Examination of Human Body Mass Influence on Pedestrian Pelvis Injury Prediction Using a Human FE Model

Yasuaki Gunji[1] , Masayoshi Okamoto[1] , Yukou Takahashi[1]

Abstract This research examined the influence of the change of the mass of each part of a human body on pelvis injury using the compression between the right and left acetabulum of the human FE model, which was identified as the best predictor of pubic rami fracture by a previous research. Four vehicle models were used to represent different loading locations from the hood edge. The sensitivity of the mass of each part of a human body to the pelvis injury index was analyzed by changing the mass density of the following parts to 1/10: 1) contralateral thigh and leg flesh, 2) contralateral leg flesh, 3) struck side thigh and leg flesh, 4) struck side leg flesh. In addition, 5) the mass of the upper body was reduced to 1/10. The changes of the peak values of the pelvis injury index were investigated for the combinations of these cases and the four vehicles. The mechanism behind these differences was discussed by investigating time histories of the pelvis injury index, pelvis and lower limb internal loads. In addition, the assumptions of the mechanism were developed and validated using a simplified pedestrian model that represents the mechanism in a more simplistic manner than that of the actual human.

Keywords PEDESTRIAN, PELVIS, HUMAN BODY, FINITE ELEMENT METHOD

I. INTRODUCTION

The distribution of the source of injury in pedestrian accidents from the US accident statistics (NASS-PCDS: National Automotive Sampling System Pedestrian Crash Data Study) [1] shows that while the hood and the bumper account for high percentages in passenger cars, the percentage of the hood edge is the highest, accounting for 34.2% in SUVs, within which more than 90% resulted in pelvis injury. The Japanese accident statistics from ITARDA (Institute of Traffic Accident Research and Data Analysis) [2] show that the number of pedestrian fatalities exceeded that of the occupant in 2008, with the difference continuing to grow. In fatal pedestrian accidents, the pelvis accounts for 5.8% of all most severely injured body regions in 2000, which increased to 10.5 % in 2009. This trend is the same in seriously injured pedestrians as well. Tanaka et al. [3] examined the distribution of the injury severity by body region for each accident type using the data for 13,258 patients sustaining traumatic injuries due to traffic accidents from JTDB (Japan Trauma Data Bank) from 2004 to 2008. In pedestrian accidents, it was shown that there was a significant number of severe to critical injuries accompanied by unstable pelvis fracture with the disruption of the pelvic ring.

With regard to vehicle testing of the safety performance for pedestrian pelvis and thigh injuries, Euro NCAP (European New Car Assessment Program) uses the bonnet leading edge (BLE) test procedure using the upper legform impactor developed by EEVC (European Enhanced Vehicle-safety Committee). However, GTR (Global Technical Regulation) number 9 [4] on pedestrian safety adopted by the World Forum for Harmonization of Vehicle Regulations (WP.29) under the United Nations in 2008 does not incorporate this test procedure because of the lack of the biofidelity of the upper legform impactor and the validity of the test conditions (paragraph 67 of the preamble in [4]). In order to address this issue, Lubbe et al. [5] proposed a modified BLE test procedure used by Euro NCAP to better represent car-pedestrian collisions in real-world accidents. The proposed modifications included the use of the bending moment and the force for evaluating femur fracture and pelvis fracture, respectively. Although the modified procedure addresses the issue of uncertainties as to the correlation between the impactor measurements and thigh and pelvis injuries with the current test

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procedure to some extent, there are some limitations due to the restrictions from the use of the existing impactor and the testing equipment. In order to further improve the correlation between the injury measurements of the impactor and pedestrian pelvis fracture, it is necessary to develop a more biofidelic alternative impactor specifically designed to evaluate such injuries that is capable of representing pelvis impact conditions in pedestrian accidents.

In a past research, Takahashi et al. [6] clarified the mechanism of pelvis fracture due to the input from the hood edge. The influence of the loading location from the hood edge on the pelvis loading mechanism was investigated from the impact simulations using the vehicle models of a sedan, an SUV and a minivan along with a human FE model. As a result, it was shown that the difference in vehicle front shape along with the elimination of the upper body (all the body segments above the pelvis) or the contralateral lower limb and the mass reduction of the pelvis itself yield changes in the pelvis loading situation. It was also shown that the lack of the upper body or the contralateral lower limb cannot be compensated by simply adding a concentrated mass of the same amount at the joint between the body segment and the pelvis. Although this result suggest that the location of the center of gravity of the body segment has a larger effect than the amount of mass, the effect of the mass reduction of the upper body and the lower limbs, while maintaining the locations of the center of gravity of these body segments, has not been clarified. In addition, the inertial contribution from the legs also needed further clarifications to gain insight into the development of the subsystem test devices for pedestrian pelvis fracture evaluation.

This research examined the influence of the change of the mass of each part of the human body on pelvis fractures using the compression between the right and left acetabula of the human FE model, which was identified as the best predictor of pubic rami fracture by the previous research by Gunji et al. [7]. In order to maintain the location of the center of gravity of the body segments, the mass of the upper body and the lower limbs were changed by reducing the mass density. The effect of the mass reduction was investigated for the legs as well. In addition, the effect of the elimination of the contact of the body segments with the vehicle was examined to compensate for the reduced inertia.

II. METHODS

Human FE Model

In this research, the Human FE model developed by Takahashi et al. [6] that improved reproducibility of pelvis fracture relative to the former version of the human model developed by Kikuchi et al. [8][9] was used (Figure 1). The load-deformation characteristics of the pelvis were validated against the dynamic compression tests of the isolated pelvis in the lateral direction performed by Salzar et al. [10].The pelvis model incorporates the acetabulum cartilage and the sacroiliac joint cartilage to improve the biofidelity in lateral compression. The shape of the pubic symphysis was more accurately represented using the CT image. In addition, the pelvis geometry was scaled to represent that of an average male from UMTRI [11]. In addition, the insertion points and material characteristics of the ilium-thigh ligament, pelvic-thigh ligament, and hipbone-thigh ligament were improved so that the load to the pubic rami in thigh adduction is reduced.

