable in contact between them in free impact with car.

2.7 Hip joint

The joint of the Eurosid-1 seat model was only one side, which was in the impact test; the other side was simpler than the previous side regarding properties. The hip joint is very important in pelvis displacement on hood surfaces, and also plays a key role in knee displacement. The hip joint in the pedestrian model was improved with the same properties at both sides by copying the properties of impact side to build the remaining side as shown in Fig. 8. This improvement can help the model balance the pelvis weight, thus affecting parts displacement in falling down of the pedestrian model after impact with a vehicle. The adduction and abduction angles are limited by the deformation capability of the foam in the pelvis area and in the two thigh upper extremities.

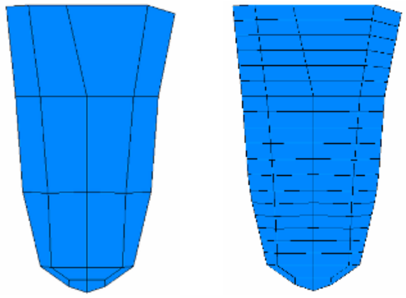

(a) (b)

Fig. 9. Thigh models (a) seat model (b) pedestrian model.

2.8 Thigh

In free impacts between cars and pedestrians, the displacement of the head, pelvis, knee and foot not only depends on joint properties but also depends on the deformation of certain components on impact, especially the thigh and leg. For the above reason, the thigh was softened in the impact side of the model; otherwise the thigh model was also rebuilt using 580 nodes rather than 77 nodes to analyze pedestrian injuries, as shown in Fig. 9. As a finite element problem is always calculated based on the model nodes, in certain respects the calculation results can be improved when the model includes more nodes. When analyzing thigh injuries, the results of impact force used for the assessment are obtained from nodes. The results used to analyze thigh injuries demonstrated that the softening of the thigh model is reasonable.

2.9 Knee

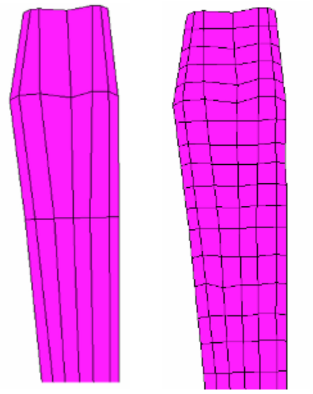
Because knee stiffness has little influence on the kinematics of the pedestrian model [14], particularly on the upper torso, this study retained the knee joint from the seated model despite its simplicity (comprising one non-linear spring and one damper). When analyzing the injuries in the pedestrian model, the suitability of the knee can be improved to assess the shear displacement.

2.10 Leg

The original left leg models were also extremely simple, with one half on the impact test side comprising deformable material, while the other side consisted of rigid material. Thus, in the pedestrian model, the left leg was rebuilt with 572 nodes rather than 74 nodes to more accurately determine the force results, and the deformable material was used in the whole left leg for easily demonstrating how to deform the leg by the impact of the bumper. Fig. 10 shows the old and new models. Both the thigh and leg were softened by changing the Young's Modulus to provide the model with sufficient flexibility to absorb some of the impact energy rather than by forcing the joints to absorb all of the energy as in the rigid model. The deformable model can model human reaction to impacts due to this feature, and it is better than the rigid model.

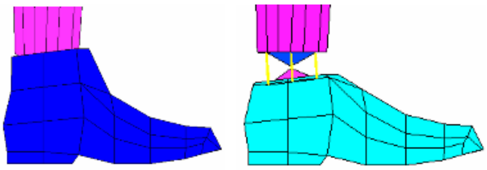
2.11 Ankle joint

Since the original model lacked ankle joints, the revised model was modified to include them. The ankle joints were used to analyze ankle injuries (inversion/eversion degree) suffered by pedestrians. The ankle joints contained six springs and four dampers, as shown in Fig. 11.



(a) (b)

Fig. 10. Leg models (a) seat model (b) pedestrian model.



(a) (b)

Fig. 11. Leg models (a) seat model (b) pedestrian model.

2.12 Foot

The weight of each foot was increased to 1 kg including the shoe. Because the foot model in Eurosid-1 was not heavy enough, it was not suitable for assessing ankle injuries associated with free impacts.

2.13 Contact interactions

All internal dummy contact interactions in the model are predefined. Furthermore, contact sets are defined for the parts of dummy that contact with the environment. This arrangement permits engineers to define contact type with the environment in a user-friendly and consistent way.

The size of the model is compared with the PMHS data (normalized), as shown in Table 1. The size of the pedestrian model fits the PMHS limitations, and can be used to reconstruct real cases. The model was set to stand on the street and had no arms because the arms affect the displacement trajectory of pedestrians in falling down after impact with a car, so the armless model was selected for validation.

