The Clarification of Individual Injury Mechanism Difference in Pedestrian FE Model Utilizing Cadaver Scaling and Posturing Techniques

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Paper Number 11-0414

ABSTRACT

In car-pedestrian accidents, the pedestrian's body size exerts strong influence on the degrees of the impacts by the vehicle on the lower limbs and the pelvis. Such individual difference affects the loading mechanism of the pedestrian accident and relates to the injury outcome. The ultimate goal of this research is to clarify the injury mechanisms of accidents of this sort. To fulfill this purpose, a 50th percentile finite element pedestrian model was developed and validated by Japan Automobile Research Institute (JARI) in the human finite element model development project by the Japan Automobile Manufacturers Association (JAMA). This model was employed in this study to reproduce full scale tests in which cadaver (Post Mortem Human Subjects) in standing position were struck by vehicles to investigate the body kinematics and the injuries caused by car-pedestrian impact. In addition, two kinds of individual scaled models were generated based on the 50th percentile standard model. In this process, the radiological data, as well as body external measurements of the cadaver recorded in the experiments, were utilized. The individual scaled models were applied to simulate two full scale tests in which two cadavers of different sizes were struck by a SUV type vehicle and a Small City Car type vehicle, respectively. For the purpose of comparison, the 50th percentile standard model was also applied to the car-pedestrian simulation. The body kinematics and the injury outcome of the models were analyzed and compared with the experimental results. It was found that, while all the models indicated acceptably good kinematics, only the scaled models could reproduce accurate injuries such as the knee ligament rupture found in the experiments.

INTRODUCTION

The number of traffic related fatalities in Japan has shown a constant descending tendency since the early 90's. Moreover, the increasing tendency in the annual number of injuries was inverted and has shown a downward trend since 2005. However, these downward trends seem to have been slowing down since 2007 (Figure 1)[1].

Fig. 1 Traffic related fatalities and injuries in Japan (1990-2010)

Despite the effort made by the automotive industry and the public institutions, the still enormous number of fatalities and injuries demand increased effort to keep on improving vehicle safety. According to the most recent accident data collected and published by the Japanese police, 33% of the traffic related fatalities in 2008 involved pedestrians (Figure 2)[1].

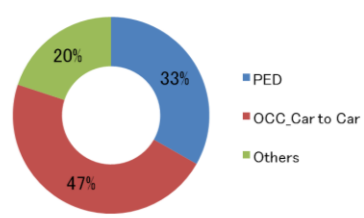

Fig. 2 Traffic fatalities in Japan (2008)

As for pedestrian injuries, the accident data collected by the Institute for Traffic Accident Research and Data Analysis of Japan (ITARDA) indicate that head and lower limbs (including the pelvis) are the most frequently injured body regions (AIS2+ injuries) with over 30% frequency each [2]. This figure indicates that specific countermeasures are needed to reinforce the protection of pedestrians involved in traffic accidents. Among all the methods employed to improve the vehicle safety, human models appear to be the most promising tool. Such models, if used in appropriate combination with experimental bio-mechanics, accident reconstruction, and epidemiology, can contribute to a better understanding of injury mechanisms. The knowledge thus acquired can later be applied to the development of safer vehicles. With the objective of clarifying injury mechanisms in accidents for which adequate countermeasures can be taken to improve vehicle safety, JAMA initiated in 2004 a longitudinal project, and JARI has been developing and validating the human FE models [3] for over 7 years. In the research presented here, the 50th percentile Finite Element (FE) human pedestrian model developed within the frame of this project was utilized (Figure 3).