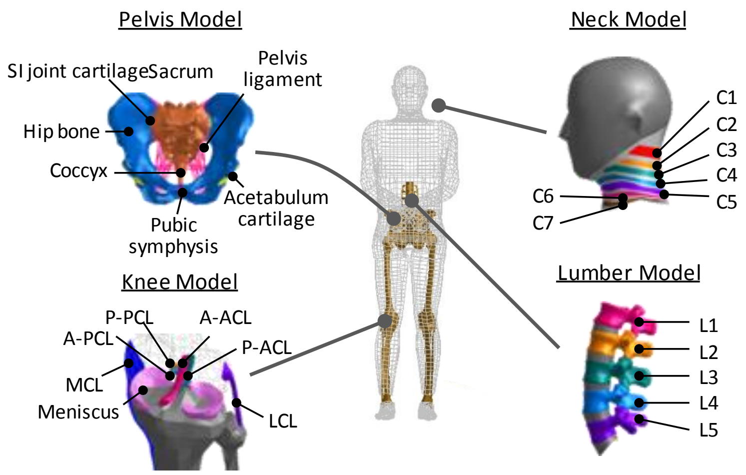

Fig. 1. Human FE model

Pelvis Injury Evaluation

Pelvis fracture may occur due to indirect loading through the thigh, indirect loading to the greater trochanter, or direct loading to the ilium. In this research, the displacement between the right and left acetabula proposed by Gunji et al. [7] was used as the pelvis fracture measure. The injury probability function for public fracture developed by Gunji et al. is shown in Figure 2 and Equation 1. The injury index for pelvis fracture is illustrated in Figure 3.

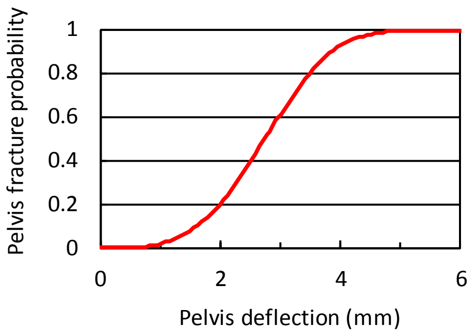

Fig. 2. Pelvis fracture probability function

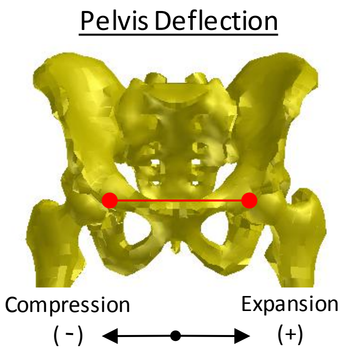

Fig. 3. Index for pelvis fracture

$$P=1-\exp[-\exp\{(\ln(X)-1.116) / 0.292\}] , \quad (1)$$

where P is pelvis fracture probability, X is Pelvis deflection (mm) of a human FE model.

Crash Simulation of Baseline Human FE Model

In order to predict the maximum pelvis fracture index generated by collisions against vehicles with various loading locations to the pelvis and thigh area, car-pedestrian crash simulations were conducted using representative vehicle models. In this research, four vehicle models were used to represent different loading locations to the thigh and the pelvis of a pedestrian. The models of two vehicles (Sedan-1, Sedan-2) represented the loading location from the hood edge below and above the height of the center of gravity of the thigh. The model for an SUV loading location near the greater trochanter, and the model representing a Minivan simulated the loading location at the ilium. The schematics of each vehicle model and a human FE model are shown in Figure 4. PAM-CRASH, a dynamic explicit code, was used for this crash simulation. The finite element vehicle models were made to collide with the left-hand side of the human FE model at the velocity of 40 km/h.

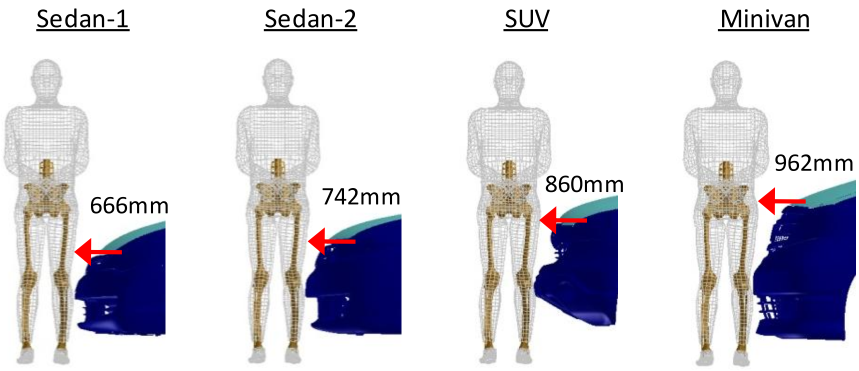

Fig. 2. Collision condition of human FE model and vehicle type

Examination of Influence of Human Body Mass on Pelvis Fracture Index

Since the results of the baseline model simulations showed that the pelvis deflection and associated pelvis fracture probability are much lower for Sedan-1 than those from the other three vehicle models, it was decided not to include Sedan-1 in this and following analyses. In order to examine the sensitivity of the mass of each region of a human body to the pelvis fracture index, a series of crash simulations were conducted using human models with different inertial characteristics of the body. When the load is applied to the struck side lower limb, the load is transmitted to the acetabulum through the femur, generating a compressive force to the pelvis. This compressive force generates the acceleration of the pelvis primarily in the direction of vehicle travel, and the inertial force provided by the contralateral lower limb is applied to the acetabulum of the contralateral side as a reaction force. The effect of the inertial contribution of the contralateral lower limb was investigated by changing the mass density of the following regions to 1/10: 1) contralateral thigh and leg flesh, 2) contralateral leg flesh. The inertial contribution of the struck side lower limb was investigated by changing the mass density of 3) struck side thigh and leg flesh, 4) struck side leg flesh, under the assumption that the mass of the struck side thigh, which is the primary source of the pelvis loading, have a significant effect on pelvis loading. In addition, 5) the mass of the upper body was reduced to 1/10 to investigate the effect of the upper body inertia. The three vehicle models used in the previous simulations were employed. The impact conditions were also identical to those of the previous simulations. The changes of the peak values of the pelvis fracture index were investigated for the combinations of these cases and the three vehicles.

