Recent advances in THUMS : development of individual internal organs, brain, small female, and pedestrian model

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Abbreviations: THUMS = “Total HUman Model for Safety”

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ABSTRACT

A finite element model of total human model for safety, which is called THUMS, has been developed in order to study human body responses for impact loads. In previous report, a mid-size adult male occupant model of THUMS was developed and validated for several impact loads. This paper briefly describes recent advances in THUMS. Individual internal organ models and a detailed brain model have been developed to be integrated with the occupant model. In addition to the mid-size male occupant model, a small female occupant model and a mid-size male pedestrian model have been also developed and validated in order to simulate impact responses of female occupants and male pedestrians.

INTRODUCTION

A finite element model of the whole human body called THUMS has been developed. The purpose of the THUMS model is for the LS-DYNA users to simulate responses of the human body sustaining impact loads. We reported on development of a mid-size adult male occupant model of THUMS in 2002 [1]. The model was validated for frontal and/or lateral impacts to the thorax, abdomen, and hip. The responses showed good agreement with those of cadavers sustaining impact loads. Howerver, the internal organs and brain were simplified with continuum bodies and homogeneous material properties. Therefore, the model did not allow the users to investigate motions and injuries of the individual internal organs and brain during impact situations. In this study, individual internal organs and a detailed brain have been modeled by reproducing their complicated structures as faithfully as possible and defining necessary connections and sliding interfaces which associate each componet with the others. These models have been used for investigating if they are enough models to predict responses of the internal organs and brain for impact loadings. On the other hand, a female occupant model should be newly developed in order to simulate impact responses of female occupants because females and males are different in geometry and material property of some skeletal parts and soft tissues. Therefore, a female occupant model has been developed and validated with attention to the differences between females and males. Additionally, a mid-size male pedestrian model has been developed by modifying the postures of the occupant model at the knee, hip, elbow, shoulder, and spinal joints. This paper briefly describes the structures of individual internal organs, a detaied brain, a small female and a mid-size male pedestrian model, which have been recently developed, as well as some results of the simulations using the models. Finally, we describe further development plan of the model.

Overview of the THUMS model

Figure 1 shows a mid-size adult male occupant model of THUMS, which is called THUMS-AM50, with some soft tissues removed to expose the skeletal structure. This model represents 50 percentile American male (AM50) with 175cm height and weighing 77kg in a seating posture. The model contains about 60,000 nodes and 80,000 elements. Each bone consists of cancellous bone modeled using solid elements and cortical bone modeled using shell elements. In the joints of the THUMS model, ligaments that connect the bones are modeled using shell elements or beam elements and sliding interfaces are defined on the contacting surfaces of these bones. Skins and muscles that cover the bones are modeled with solid elements.

Internal organs and brain are modeled as continuum bodies with solid elements. The material properties of the tissues have been taken from Yamada (1970) [2]. This model was validated for frontal and/or lateral impacts to the thorax, abdomen, and hip [1].

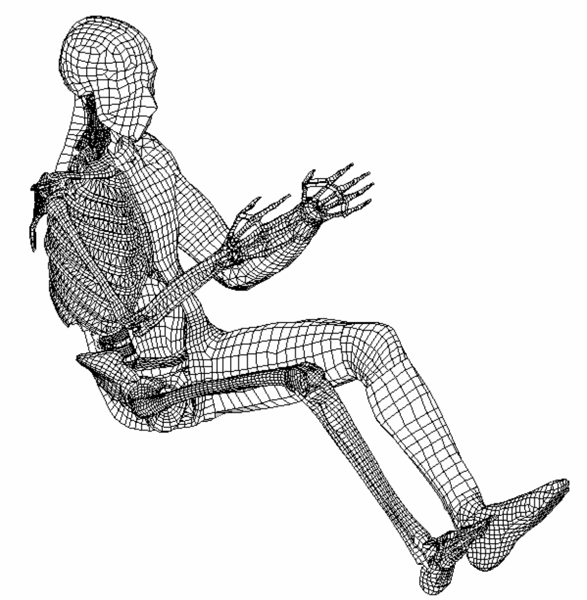
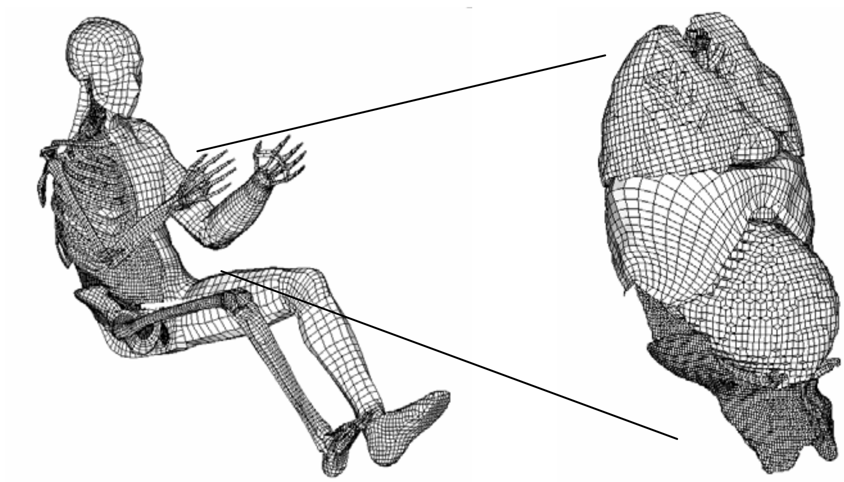