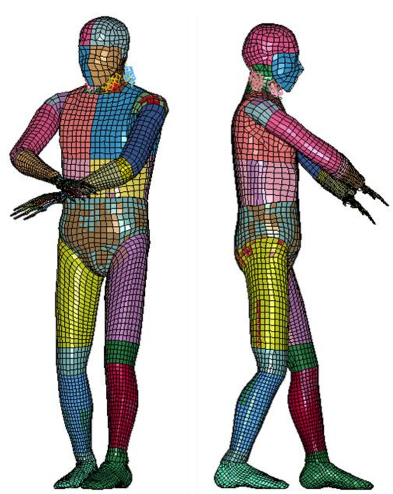

Fig. 3 50th percentile male JAMA Pedestrian model

The use of standard-size Human FE models has already been well established as a research tool to clarify injury mechanisms. The size of the majority of the models represents the standard 50th percentile male population, either in standing position for pedestrian-related research or in driving posture. However, modeling with accuracy the differences between individuals (human factors), as well as different impact environments (extrinsic factors) is essential for the clarification of injuries. The human factors that are necessary for the clarification of injury mechanisms include, among many others, variations in body size, age, gender, biomechanical tolerance, posture at the impact, and muscle activity [4]. Due to the specific nature of car- pedestrian accidents, in particular the body size strongly affects the way the knee and the pelvis are impacted by the vehicle. Such differences between individuals affect the body loading mechanism during the impact, and hence need to be taken into account by the human models to clarify injury mechanisms. As for the extrinsic factors to consider when reproducing car-pedestrian accidents, the posture of the pedestrian surrogates with respect to the vehicle has been experimentally proved to affect, for example, the thrown distance when impacted by vehicles [5]. Moreover, the differences between the types of vehicles involved in this kind of accidents also affect the kinematics of the pedestrians and the injury output. This paper introduces the effect of both intrinsic and extrinsic human factors by employing individual pedestrian model utilizing the cadaver scaling and posturing techniques. In this research, these factors were taken into consideration in simulating full scale car-pedestrian experiments with cadaver in the manner described.

METHODOLOGY

The 50th percentile pedestrian FE model (base model) is now being subjected to continuous validation. For this specific task, validation at the component-level of the lower limbs and the hip was carried out. Then, two full scale car-pedestrian tests were selected. In the first case, a 165cm of height and 60kg of weight cadaver was impacted by a SUV-type car [6]. In the second case, a 161cm of height and 86kg of weight specimen was impacted by a Small City Car-type vehicle [7]. The base model was then scaled by using radiological image data and external measurement data from the cadaver used in the full scale tests. Finally, each of the two experimental cases was simulated with its corresponding scaled model, respectively. In addition, the base model also applied to simulate the Small City Car-pedestrian accident for comparison. Thus, the differences between the base model and the scaled model could be analyzed under the same impact conditions. In the simulations carried out, an accurate model of the front part of each of the vehicles used in the actual experiments was employed. In addition, the initial posture of the individual models was adjusted by using the position markers from the cadaver just before the impact.

Base Human Model Component Validation

The geometry of the organs of the human model of relevance for injury research has been under continuous improvement. CT scan data from cadaver are being used to remodel the organs. Besides the improved geometry, especial attention is paid on the bio-fidelity of the material models used for the soft tissues and the bones. The modeled tissues behave correctly at different loading strain-rates and can reproduce tissue damage thresholds. After the tissues are validated, the properties are inputted into the respective components and validated based on the component test data. A description of some of the validated components of relevance for this work is as follows.

<u>Flesh of the legs:</u>

The material properties of the leg flesh were validated based on the leg impact experiments employing volunteers, cadavers, and the Hybrid III dummy [8]. In these experiments, the subjects were impacted in the posterior and lateral part of the lower leg using a free flying pendulum. The experimental data used for the validation of the model correspond with the series of tests/experiments in which the impacts were delivered to the lower leg laterally. In the experiments, the foot of the tested leg was plantar flexed and suspended. The cadavers and the Hybrid III dummy were tested in a similar setup. All specimens were impacted at approximately 80% of their own tibial height, measured from the ground. The rigid plate which has a 45mm by 145mm rectangular and 1.84kg total mass was attached to the impactor and the impact of up to 2.5m/s was delivered. The impact force was calculated by multiplying the mass of the pendulum and its acceleration measured with an accelerometer mounted at the end of the pendulum. The displacement of the leg at the site of impact was obtained by tracking the high-speed video data. The experiments were simulated by replicating the boundary conditions, and the experiment and the simulation results were compared. Figure 4 shows a picture of the simulation setup described and a figure comparing the force deflection resulted from the experiment and the numerical simulation.

