Investigation of the Effect of the Height Alignment on the Validity of the Scaled Whole Body Trajectories in Car-to-pedestrian Collisions

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ABSTRACT: In order to identify the height alignment with a standard-sized pedestrian that best estimates the whole body trajectories by scaling those of a pedestrian in a different size, car-to-pedestrian collision simulations were conducted using five production car models in the small sedan category, human FE models in three sizes and five aligned points with the standard-sized pedestrian. The trajectories from the simulations were scaled using the distance between the aligned point and the measurement point of the trajectory. The results showed that aligning with the knee-joint height provided the best estimation of the trajectories in the small sedan category.

KEY WORDS: safety, biomechanics, pedestrian safety, trajectories, scaling [C1]

1. Introduction

Although the number of traffic fatalities in Japan decreased by 50% from 2001 to 2011, pedestrian fatalities decreased by only 30% during the same period(1). In order to further reduce pedestrian fatalities, it is necessary to further improve pedestrian safety technologies based on whole body injury mechanisms in car-to-pedestrian accidents because the subsystem test method adopted by regulations and New Car Assessment Programs (NCAPs) can not evaluate mechanical interaction between different body regions.

A whole body pedestrian dummy(2) representing such mechanical interaction has been developed as a useful tool to investigate injury mechanisms. In order to assess the biofidelity of the pedestrian dummy, biofidelity corridors were needed. Due to difficulty in the use of subjects with similar stature in the test using human subjects, the test results for each subject were needed to be scaled to a standard-size pedestrian to develop such biofidelity corridors.

The SAE Information Report J2782(3) specifies the requirement for the whole body and the components of the dummy, such as dimensions, mass distribution, biofidelity and repeatability. In addition, the procedure to develop trajectory corridors for each body region from full-scale impact testing against PMHSs, along with an example of the trajectory corridors for the head centroid (Head), upper spine (T1), mid-thorax (T8) and pelvis (Pelvis), are presented in the SAE Information Report J2868(4). Using the test results from Kerrigan et al.(5) in which the hindfoot of the PMHS was aligned to the ground, the procedure applies a scaling technique to both components of the trajectories in the vertical direction and the longitudinal direction of the car using the vertical distance between the trajectory target point and the ground to compensate for the difference in the size of the subjects used in the tests. Since a car cannot be scaled based on the size of the subject used in the impact test, it is obvious that geometric scaling does not perfectly apply. However, considering that the primary motion of the whole body of a pedestrian relative to a car during a car collision is a rotation toward the car, it is assumed that identification of the effective center of rotation of a pedestrian during a car collision would provide a more accurate approximation of scaled trajectories when the height of the identified center of rotation is aligned between subjects of different sizes, and the scaling length is determined relative to it. This assumption suggests that the test condition and scaling procedure described in J2868(4) may not be optimal because the effective center of rotation of a pedestrian may not be best represented by the hindfoot. More reasonable estimation of the effective center of rotation would be the initial contact location of a pedestrian against a car.

The objective of this study is to identify the location on a pedestrian that provides the most accurate prediction of scaled trajectories, when full-scale tests were conducted with the height of the identified location aligned among subjects of different sizes and the trajectories are scaled using the lengths relative to the identified location. The current study focused on a 40 km/h impact against a car in the sedan category, and a scaling procedure to the mid-sized American male as described in J2868(4) because this condition accounted for 55% of all the car-to-pedestrian accidents in Japan(6), which meant that this condition was interpreted as the most representative crash scenario in car-to-pedestrian accidents.

2. Method

FE simulations were conducted using the combinations of five production car models in the small sedan category and three pedestrian models of different statures including that of a mid-sized American male. For each combination of car model and aligned location, the trajectories of each body region with respect to the car from the pedestrian models of different sizes were...
scaled to that of the mid-sized American male pedestrian to identify the aligned location that provides the best estimation of the trajectories of the mid-sized male pedestrian.

2.1. Pedestrian FE model

Three different statures of the pedestrian FE model were investigated in this study – mid-sized American male (AM50), small (5th percentile) American female (AF05) and large (95th percentile) American male (AM95). Although the size of the subjects used in the tests is likely to be more controlled, these sizes were used to exaggerate the difference of the accuracy of the prediction. The AF05 and AM95 models were created by scaling the AM50 model.