3. Validation of the pedestrian finite element model

The pedestrian model was validated by using post-mortem human subject (PMHS) corridor for the head, pelvis, knee, foot, and the resultant head velocities are obtained from experimental data [13].

3.1 Validation processes for the PMHS corridor for pedestrian model

3.1.1 PMHS corridor for vehicle

Fig. 12 shows the vehicle shape used for the validation. 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

Table 1. Pedestrian size corresponding with PMHS size for trajectory and velocity corridors.

Velocities (km/h)	Height (cm)		Weight (kg)	
	PMHS	Simulation	PMHS	Simulation
25	173.5 ± 6.5	174	65.5 ± 9.5	74
32	181.5 ± 6.8	174	79.8 ± 11.7	74
40	170.5 ± 4.5	174	71 ± 17	74
Normalized for trajectories corridor	177.7 ± 7.9	174	75.2 ± 13.9	74

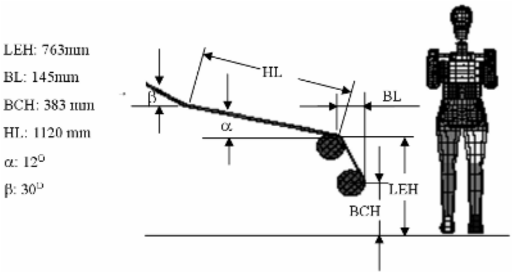


Fig. 12. Car-Pedestrian impact posture.

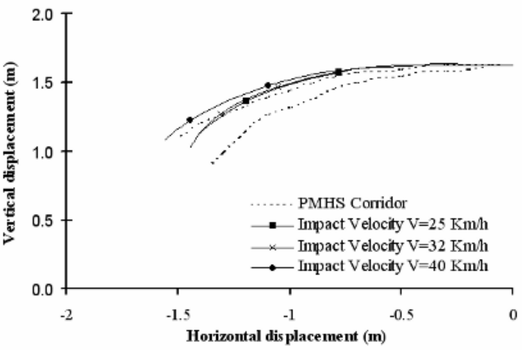


Fig. 13. Head trajectory of pedestrian model together with PMHS.

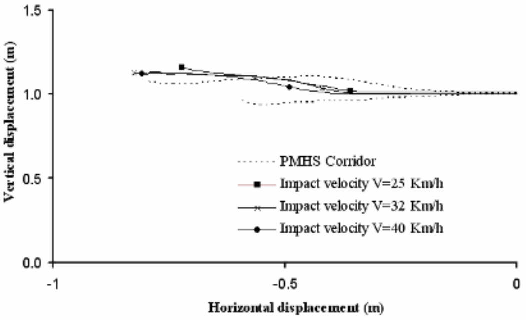


Fig. 14. Pelvis trajectory of pedestrian model together with PMHS corridor.

hood), and BCH is the bumper center height.

3.1.2 PMHS corridor for pedestrian

The pedestrian model was validated by using impacts at three velocities (25, 32, and 40 km/h). Table 1 lists the average PMHS height and weight used to create the trajectory and velocity corridors for each of the three velocities (the corridors were normalized for the three speeds in the trajectory plots) [13]. If the model trajectory curves were similarly shaped and fell within the published PMHS corridors on head impact, they were considered sufficiently accurate for use in case of reconstructions.

Table 2. Dimensions of car model and PMHS data.

Items	PMHS	Simulation Car Model
BCH : Bumper height (mm)	383	383
BL : Bumper lead (mm)	145	145
LEH : Hood leading edge height (mm)	763	763
HL : Hood length (mm)	-	1120
α : Hood inclination (degrees)	-	12
β : Windshield inclination (degrees)	-	30

Fig. 13 lists the PMHS corridor of the head, pelvis, knee, and foot trajectories, together with simulation results for all three velocities 25km/h, 32 km/h, and 40 km/h., and Fig.14 lists the time histories for head resultant velocity relative to the car body.

3.2 Finite element car model

The front shape of the car model was built by using PMHS corridor with five parameters shown in Fig. 12. The first two parameters are hood length (HL) and hood angle (α); the rest of three are the height of the leading edge of the hood, the bumper lead and the bumper center, and they are similar to the experimental data. The model weight and gravity were directly taken from a Ford Taurus model. These two parameters were set as in the Ford Taurus model to make the impact kinematics behavior reasonable as in actual impact. Two friction coefficients were set: foot to ground, 0.67 and model to car hood, 0.25 [13]. The car model is a rigid model, and contacts between cars and pedestrians were automatically surface-to-surface. The model and dimensions are shown in Table 2 and Fig. 12.

The validation process only considers joint displacement of pedestrians, and thus these geometric parameters must be satisfied because they affect the movement trajectory.