Figure 1 THUMS-AM50 occupant model with some soft tissues removed to expose

Individual Internal Organs

As described previously, internal organs are not modeled individually, several internal organs are fused to form continuum bodies with homogeneous material properties.



(a) THUMS AM50 occupant model (b) Individual internal organs

Figure 2 THUMS AM50 occupant model with individual internal organs

Recently, we have developed finite element models of individual internal organs, which include the heart, lung, stomach, liver, spleen, pancreas, kidney, intestine, aorta, and vena cava, using an explicit finite element code PAM-CRASH [3]. These models were modified to simulate using LS-DYNA ver.960. Figure 2 shows THUMS AM50 occupant model with individual internal organs. The individual internal organ models contain about 30,000 nodes and 73,000 elements that include about 20,000 solid elements, 18,000 shell elements and 35,000 bar or beam elements. Figure 3 demonstrates the respiratory, circulatory, and digestive system of the model. Solid organs of the liver, spleen, pancreas, and kidney are modeled using solid elements. The heart, lung, stomach, duodenum, intestine are not solid organs actually, but they are filled with solid elements in order to represent blood, air, and other contents inside. The trachea, bronchus, diaphragm, aorta, vena cava, and esophagus are modeled using shell elements. Bar elements are used to model the bronchiolus of the lungs, the interlobularis of the liver, and the capillary of the kidneys. Sliding interfaces are defined on the contacting surfaces of adjacent organs. The upper part of the trachea and esophagus are fixed with shell elements at the upper part of the cervical spine. The lower part of the intestine are fixed with soft tissue of buttock while the rear part of it are fixed with the lumbar spine using bar elements. Most organs are modeled using non-linear elastic material. Different material properties, which are obtained from Yamada [2] and Ishihara [4], were assigned to these organs. Although this model has been integrated with THUMS AM50 occupant model and validated for frontal and/or lateral impacts to the thorax, abdomen, and hip using PAM-CRASH, it is still used for the verifications in LS-DYNA.

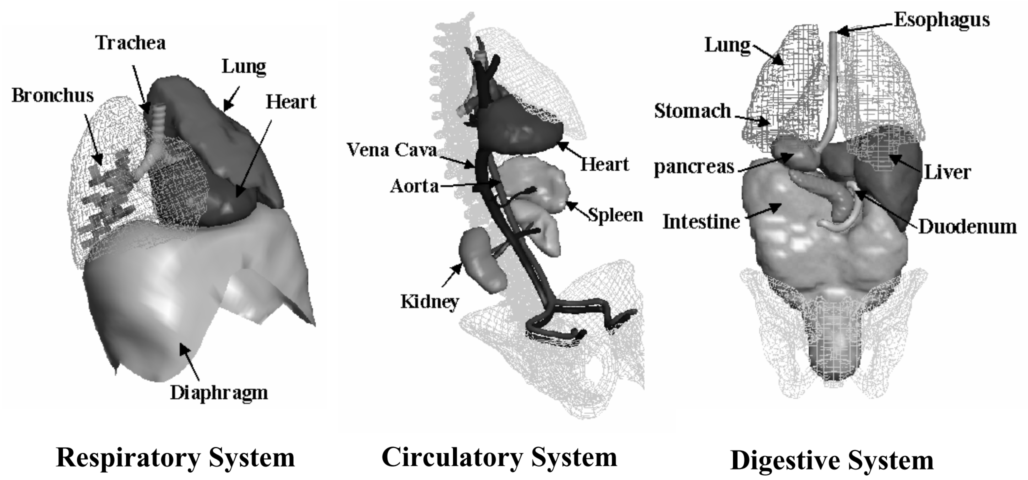
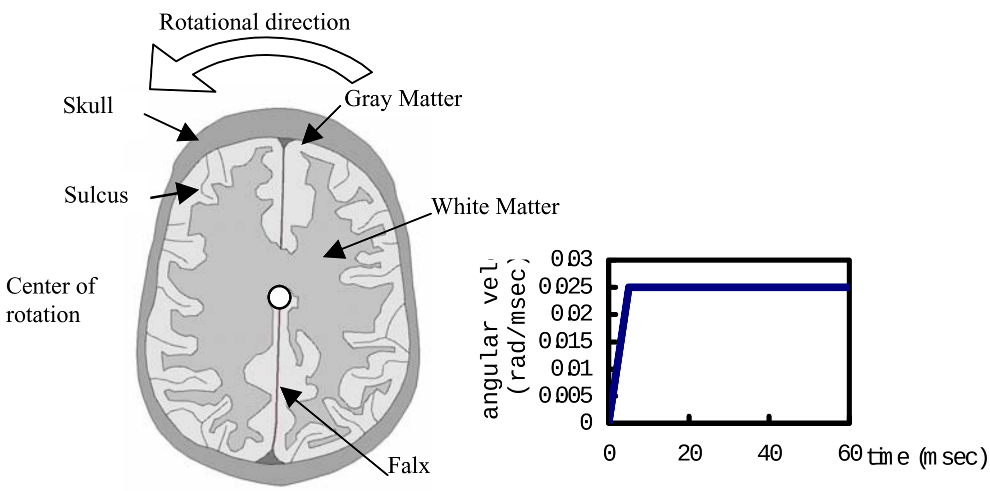