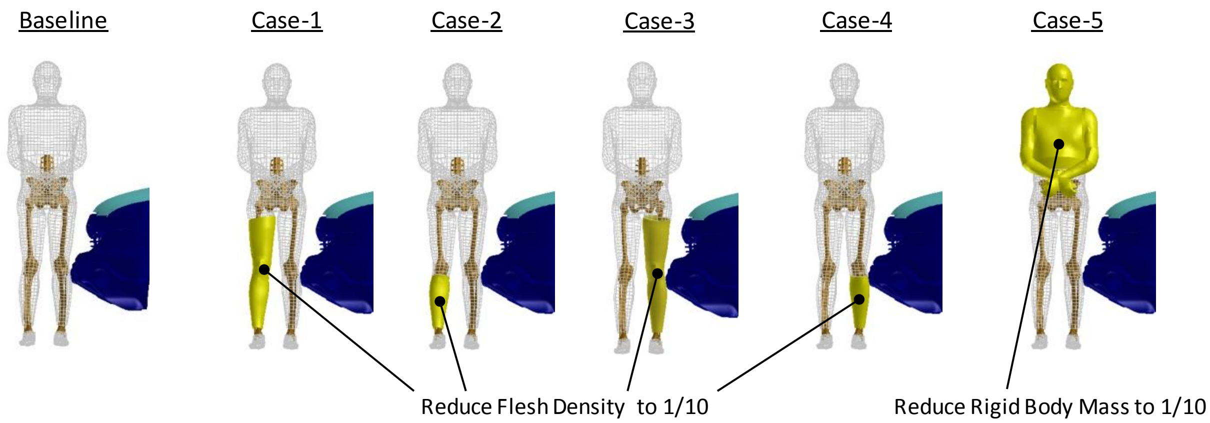

Fig. 6. Human FE models used to investigate the effect of the inertia of each body region on the pelvis fracture index

Examination of Influence of Contact between Lower Limb and Vehicle

The results of the examination of the influence of the inertia from the lower limbs and the upper body showed that the upper body inertia has an insignificant effect on the pelvis compression. The results also showed that the inertia of the contralateral lower limb has a significant effect. Since the inertial contribution of the lower limb should decrease after it contacts the vehicle front, it may be possible to compensate for the decrease in the inertial contribution by eliminating the contact with the vehicle. In order to verify the effect of the elimination of the contact to compensate for the decreased inertial contribution, the contact definition for 1') contralateral lower limb, or 2') contralateral leg, was eliminated to examine the difference of the peak pelvis deflection compared with the baseline model. Although the reduction of the mass of the struck side leg had an insignificant effect, the contact definition for 4') struck side leg was also eliminated, since the leg directly contacts the bumper. Next, the effect of the combination of the mass reduction and the elimination of the contact definition was investigated. Since the mass of the upper body had an insignificant effect, the upper body mass of the human model was reduced to 1/10 with the elimination of the contact definition with the vehicle. For the pelvis and below, based on the results of the previous simulations, two human body models were set up – Concept-1: mass density of the contralateral lower limb and the struck side leg reduced to 1/10, along with the elimination of the contact definitions between these regions and the vehicle, Concept-2: mass density of the contralateral and struck side legs reduced to 1/10, along with the elimination of the contact definitions between these regions and the vehicle. Again, the same three vehicle models and impact conditions as those of the former series of crash simulations were used. The changes of the peak values of the pelvis fracture index were investigated for the combinations of these cases and the three vehicles.

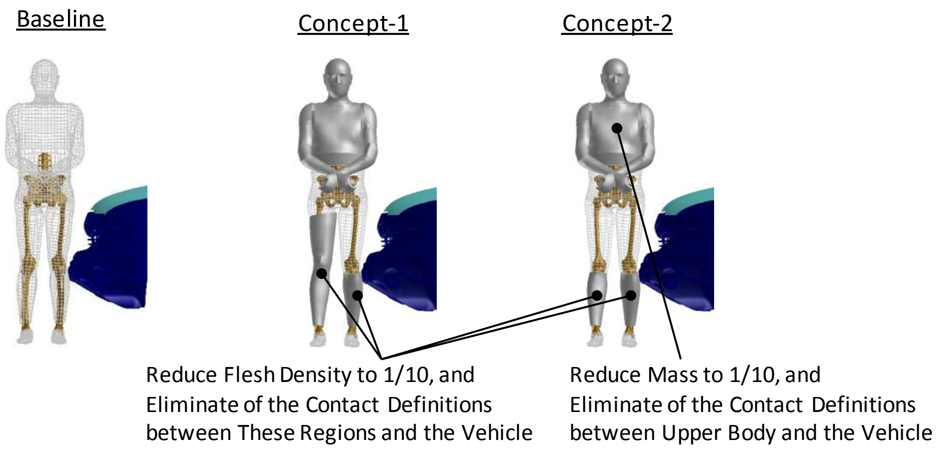

Fig. 7. Human FE models used to investigate the effect of the contact between the lower limb and the vehicle

III. RESULTS

Crash Simulation of Baseline Human FE Model

For each of the four vehicles, the peak pelvis fracture index and associated injury probability estimated using Equation 1 for each vehicle along with the time of onset of the contact between the contralateral lower limb and the vehicle front are summarized in Table 1. Since the inertia of the lower limb influences the pelvis compression through the acetabulum, the peak values of the acetabulum contact forces are also included. Sedan-2 for which the hood edge collided above the thigh center of gravity resulted in the pelvis fracture probability close to 40%. With regard to SUV and Minivan for which the hood edge collided at the greater trochanter and the ilium, respectively, the predicted pelvis fracture probability both exceeded 90%. The fracture probability for Sedan-1 was less than 5%.

TABLE 1
PELVIS DEFLECTION AND INJURY PROBABILITY OF EACH VEHICLE

		Sedan-1	Sedan-2	SUV	Minivan
Pelvis Deflection [mm]		0.86	2.49	5.11	4.17
Injury Probability [%]		1.2	38.7	99.8	95.0
Acetabulum Contact Force[kN]	**Contralateral side**	1.29	1.60	1.88	2.25
	Struck side	3.11	4.10	4.87	2.26
Contralateral Lower Limb Contact Timing [ms]	**Thigh**	28.0	26.1	25.8	22.6
	Leg	23.9	20.7	24.9	20.4

Examination of Influence of Human Body Mass on Pelvis Fracture Index

The time histories of the contact force between the pelvis/thigh and the vehicle, pelvis deflection, and right and left acetabulum contact forces were compared. Figure 8 presents the results for SUV. The results for the rest of the vehicles can be found in the APPENDIX. Figures 9 and 10 show the comparisons of the peak pelvis deflection and the right and left acetabulum forces, respectively, normalized by the results from the baseline model.