2.1.1. Baseline pedestrian FE model

The AM50 pedestrian FE model developed by Takahashi et al.\(^7\) and Kikuchi et al.\(^8\) was used as the baseline model. Fig. 1 and Table 1 show the schematic view of the baseline model and element type used in the baseline model. The lower extremity and the pelvis of the AM50 model consist of shell, solid and bar elements so that the model can predict the probability of injury to these body regions at the tissue level. The lower extremity and the pelvis of this model were validated under quasi-static and dynamic conditions against published experiments, including lateral compression of the pelvis in acetabulum and iliac loadings, 3-point bending of the thigh, femur, leg, tibia and fibula at multiple loading locations, tension of the individual knee ligament and 4-point valgus bending of an isolated knee joint. The upper body of this model consists of rigid bodies representing the upper extremities, outer contour of the torso, and all of the seven cervical and five lumbar vertebrae in order to reproduce the kinematics during car collisions. The trajectories of Head, T1, T8 and Pelvis of the assembled whole body model were validated against the full-scale PMHS experiments using the sled bucks mounting the front structure of production models of a small sedan and a large SUV. Fig. 2 and 3 show the comparison between the trajectory corridors for the head, T1, T8 and pelvis obtained from the experiment and the trajectories of corresponding body regions predicted by the full-scale pedestrian model for a small sedan\(^8\).

2.1.2. Scaled pedestrian FE models

In order to compare the accuracy of the scaled trajectories from AF05 or AM95 to AM50 between different aligned locations in car-pedestrian crashes, the AF05 and AM95 models were created by geometrically scaling the AM50 model. The stature and the weight of the AF05 and AM95 were determined from the UMTRI studies\(^9(10)(11)\). Table 2 shows the stature and weight of AM50,

| Element Type     | Table 1 Summary of the structure of the baseline pedestrian FE model |
|------------------|---------------------------------------------------------------|
| Lower Limbs (Thigh and Leg) | Shell/Solid/Bar                                    |
| Pelvis           | Shell/Solid/Bar                                             |
| Upper Body       | 12 Rigid Bodies articulated by Joints (5 lumbar and 7 cervical vertebrae) |

Fig. 1 Overview of the baseline pedestrian FE model

Fig. 2 Comparison between the trajectory corridors for the head, T1, T8 and pelvis obtained from the experiment and the trajectories of corresponding body regions predicted by the full-scale pedestrian model for a small sedan\(^8\)

Fig. 3 Comparison between the trajectory corridors for the head, T1, T8 and pelvis obtained from the experiment and the trajectories of corresponding body regions predicted by the full-scale pedestrian model for a large SUV\(^8\)
along with those of AF05 and AM95 determined by the UMTRI studies\(^9\)(10)(11). The AF05 and AM95 models were created in the following two steps: 1) the scaling factors for the dimensions and displacement, force, moment and density, and moment of inertia were determined by \(\lambda_1, \lambda_2, \lambda_3,\) and \(\lambda_4\), respectively, where the length scale factor \(\lambda\) is determined by the ratio of the stature of a pedestrian to that of an AM50 pedestrian; and 2) the whole body mass of the scaled pedestrian model was adjusted by changing the density of the flesh part of the model. Fig. 4 shows a comparison of the pedestrian models of different sizes.

| Stature (cm) | Weight (kg) |
|-------------|-------------|
| Mid-sized Male (Baseline: AM50) | 172.4 | 73.9 |
| Small Female (AF05) | 151.3 | 46.9 |
| Large Male (AM95) | 186.4 | 102.6 |

2.2. Vehicle FE model

Car-to-pedestrian crash simulations were conducted using the FE models of multiple production cars. Considering the variations in the geometry and reaction force characteristics of the car, five production cars were used in order to capture variations in those characteristics within the small sedan category. The five production cars used by Takahashi et al.\(^12\) were chosen to identify the location on a pedestrian that provides the most accurate prediction of scaled trajectories in the small sedan category, since the geometry of the bumper and the hood edge and the peak values of the reaction forces of those cars roughly covered the upper and lower bounds of their variations among the cars in the same category that are rated green in Euro NCAP pedestrian subsystem tests as investigated by the European APROSYS (Advanced Protection Systems) project\(^13\)(14). Fig. 5 shows an overview of the FE models of the five cars used in this study.