3.3 Validation result and discussion

The head displacement separates a little from the limitation, particularly at the end of the curve (Fig. 13). The head moves further from the PMHS corridor with increasing speeds. This undesired movement can be explained by the movement of the pelvis on the hood surface. As the slope angle of hood surface is 12 relative to the ground, it will force the pelvis to move upwards when it contacts and slides on the hood. The increase in upwards pelvis movement is accumulated during the sliding process so that the final position is higher than the upper limitation of PMHS data according to the pelvis curve (Fig. 14). Consequently, the head displacement also exceeds the upper limitation because of the relation between the pelvis and the head, together with upwards movement of the pelvis. At 40 km/h, the head trajectory is furthest from corridor, while at 25 and 32 km/h the two trajectories are close together and mostly follow the upper limitation. This difference results from the kinematic energy associated with the impact; the model is more suitable for impact energy at 25 and 32 km/h than that at 40 km/h. In this study, the PMHS data is not available for the hood angle parameter of car; thus the hood angle is designed by using the hood angle of the Ford Taurus car model. The pelvis displacement trajectories at 25km/h and 32 km/h are very close to each other, and the knee trajectories fall entirely within the corridor at 3 velocities 25, 32 and 40 km/h (Fig. 15). 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, because knee joint movement is primarily decided by the hip joint and only partially by thigh deformation. 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 (Fig. 16). The leg deformed by the impact fails to recover its original shape after leaving from the bumper.

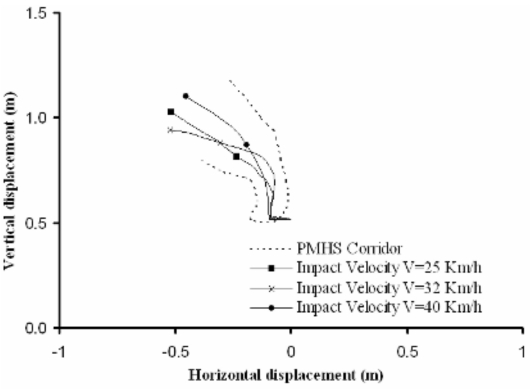


Fig. 15. Knee trajectory of pedestrian model together with PMHS corridor.

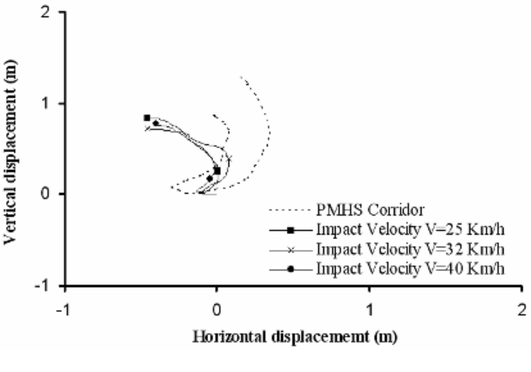
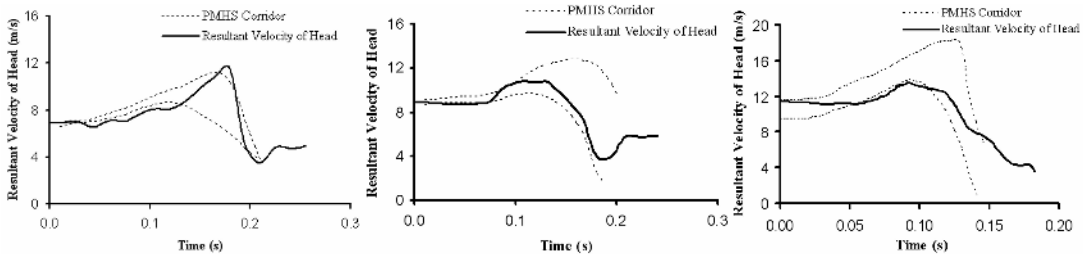


Fig. 16. Foot trajectory of pedestrian model together with PMHS corridor.

The head resultant velocity trajectories fall entirely within the corridor at 32 km/h, but at 25 km/h the curves are very close to the upper corridor and at 40 km/h it approaches the lower limitation of PMHS data (Fig. 14).