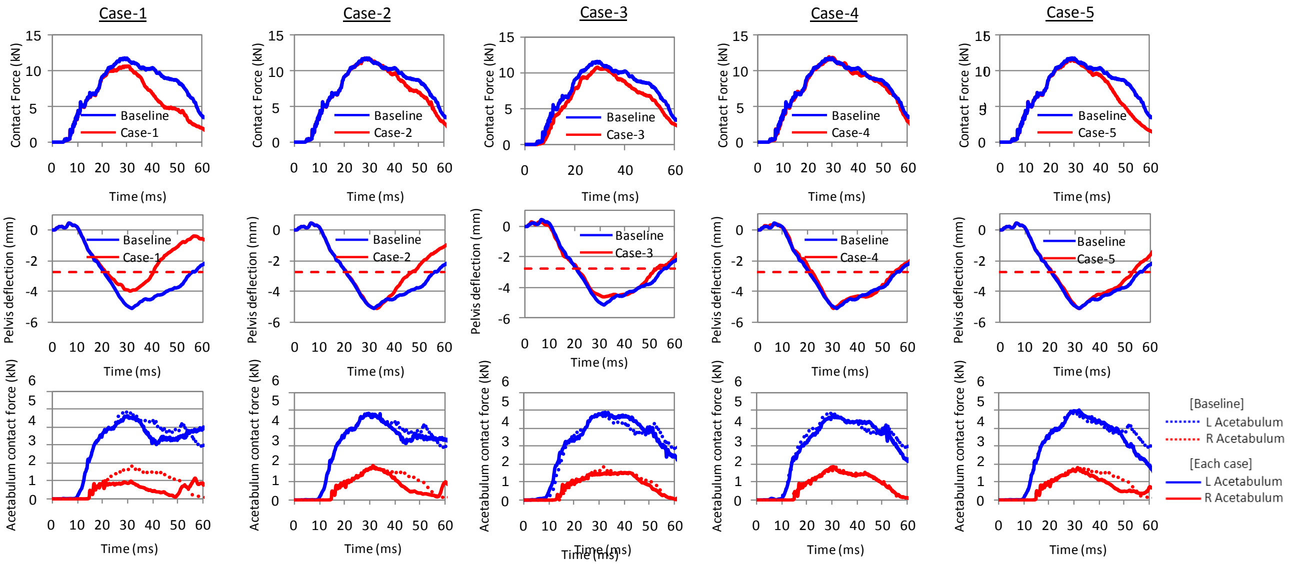

Fig. 8. Comparison of time histories of contact force between the pelvis/thigh and the vehicle, pelvis deflection, and right and left acetabulum contact force relative to the results of the baseline model (SUV)

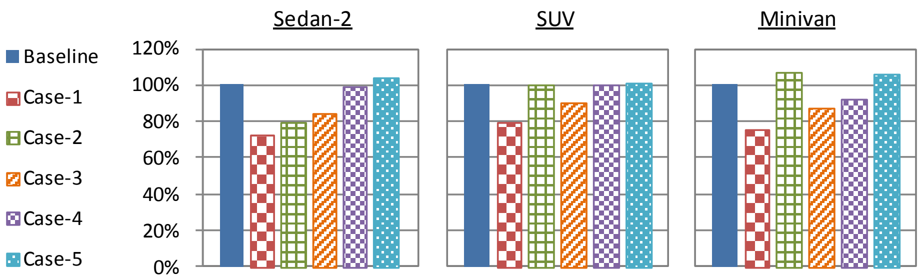

Fig. 9. Comparison of peak pelvis deflection

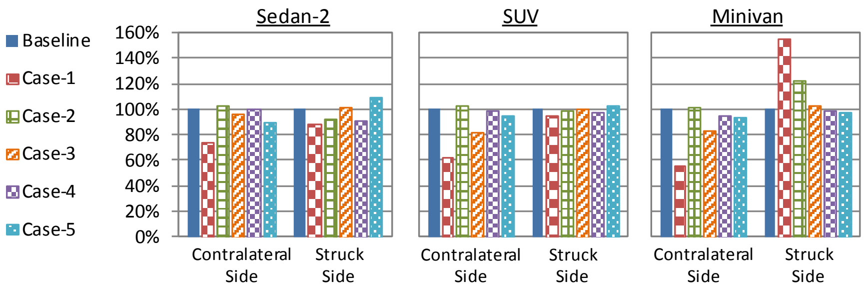

Fig. 10. Comparison of peak right and left acetabulum contact forces

The largest difference of the peak pelvis deflection was seen in Case-1 for all of the three vehicles. This trend was also seen in the contralateral acetabulum contact force as well. In Case-2, the difference varied between the three vehicles, suggesting that the influence of the vehicle front shape and the loading locations is a significant factor. In Case-3, both the pelvis deflection and the acetabulum contact force on the contralateral side significantly reduced due to the decrease in the mass of the struck side lower limb for all of the three vehicles. In Case-4 and Case-5, the maximum difference was seen for Minivan (approximately 5%), showing that the influence of the mass of the upper body is not significant.

Examination of Influence of Contact between Lower Limb and Vehicle

Fig.11 compares the peak pelvis deflection when the mass reduction and the elimination of the contact definition were applied to either the contralateral lower limb (Case-1') or the contralateral leg (Case-2') with that of the baseline model. The difference of the peak pelvis deflection from the baseline model was not significant (approximately 6% on the average of the three vehicles). Fig.12 shows the peak pelvis deflection when the mass of the struck side leg was reduced and its contact definition was eliminated (Case-4'), compared to that of the baseline model. The difference of the peak pelvis deflection from the baseline model was not significant (approximately 6% on the average of the three vehicles). These results showed that the elimination of the contact of the contralateral lower limb or leg effectively compensate for the inertial effect of these regions on pelvis loading. It was also shown that both the mass reduction and the contact elimination have an insignificant effect on pelvis loading for the leg on the struck side.