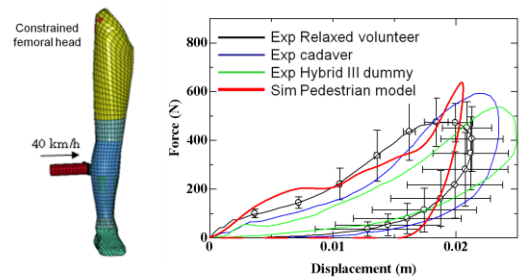

Fig. 4 Flesh validation simulation setup (left) and experiment and simulation results comparison (right).

The simulation results (in red) showed good correlation with the experimental corridor built from the volunteer tests (black), proximity to the cadaver (blue), and the Hybrid III dummy data (green).

<u>Knee complex:</u>

The entire knee complex was remodeled. While the head of the femur, the tibia, and the fibula were redesigned based on CT images, the geometry and the insertions of the ligaments into the bones were modeled by following medical literature [9]. The material properties of the ligaments consisted of a strain-rate based elastic-plastic material model including ultimate strain previously validated in other projects [10]. Figure 5 shows three different views of the new knee complex, including the ligaments.

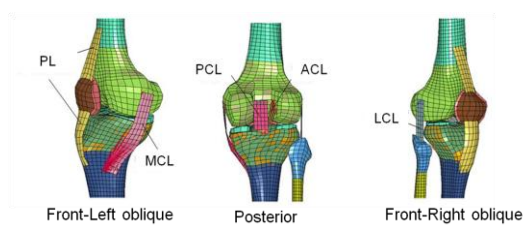

Fig. 5 Remodeled Knee complex

The new knee model was validated against knee bending tests with cadavers [11][12]. In these experiments, the internal part of the right leg of cadaver lying supine on a table was subjected to high speed impacts at the ankle region. To generate bending effort at the knee, the trochanter and the knee were fixed with screws. The impacts were delivered at around 40km/h. Figure 6 shows an image of the simulation setup (left) and the experiment and simulation results comparison for the bending angle rotated by the knee in the coronal plane (right).

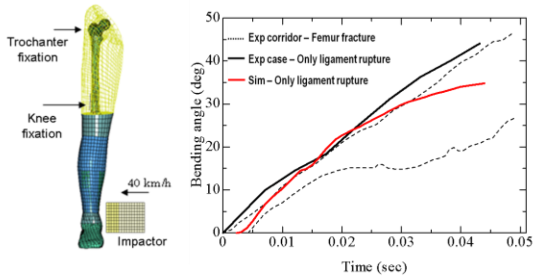

Fig. 6 Knee complex validation simulation setup (left) and experiment and simulation results comparison (right)

The corridor built with the experimental cases that indicate femoral fracture is represented with black dotted lines. The thick black line represents one case in which ligament rupture with no bone fracture occurred. The numerical result, in red, shows ligament rupture with no bone fracture, and it behaves similarly to the experiments

Pelvis Cortical bone thickness and Material properties:

The thickness of the cortical bone of the pelvic bones at eight different segments was modified from the original model based on literature [13]. Such modifications were confirmed by measuring the cortical bone thickness from radiological data of cadavers.

	Cortical thickness (mm)
Face	1
Wing	1.5
Top	2
Notch	2
Acetabulum	1.5
Aceta-Rami	1.25
Rami	1.25
Pubic	1