Fig. 5  FE models for the five production cars

2.3. Simulation conditions

Car-to-pedestrian accidents where a pedestrian is hit by a car laterally at an impact speed no more than 40 km/h account for 55% of all the car-to-pedestrian accidents in Japan\(^6\). For this reason, this condition was interpreted as the most representative crash scenario in car-to-pedestrian accidents. Therefore, car-to-pedestrian crash simulations were conducted where one of the FE models for the five cars was made to collide with one of the three pedestrian FE models of differing statures laterally at 40 km/h. The baseline model was positioned in accordance with the description of SAE Information Report J2782\(^3\). The head, T1, T8 and pelvis specified in the report were defined as the locations whose trajectories relative to the car were investigated (hereafter, “Target Points”). The trajectories of these four Target Points relative to the car were calculated using a coordinate system specified as follows: 1) the local 2D (x-z) coordinate system affixed to the car model was defined; 2) the origin point was defined by the intersection between the sagittal plane of the human model and the ground plane; 3) the positive direction of the x-axis was defined as parallel to the longitudinal axis of the car model pointing from the pedestrian model to the car model; and 4) the positive direction of the z-axis was defined as the inferior-superior direction of the pedestrian model. In this study, as used in SAE Information Report J2782\(^3\) for the calculation of the trajectories, the trajectories in this coordinate system were investigated. In addition, the trajectories were investigated until the head contacts the car also in accordance with SAE Information Report J2782\(^3\). Fig. 6 shows an overview of the simulation set up using the Car-1 car model and the AM50 pedestrian model, along with the locations of the Target Points.
Fig. 6 Summary of the simulation conditions and the Target Points to investigate the trajectories

The posture of AF05 and AM95 models in car-to-pedestrian crash simulations was the same as that of the AM50 model with the normal walking posture specified in SAE Information Report J2782(3). The AF05 and AM95 models were positioned so that the height of a pre-determined location on the pedestrian model (hereafter, “Aligned Points”) from the ground was aligned to that of the AM50 model positioned on the ground in accordance with SAE Information Report J2782(3). The ground, knee joint, hip joint, pelvis and T8 target points were chosen as the Aligned Points. In addition, the condition in which the ground was set as the Aligned Point was the same as described in SAE Information Report J2868(4). Fig. 7 shows a comparison of the model setup for the five Aligned Points. For each car model, car-to-pedestrian crash simulations were conducted for the AM50 model, and for all the combinations of the five Aligned Points and the two sizes of the pedestrians (AF05 and AM95).

2.4. Scaling method of the trajectories to AM50

The trajectories of the four Target Points from the AF05 and AM95 models were scaled to those of the AM50 stature for each Aligned Point. The x- and z-coordinates of the Target Points were scaled to the AM50 stature by equations (1) and (2), respectively, using the distance in the z-direction between the Aligned Point and the Target Point (L2 for AM50, L2sc for AF05 and AM95), and that between the ground and the Aligned Point (L1) as shown in Fig. 8.

\[
T_{x_{\text{scaled}}} = T_x \times \frac{L_2}{L_{2\text{sc}}} \quad (1)
\]

\[
T_{z_{\text{scaled}}} = (T_z - L_1) \times \frac{L_2}{L_{2\text{sc}}} + L_1 \quad (2)
\]

where \(T_x\) and \(T_z\) are the respectively x- and z-coordinates of a Target Point of the AF05 or AM95 models, and \(T_{x_{\text{sc}}} \) and \(T_{z_{\text{sc}}} \) are the respectively scaled x- and z-coordinates of a Target Point to the AM50.

2.5. Evaluation criterion for the accuracy of the estimated trajectories

The estimated trajectory for each Target Point was compared to the simulation results using the AM50 model. In addition, the accuracy of the estimation by scaling was evaluated using the Averaged Root Mean Square Error (ARMSE), which can evaluate the accuracy of the estimation in terms of the time history of the trajectories. The ARMSE was calculated in the following steps:

Step 1: The time was normalized by the duration between the initial contact and the head contact for each of the three pedestrian models.

Step 2: The data for every 1/1,500 of the normalized time was created by interpolating the displacement time histories in the x- and z-directions for each of the three pedestrian models.