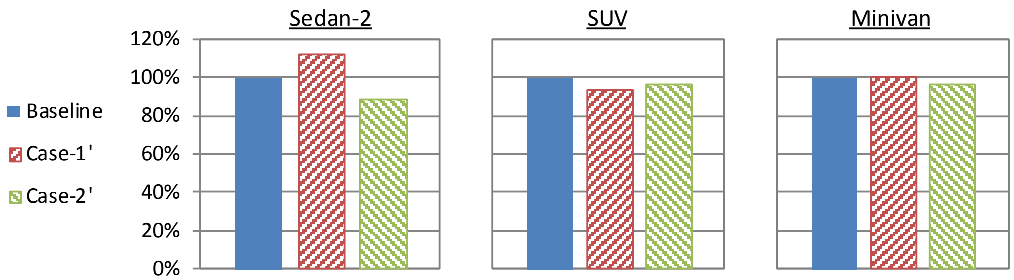

Fig. 11. Comparison of peak pelvis deflection in case of Case-1' and Case-2'

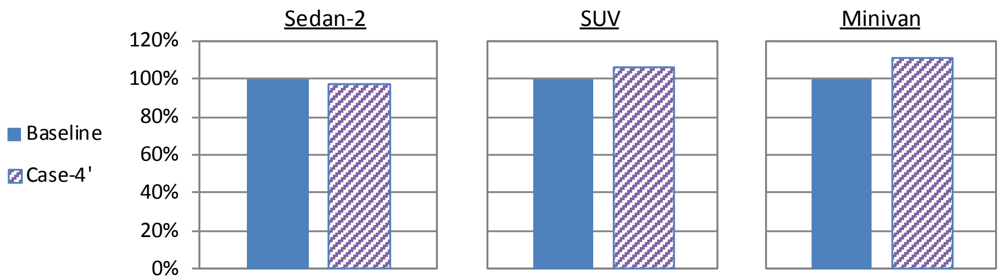

Fig. 12. Comparison of peak pelvis deflection in case of Case-4'

Therefore, the same comparisons of the time histories and the peak values as those for the previous analysis were also performed. Figure 13 compares the time histories, and Figures 14 and 15 compare the peak pelvis deflection and the peak right and left acetabulum contact forces, respectively. The same comparisons for the rest of the vehicles as those presented in Figure 14 for SUV can be found in the APPENDIX.

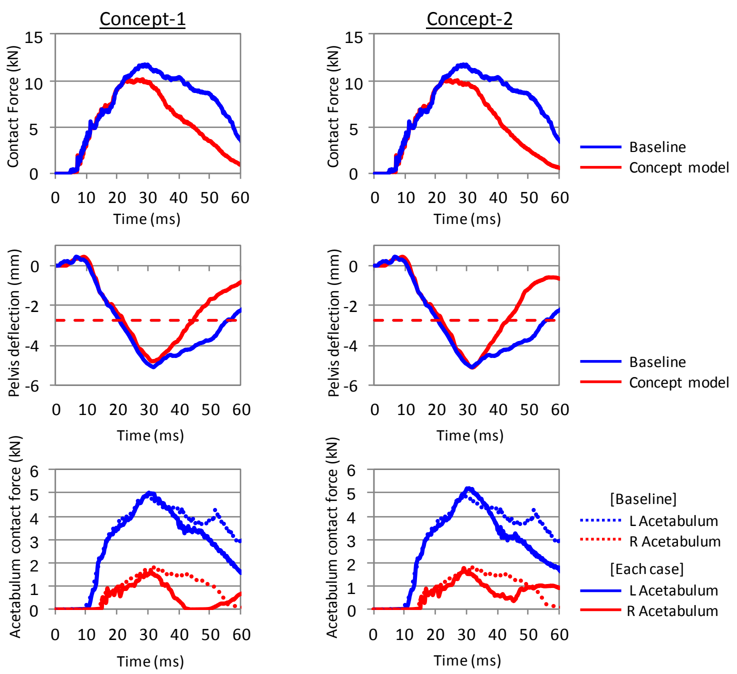

Fig. 13. Comparison of time histories of contact force between the pelvis/thigh and the vehicle, pelvis deflection, and right and left acetabulum contact force relative to the results of the baseline model (SUV)

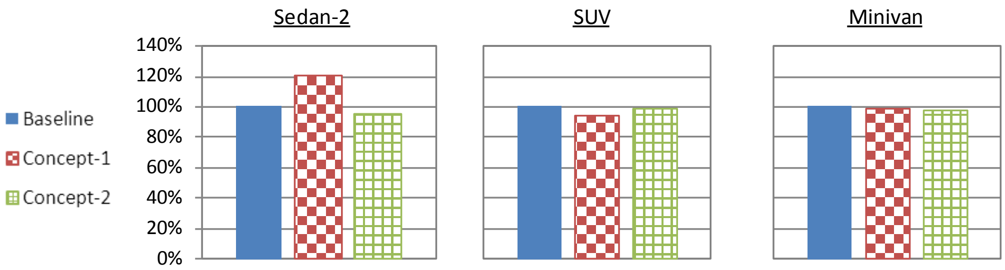

Fig. 14. Comparison of peak pelvis deflection

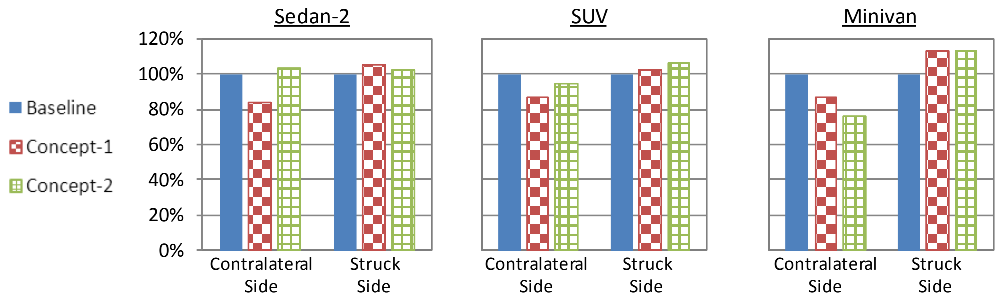

Fig. 15. Comparison of peak right and left acetabulum contact forces

As for Sedan-2 and SUV, the peak pelvis deflection in Concept-2 was the closest to that of the baseline model. In contrast, when it comes to Minivan, the peak pelvis deflection in Concept-1 resulted in the peak pelvis deflection closest to that of the baseline model. For all of the three vehicles, it was also found that the cases that resulted in the peak pelvis deflection closest to that of the baseline model also yielded the contralateral acetabulum contact force closest to that of the baseline model.