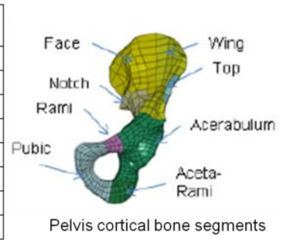

Fig. 7 Pelvic cortical bone thicknesses

The pelvis was validated against dynamic tests on isolated pelvic bony structures [14]. In the experiments, the pelvic structures were immobilized using a low melting temperature alloy, up to the external edge of the ischial tuberosity and leaving the pelvic ring free. The pelvis was oriented so that the line between the two anterior superior iliac spines was vertical. The drop tower was used to guide a falling mass which enabled impact speed at around 4m/s. The mass was equipped with accelerometers, and a displacement sensor was utilized to measure the pelvis deflection. The metallic sphere was fitted into the impacted acetabulum to distribute the load around the joint surface. To avoid direct contact between the metallic impactor and the sphere, 11mm thick silicon padding was fitted at the impacting face of the falling mass. The experiments were simulated by replicating the boundary conditions as described in the original documents, and the experimental and the simulation results were compared. Figure 8 shows an image of the simulation setup (right) and the results comparison for the impact force (left).

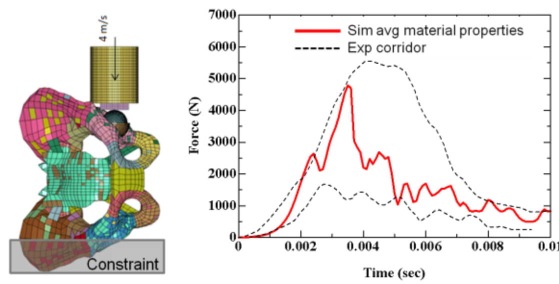

Fig. 8 Pelvis validation simulation setup (left) and experiment and simulation results comparison (right)

The sustained force by the simulated impact presented results within the limits of the experimental corridor.

Scaling Method and posture change

The geometry of the skeleton and the flesh of the validated standard-size model were modified based on individual data taken from the cadaver used in this study. For this modification, a custom-made scaling and posturing software tool was utilized. Such tool modifies the geometry of the base model based on two groups of measurements taken from the cadaver. The first group consists of around 20 measurements from the CT scans. These data include a variety of data such as the length and the dimensions of the cross sections of long bones and key parameters of the pelvis. The second group of measurements consists of around 30 external measurements taken from the cadaver at the specimen’s impact position. Figure 9 shows the images with some of the measurements used to scale the models.

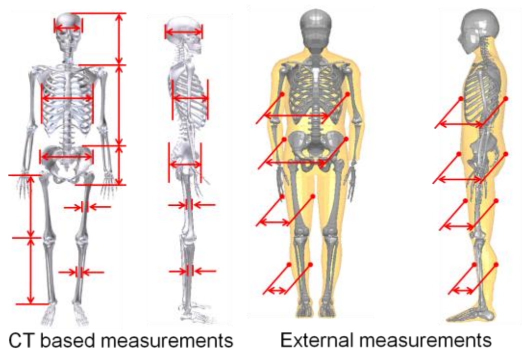

Fig. 9 CT based measurements (left) and external measurement (right) used to scale the base model

As a result of the application of the scaling method, two scaled versions of the JAMA pedestrian model were obtained. The first scaled model corresponds with a subject with a height of 165cm and a body mass of 60kg. The second scaled model is based on a subject 161cm tall and a weight of 86kg (Figure 10).

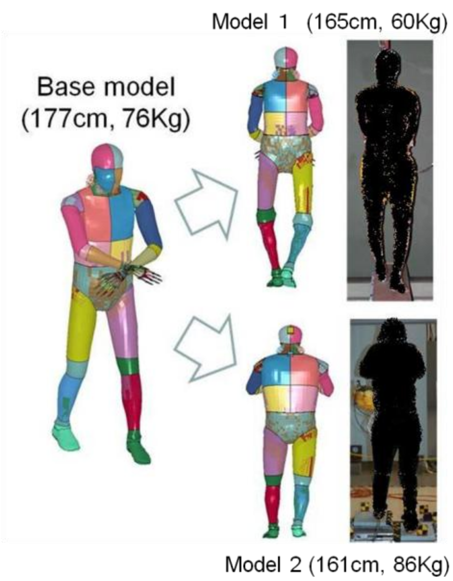

Fig. 10 Base model and scaled models

RESULTS

Body Kinematics

Each of the two experimental cases was simulated with its corresponding scaled model. For the purpose of comparison the base model also applied to this simulation. All the simulations were run until the impact of the head with the vehicle. Figure 11 shows a comparison of the behavior of the cadaver at the experiment and that of the scaled models at the simulated impact. The images on the left correspond with the test in which the frontal part of a SUV-type vehicle was used (impact from the left side of the specimen). The images on the right correspond with the test in which the frontal part of a Small City Car was used (impact from the right side of the specimen). Both simulated cases presented good kinematics in comparison with the experimental results.