Step 3: The Root Mean Square Error (RMSE) against the results of the AM50 model defined in equation (3) was calculated using the data created in Step 2 for each Target Point and each of the AF05 and AM95 models:

\[
\text{RMSE} = \frac{1}{1500} \sum_{i=1}^{1500} \left( \left( x_{50,i} - x_{50,i} \right)^2 + \left( z_{50,i} - z_{50,i} \right)^2 \right)
\]

where \(x_{50,i}\) and \(z_{50,i}\) are the i-th data of displacement in the x- and z-directions from the AM50 model created in Step 2, and \(x_{50,i} \) and \(z_{50,i} \) are the i-th data of the estimated displacement in the x- and z-directions scaled from the AF05 or the AM95 model created in Step 2.
Step 4: The ARMSE was calculated by averaging the RMSE for all the combinations of the Target Points and the pedestrian models (except the AM50 model) using equation (4)

\[
ARMSE = \frac{\sum_{i} RMSE_{AF05} + \sum_{i} RMSE_{AM95}}{8}
\]

\[
\sum_{i} RMSE_{AF05} = RMSE_{AF05}^{Head} + RMSE_{AF05}^{T_1} + RMSE_{AF05}^{T_8} + RMSE_{AF05}^{Pelvis}
\]

\[
\sum_{i} RMSE_{AM95} = RMSE_{AM95}^{Head} + RMSE_{AM95}^{T_1} + RMSE_{AM95}^{T_8} + RMSE_{AM95}^{Pelvis}
\]

where RMSE_{AF05} and RMSE_{AM95} are the RMSEs calculated from the trajectories of each Target Point scaled to the AM50 stature for the AF05 and AM95 models, respectively.

The Aligned Point that shows the greatest accuracy of the estimation was identified by the lowest value of the ARMSE for each of the five car models.

3. Results

3.1. Comparison of the scaled trajectories for each aligned height

Fig. 9 to 13 respectively compare the trajectories of the four Target Points from the AM50 model with the scaled trajectories to the AM50 stature in the collision with Car-1 for the five height alignments illustrated in Fig. 7.

Fig. 9  Comparison of the scaled trajectories for each size (Car-1, ground-aligned)

Fig. 10  Comparison of the scaled trajectories for each size (Car-1, knee joint-aligned)

Fig. 11  Comparison of the scaled trajectories for each size (Car-1, hip joint-aligned)

Fig. 12  Comparison of the scaled trajectories for each size (Car-1, pelvis-aligned)
The results show that for all of the Target Points, the x-component of the scaled trajectories from the AF05 model increased with the increase of the height in the Aligned Point from the ground, as opposed to the decrease in those from the AM95 model.

It was also found that for the Target Point of Pelvis, the z-component of the scaled trajectories from the AF05 model decreased with the increase in the height of the Aligned Point from the ground, as opposed to the increase in those from the AM95 model.

3.2. Comparison of ARMSE for each aligned point

Fig. 14 shows a comparison of the ARMSE for the five car models and the five Aligned Points.

The lowest ARMSE was indicated when the knee joint was set as the Aligned Point for all the car models investigated in this study. In other words, it was clarified that the trajectories of the Target Points of the AM50 model could be estimated most accurately from the scaling of the results of the AF05 and AM95 models when the height of the knee joint was aligned to that of the AM50 model.

4. Discussion

This study focused on the scaling method for the trajectories. The contact location between vehicle and pedestrian differed in each car-to-pedestrian collision test using PMHSs whose size differed in each subject, since the size of the vehicle could not be scaled in the tests. It was thought that the kinetic responses could not be estimated by scaling of the result because the difference in the contact location between vehicle and pedestrian significantly influenced the kinetic responses. On the other hand, for the trajectories, it was thought that the influence of the difference in the contact location was small since, as shown in the study of Kerrigan et al. (5), the whole body moved so that it wrapped around the vehicle. These were the reasons for focusing on the scaling method of the trajectories in this study. As shown in Figs. 10 and 14, it can be said that the influence of the difference in the contact location was small enough to estimate the trajectories of the AM50 by scaling.