IV. DISCUSSION

Examination of Influence of Human Body Mass on Pelvis Fracture Index

As shown in Figure 9, for all of the three vehicles, the change of the peak pelvis deflection was larger in Case-1 where the mass of the entire contralateral lower limb was reduced. The reduction in the mass of the contralateral lower limb reduces the inertial force applied to the pelvis through the contralateral acetabulum, which reduces the reaction force to the pelvis. This explains why the reduction in the mass of the contralateral lower limb significantly reduced the peak pelvis deflection for all vehicles. When the mass of the contralateral leg was reduced, the largest difference of the peak pelvis deflection was seen with Sedan-2. This can be explained by the fact that the load from the hood edge of Sedan-2 to the contralateral lower limb was applied to the lower part of the thigh and that a significant rotation of the lower limb was generated due to the front shape of this vehicle. Case-4 and Case-5 resulted in an insignificant difference in the peak pelvis deflection, suggesting that the mass of the struck side leg and the upper body have only a minor effect on pelvis loading.

Examination of Influence of Contact between Lower Limb and Vehicle

In the case of Concept-1, the peak pelvis deflection from Sedan-2 differed from that of the baseline model by approximately 20%. This means that in the case of Sedan-2, the continued application of the reduced inertia of the contralateral lower limb by eliminating the contact definition overly compensated for the reduction in the inertia of the contralateral lower limb. In contrast, in the cases of SUV and Minivan, the fact that the difference of the peak pelvis deflection was much smaller suggests that in these cases where the primary direction of the applied and reaction forces to the pelvis is in the lateral direction, the application of the continued inertial force well compensated for the reduction in the inertial mass.

In the case of Concept-2, the difference in the peak pelvis deflection was insignificant for all of the three vehicle models, suggesting that in this case the continued application of the inertial force of both legs due to the lack of the contact with the vehicle well compensated for the reduction in the mass of both legs.

The results of the examination of the influence of the contact between the lower limb and the vehicle showed that the models resulting in the peak pelvis deflection closest to that of the baseline model also resulted in the contralateral acetabulum contact force closest to the baseline model. Figure 14 shows the peak right and left acetabulum contact forces for SUV. The left graph represent the peak resultant force, while the right one illustrates the X (lateral) and Z (superior-inferior) components of the forces for the baseline, Concept-1, and Concept-2 models. Similar results for the other vehicles can be found in the APPENDIX. Although the Z component of the peak contralateral acetabulum contact force was much lower than that of the baseline model, X component of the force was close to that of the baseline model. Since both Concept-1 and Concept-2 models succeeded in reproducing the peak pelvis deflection of the baseline model, it is presumed that the peak pelvis deflection can be reproduced when the X component of the contralateral acetabulum contact force is accurately reproduced. Based on this result, a subsystem impactor could be developed that is capable of representing the pelvis response in impacts with various vehicles can be developed given that the X component of the force applied from the vehicle and the reaction force applied to the contralateral acetabulum from the inertia of the contralateral lower limb are accurately represented.

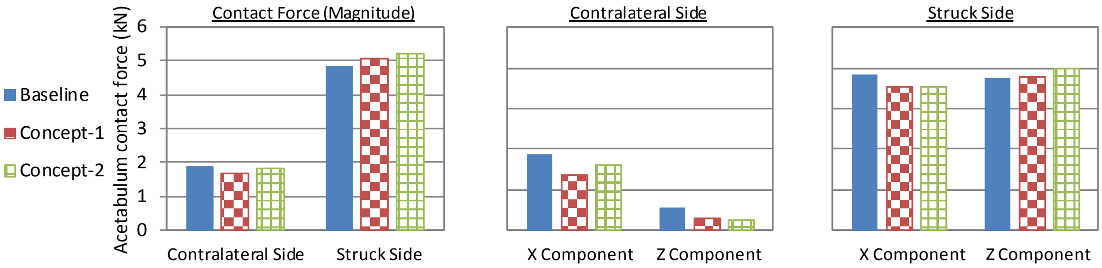

Fig. 16. Comparison of acetabulum contact force (SUV)

V. CONCLUSIONS

Crash simulations using a human FE model and vehicle models with various front shapes were conducted. In order to clarify the sensitivity of the human body mass to pelvis loading, the peak pelvis fracture index was compared between the results from the baseline simulation and those from the simulations using various human models with the masses of lower limbs and upper body changed. In addition, the effect of the contact between the lower limb and the vehicle was also investigated by eliminating the contact definition to apply the reduced inertial force continuously and compensate for the reduction in the inertial load. From the results of these crash simulations, the following conclusions were reached:

- The significant reduction in the mass of the contralateral lower limb resulted in the significant reduction in the peak pelvis deflection for all of the three vehicles.
- Similar effect was observed only for Sedan-2 when the mass of the contralateral leg was significantly reduced.
- No significant change in the peak pelvis deflection was seen for all of the three vehicles when the mass of either the struck side leg or the upper body was significantly reduced.
- For SUV and Minivan, the peak pelvis deflection from the baseline model was well reproduced when the significant mass reduction and the elimination of the contact definition were applied to either the contralateral lower limb and the struck side leg, or the contralateral and the struck side legs.
- For Sedan-2, the significant reduction of the mass and the elimination of the contact definition applied to the contralateral lower limb and the struck side leg resulted in significant increase in the peak pelvis deflection relative to the baseline model, while the peak pelvis deflection was well represented when the same changes were applied to the contralateral and the struck side legs.