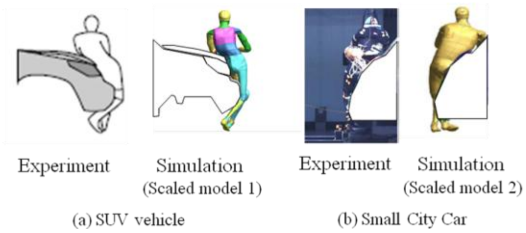

Fig. 11 Comparison of the behavior of the cadaver and the scaled models for the SUV (left) and the Small City Car (right).

Figure 12 shows a comparison of the trajectories in the vertical plane (longitudinal plane of the vehicle) followed by the Head, the 1st and the 6th thoracic vertebra (T1,T6), the fifth lumbar vertebra (L5), the Left Knee, and the Left Foot in the SUV vehicle case. The results correspond with the displacements of the body with respect to the vehicle. The experimental results are represented with black dotted lines, while the simulation results with continuous red lines. The markers represent the position of each marker at 20ms intervals. In a similar way, Figure 13 shows the results of the Small City Car case (from the right side of the body). The trajectories of Head, T1, T8, Right Femur, Tibia, and Heel were used in this case. Both cases show good correlation in the trajectories between the experiments and the simulation.

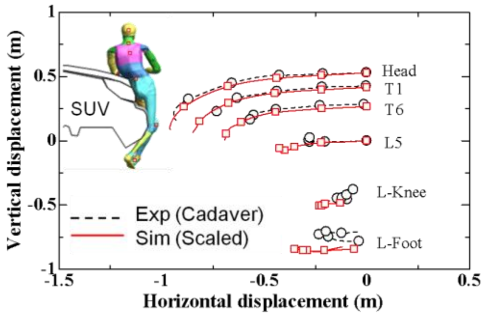

Fig. 12 Comparison of the simulated trajectories with the scaled model (red) and the experimental results (black) in the case of SUV type vehicle

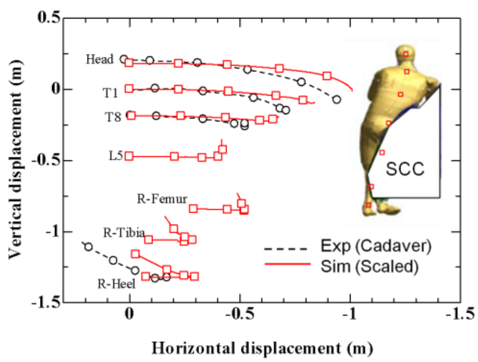

Fig. 13 Comparison of the simulated trajectories with the scaled model (red) and the experimental test results (black) for the case with Small City Car

Leg injuries: Standard model vs Scaled model.

In the experiment with the Small City Car, the cadaver sustained a rupture of the Medial Collateral Ligament (MCL) of the right knee (internal part of the knee at the struck side) by its insertion into the femur. Figure 14 shows a sequence of photos (10ms interval) with the strain distribution sustained by the ligaments of the the internal part of the right knee (struck side) during the simulated impact. The photos above correspond with the impact simulated with the base model, while the photos below correspond with the scaled model. The MCL ruptured in both the simulated cases, at the middle in the base model and at the insertion into the femur in the scaled model.