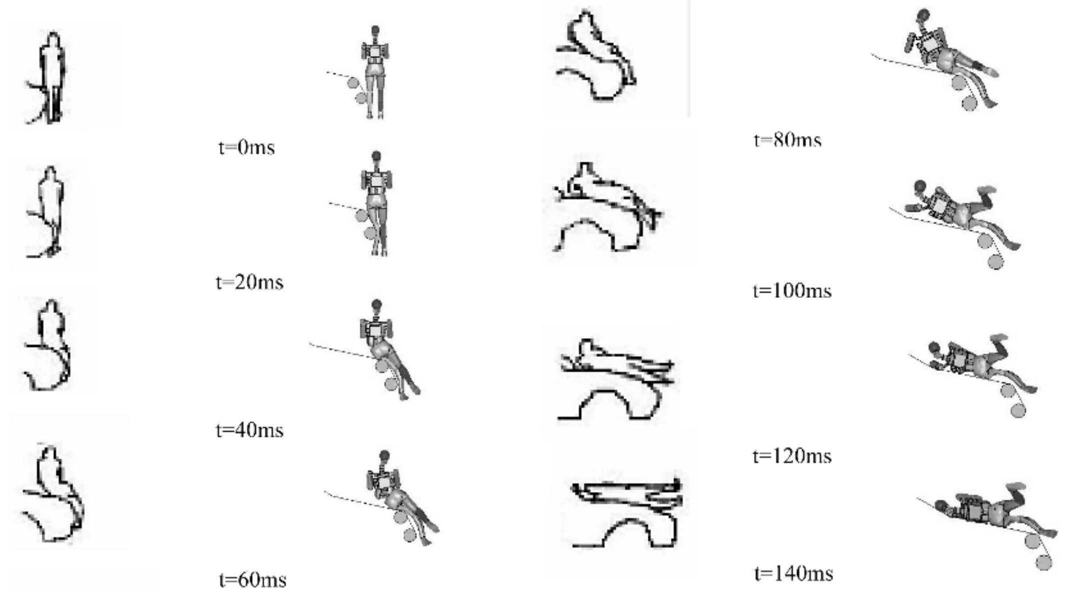
4. Kinematics of pedestrian in impact with vehicle

Fig. 17 displays typical overall pedestrian kinematics from a computer simulation and a cadaveric test-Y3 [14] at an impact speed of 40 km/h. Y3 is a cadaver with height 177 cm and weight 84 kg, and it is selected for comparison with the simulation. Because the height of the Y3 is almost identical to the pedestrian model, the kinematic response of Y3 can be used to assess the pedestrian model in impact with car. The lateral rotation of upper body segments and the leg bending motion were well predicted. Notably, the kinematics of the upper torso was almost identical up to 80 ms, though at 100 ms the upper parts moved a little a distance up the hood surface; after 100 ms the upper body segments once again display good agreement with cadaver response. The head kinematics closely resemble the cadaveric body because of the neck joint being sufficiently flexible to adapt to impact energy, and only the shoulder response differs a little after 40 ms. In the cadaveric experiment the shoulder remains upright up to 80 ms, and moreover the shoulder and chest in the pedestrian model rotate slightly with the rotation of the pelvis. The leg kinematics do not display a good agreement with the experimental data; in particular, those are for the right leg (which does not have an impact on car-the free leg). The left leg was deformed by the impact force during the crash impact. Because the leg is a deformable model, it was unable to recover its initial form after the impact occurred. As a result, the kinematics of the leg after 80 ms does not display good agreement with the cadaver. The two legs move separately after 80 ms and separate



(a) Impact velocity V=25 Km/h (b) Impact velocity V=32 Km/h (c) Impact velocity V=40 Km/h

Fig. 17. Head resultant velocity of simulation together with PMHS corridor.



(a) Cadaver test (b) Simulation result (a) Cadaver test (b) Simulation result

Fig. 18. Validation result on overall pedestrian kinematics.

rapidly during the following stages. This behavior relates to the deformable characteristic of pelvis foam, which is not tense enough to prevent the right leg from abducting a large distance.

Although the deformable pedestrian model was successfully established in this study, and although this model is very useful for analyzing pedestrian injuries and assessing vehicle pedestrian friendliness, it is in fact very complicated to construct it. The model involves too many components; thus validating the model is extremely time-consuming and the contact relation between components prevents the revision or adjustment of the model parameters.

5. Conclusion

The pedestrian and car models were developed by using LS-DYNA, and its construction was based on the experimental data (Port-Mortem Human Subject - PMHS). The current study indicated that the development and validation of pedestrian to vehicle impact simulation have a reasonable correlation with Post-Mortem Human Subject experimental data. The hood angle also has an influence in the pedestrian model displacement, especially in the head and pelvis parts. The difference in foot displacement results from the difference between real humans and the model built by simulation. Pedestrian parts displacement not only depends on the joint properties of the model, but also on the deformation ability of parts which impact the car. Using a deformable model to analyze the injuries of pedestrian is more visible in assessing pedestrian injuries and more useful in cases involving bone and the body segments inside foam of body, particularly in the pelvis and thorax of the present model. Thus, it is indispensable for one to construct and develop the deformable pedestrian full scale model in order to fully satisfy the strict requirements in pedestrian protection today. The next steps in applying this model are first to analyze and evaluate the pedestrian injuries, and second to assess the friendliness of vehicle with pedestrian and to assist with the future development of pedestrian safety technologies such as redesigning frontal shape of vehicle because developing the pedestrian protection devices is more friendly than using the impactor method.

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