Based on these results, it is recommended that a biofidelic impactor designed to evaluate pelvis fractures representing pelvis loading conditions in pedestrian accidents with various types of vehicles be developed by representing the pelvis and both thighs with additional masses compensating for the inertial effect from the upper body and both legs.

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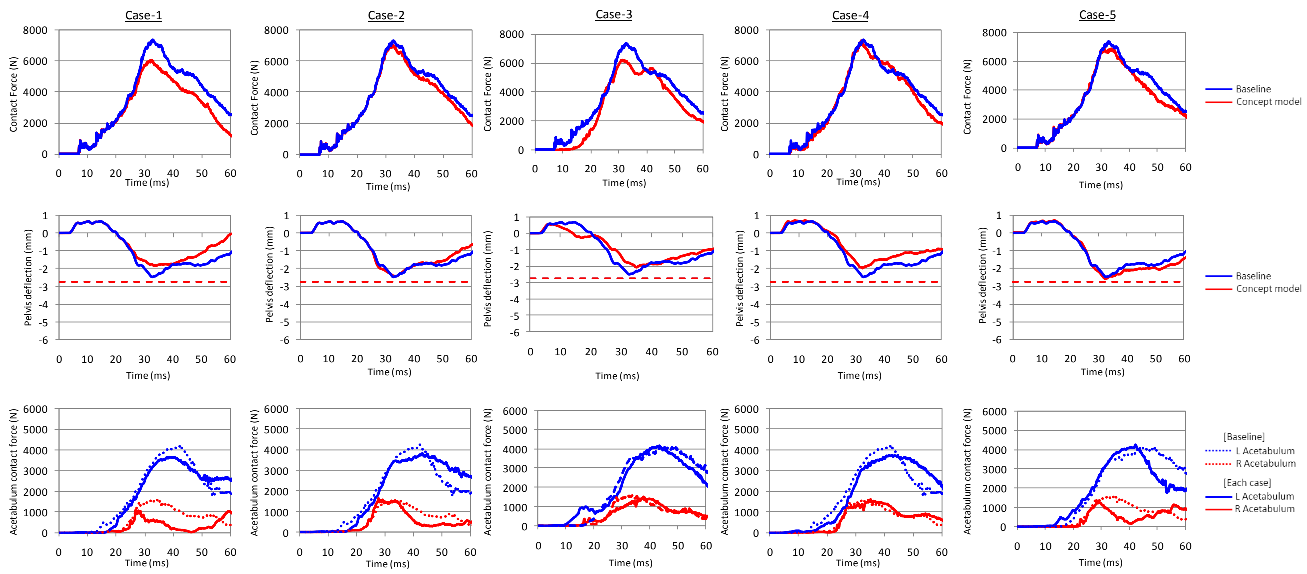
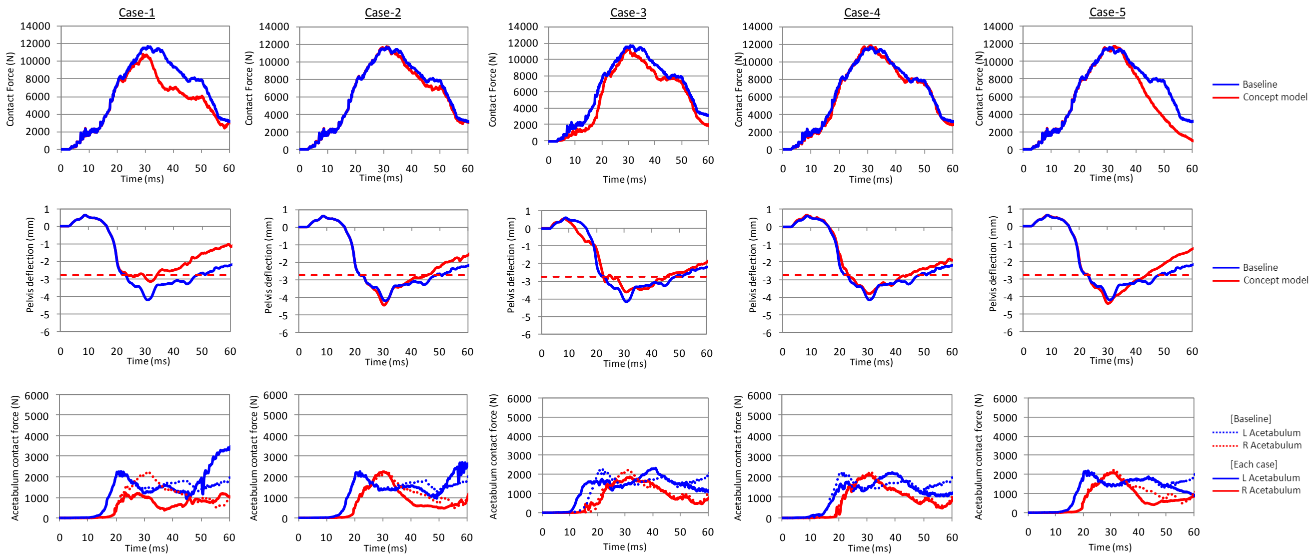
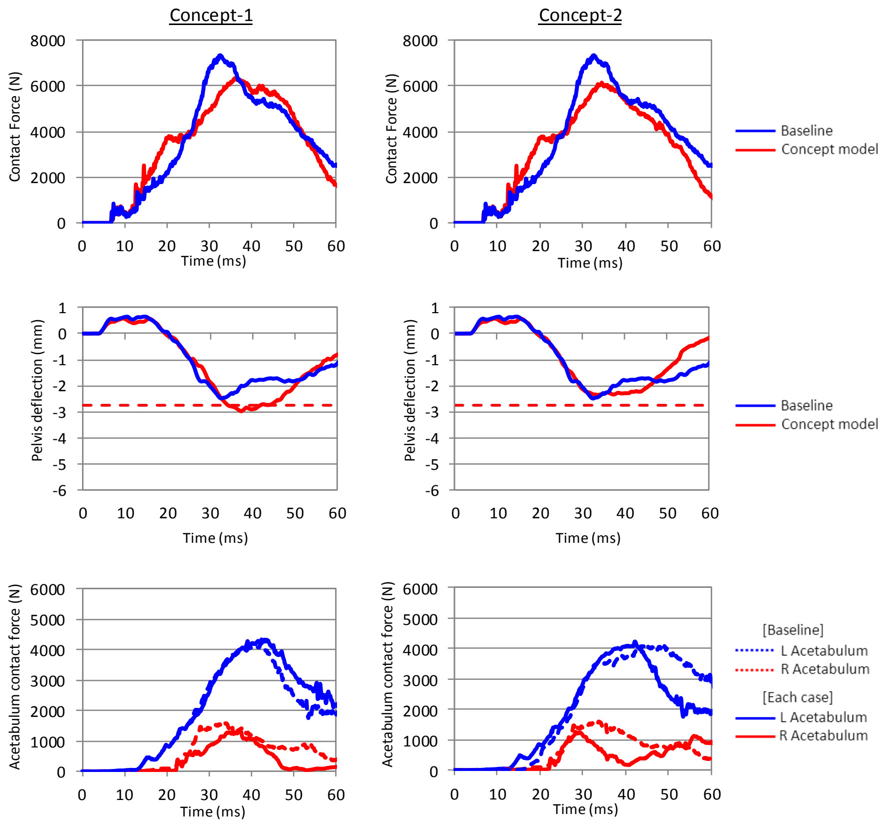
VII. APPENDIX