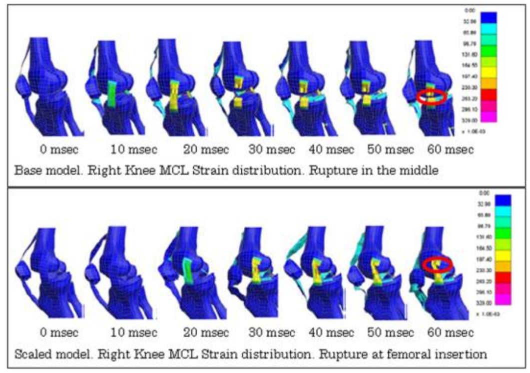

Fig. 14 Strain distribution in the knee ligaments in the Base model (above) and the Scaled model (below) of the test with a Small City Car

DISCUSSION

By using body external measurements and CT scan data measurements, two different scaled versions of the validated base model were developed. The scaled models were employed to simulate two full-scale tests with an SUV and a Small City Car, respectively. Both cases showed good correlation between the trajectories followed by the bodies in the simulations and the experimental results. In the Small City Car case, the scaled model was able to replicate the knee ligament injury sustained by the cadaver in the experiment at the exact injury site. When the same case was simulated with the base model (16cm taller than the scaled model), the same ligament rupture occurred, but at a different location. The difference in body size proved to affect the interaction between the vehicle and the loading mechanism of the lower limbs of the model from the beginning of the impact. The height at which the bumper hit the leg and loaded the knee complex defined the loading mechanism of the MCL until the rupture occurs. In the case of the base model, the bumper starts contacting with the leg at approximately the height of the knee. Both the femoral and the tibial head rotate laterally, causing tension on the MCL until it ruptures in the middle of the ligament. In the case of the scaled model, the impact is delivered at above the femoral head. This allows a bigger amount of energy to be delivered into the upper leg, causing a combined large shear-tension effort in the region closer to the insertion of the ligament into the femur, where the rupture occurs. Since it was reported from the experiments that the cadaver suffered a rupture of the MCL of the right knee at its insertion into the femur, based on the simulation results, it can be said that only when the scaled version of the pedestrian model was utilized, and the site of the ligament injury could be simulated with accuracy. Although this finding requires further investigation until more reliable conclusions can be extracted, the authors of this study believe that these results indicate the importance of intensifying the ability of human models to simulate individuality with accuracy. Such upgraded human FE models can serve as a very powerful tool to understand injury mechanisms with local accuracy to allow taking efficient countermeasures to enhance the safety of vehicles.

LIMITATIONS

Although big effort was made in order to obtain accurate geometry from the two cadavers, other important human factors were not taken into consideration in this study. For example, the difference in material properties of the tissues between specimens, especially those of bones, ligaments and flesh, was not addressed in the models used in this study. In all cases, the same material properties were used. In addition, the fact that only two experimental cases were used in this research, and each of them was impacted by a different type of vehicle and under slightly different experimental conditions, does not allow isolating factors of interest such as the influence of the type of vehicle on the injury output. Finally, it is important to clarify that, according to ITARDA data, knee ligament ruptures are relatively uncommon in real-life car-pedestrian accidents (less than 3% of the cases). However, both of the experimental cases utilized in this study presented damage at the MCL in the knee of the struck side. This makes the authors of this study suspect that the body position at which the cadaver were impacted may not be representative of the pedestrian's impact position in real-life accidents. Hence, even if the pedestrian models present good correlation with the experiments used in this study, further research to define other real-life accident based on the representative postures of the pedestrian at the impact would be required. New tests with the defined significant postures and the respective improvement of the models should then follow.

CONCLUSIONS

By using body external measurements, radiological data measurements, and a scaling and posturing technique to modify the geometry of FE models, two different scaled versions based on the validated base model were developed. The scaled models were used to simulate 2 full scale car-pedestrian tests and showed good kinematic response in comparison with the experimental data. In the small City Car case, the simulation with the scaled model reproduced with high accuracy the location of the rupture of the Medial Collateral Ligament of the knee of the struck side. However, when the same case was simulated with the base model, a similar injury was observed in the same ligament, but at a different location. These results appear to point out the importance of intensifying the research to generate reliable individual models with the capacity to reproduce injuries with local accuracy.

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