Fig. 14 clarified that the trajectories of the Target Points of the AM50 model can be estimated most accurately by the trajectories scaled from the AF05 and AM95 models when the height of the knee joint was aligned to that of the AM50 model in the small sedan category. Fig. 15 shows the location of the foot, knee joint, hip joint, T8, T1 and Head relative to the car for every 20 ms from the simulation results using the Car-1 model and the AM50 model. It was found that the head moved mostly in the x-direction in the early phase of the collision, during which time phase the motion of the knee joint was restricted by the bumper of the car and the upper body showed some bending. Since the bending and the stretch of the upper body would decrease and increase the radius of rotation of a pedestrian body, respectively, the displacement of the each Target Point relative to the foot is compared to clarify the combined effect of the rotation and the stretch on the motion of the pedestrian body. Fig. 16 compares the trajectory of each Target Point with respect to the foot from the impact simulations against the Car-1 model. The comparison was made between the results from the AM50 pedestrian model and the scaled results from the AF05 and the AM95 pedestrian models, showing that each Target Point almost traced the circumference of a circle centered at the foot. In addition, Fig. 15 shows that the foot moved around the knee joint where the pedestrian body initially collided with the car. These findings can explain why the trajectories of the Target Points of the AM50 model could be estimated most accurately by the trajectories scaled from the AF05 and the AM95 models when the height of the knee joint was aligned to that of the AM50 model.
Fig. 15 shows some sliding of the trajectories predicted from the AF05 and AM95 models still have most effective when scaled relative to the knee joint, the pedestrian body after the pelvis collides with the car. A comparison of the hood deformation between different sizes of pedestrians showed that the deformation tended to be larger as the pedestrian gets larger, due to a larger mass of the pedestrian applying larger force on the hood. This is likely to be the most relevant cause of the difference of the trajectories because a larger deformation of the hood would significantly decrease the amount of sliding due to the change of the contact angle between the pedestrian and the hood, resulting in a higher force applied to the pedestrian in the x-direction. This assumption is consistent with the fact that the scaled trajectories tended to get shrunk in the x-direction as the pedestrian gets larger (see Fig. 10).

Although it has been clarified that the trajectory scaling is most effective when scaled relative to the knee joint, the trajectories predicted from the AF05 and AM95 models still have some differences from the trajectories of the AM50 model in the later phase of the collision. Fig. 15 shows some sliding of the pedestrian body after the pelvis collides with the car. A comparison of the hood deformation between different sizes of pedestrians showed that the deformation tended to be larger as the pedestrian gets larger, due to a larger mass of the pedestrian applying larger force on the hood. This is likely to be the most relevant cause of the difference of the trajectories because a larger deformation of the hood would significantly decrease the amount of sliding due to the change of the contact angle between the pedestrian and the hood, resulting in a higher force applied to the pedestrian in the x-direction. This assumption is consistent with the fact that the scaled trajectories tended to get shrunk in the x-direction as the pedestrian gets larger (see Fig. 10).

This study only focused on collisions within the cars in the small sedan category whose initial collision locations to the pedestrian were similar. Therefore, it was presumed that the findings may not apply to a collision with a car in a different category whose initial collision location would be significantly different, since it was suggested that the initial collision location is the most significant contributor to determine the center of rotation of a pedestrian body. Further investigation is needed for the cars in different categories, such as SUVs or mini-vans whose geometry of the car front end is significantly different. The AF05 and AM95 pedestrian models used in this study have not been validated against experiments due to the lack of available PMHS test data for these sizes. Since the accuracy of the trajectories estimated from the AF05 and AM95 models should influence the evaluation of the validity of the method proposed in this study, the biofidelity of the the AF05 and AM95 models scaled from the validated AM50 model need to be validated when the experimental data are available.

5. Conclusion

This study investigated the height alignment that best estimates the trajectories of the AM50 model from the scaled trajectories of pedestrian models of differing sizes in a collision with a car in the small sedan category. As a result, it was clarified that the trajectories of the AM50 model could be estimated most accurately by the scaled trajectories from pedestrian models of differing sizes using the ratio of the distance between the knee joint and the Target Point when the knee-joint height was aligned to that of the AM50. The results of this study should provide useful knowledge, particularly when developing trajectory corridors based on the scaling of the trajectories of human subjects for which use of subjects with similar stature is typically difficult.

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