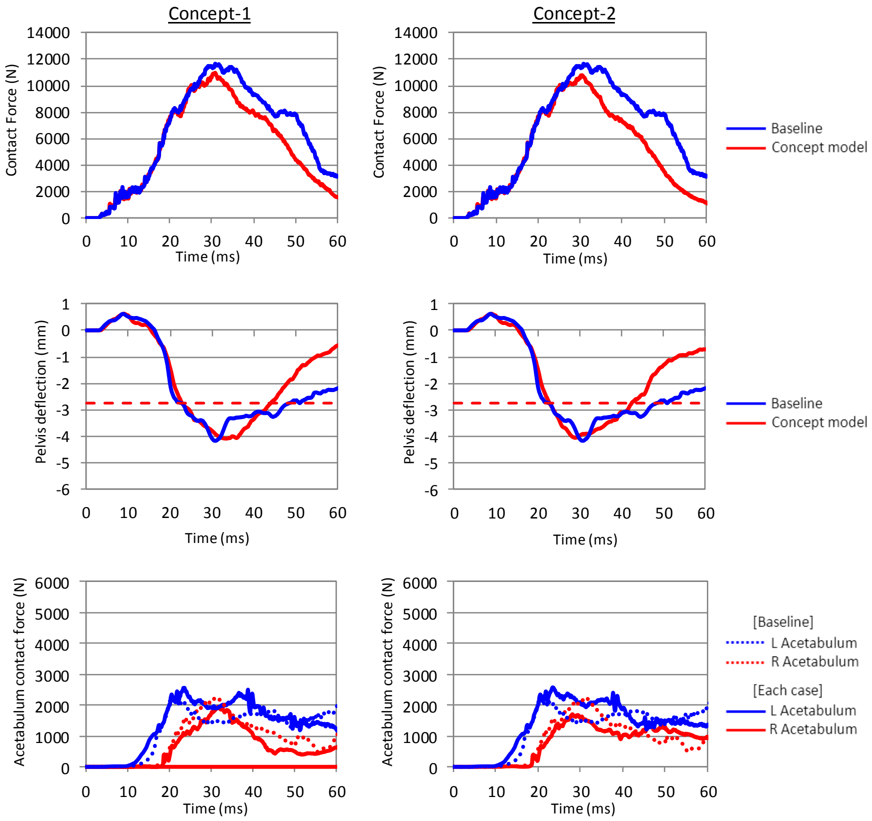
Appendix 1. Comparison of time histories of contact force between the pelvis/thigh and the vehicle, pelvis deflection, and right and left acetabulum contact force relative to the results of the baseline model (Sedan-2)



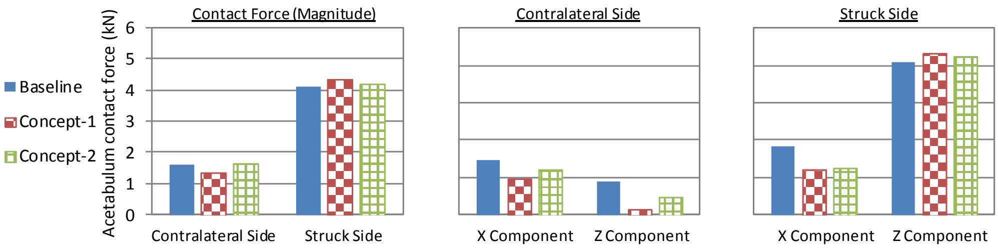
Appendix 2. Comparison of time histories of contact force between the pelvis/thigh and the vehicle, pelvis deflection, and right and left acetabulum contact force relative to the results of the baseline model (Minivan)



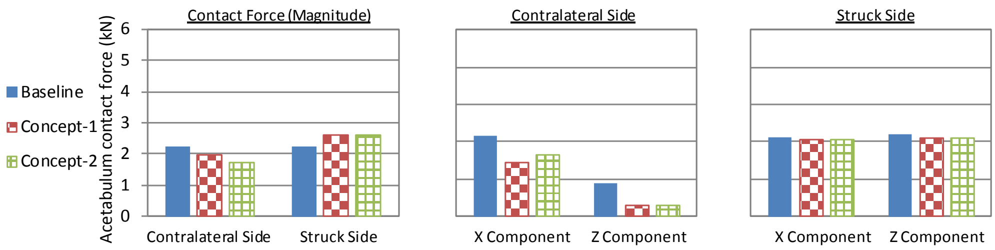
Appendix 3. Comparison of time histories of contact force between the pelvis/thigh and the vehicle, pelvis deflection, and right and left acetabulum contact force relative to the results of the baseline model (Sedan-2)



Appendix 4. Comparison of time histories of contact force between the pelvis/thigh and the vehicle, pelvis deflection, and right and left acetabulum contact force relative to the results of the baseline model (Minivan)



Appendix 5. Comparison of acetabulum contact force (Sedan-2)



Appendix 6. Comparison of acetabulum contact force (Minivan)