Figure 3 Respiratory, circulatory, and digestive system of internal organs

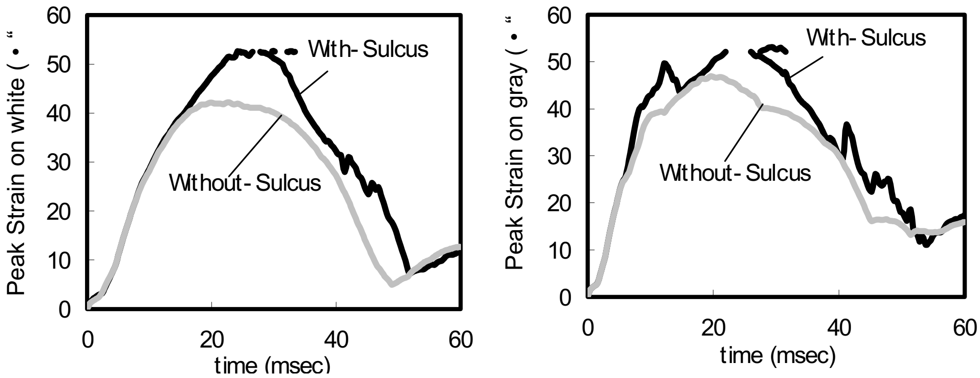
Detailed Brain Model

Traumatic brain injury is one of major injuries caused by traffic accidents and contact sports. In brain injuries, there are two types of injuries: focal injury due to direct contact and diffuse injury due to inertial loading. Diffuse injury includes concussion and diffuse axonal injury (DAI). DAI, in which structural and functional damages of the axons in the white matter occur, is the severest form of the diffuse injury. Many finite element models have been developed by several research groups in order to achieve a better understanding of these brain injuries due to direct and inertial loadings [5]. However, the injuries due to direct impacts have been often investigated using the models while DAI has not been investigated very much although DAI is one of the major causes of death. The purpose of this study is to develop a finite element model of the brain in order to predict occurrence of DAI. Figure 4(a) shows 2-dimensional head/brain model that represents an axial slice of the human head. Strains in the white matter could be one of good predictors for occurrence of DAI, based on a hypothesis that DAI could occur if strains of the axons in white matter exceed 20% due to external loading [6]. There are several factors which could affect strains in the white matter. These factors could be associated with how material properties of brain tissues are assigned, how the cerebral spinal fluid (CSF) between the skull and brain is modeled, and if the model is developed with or without sulci and blood vessels of the cerebrum. The purpose of this study is to determine if modeling sulci of the cerebrum affects prediction for occurrence of DAI [7]. In this model two different ways of modeling techniques are employed: “without-sulci” model that does not include sulci and “with-sulci” model in which sucli are modeled. In the “with-sulci” model each sulcus is modeled by defining a sliding-only contact interface on the surfaces of the cerebral cortex that face each other across the sulcus so that these surfaces move relatively along each other only in tangential direction. Each model was used to simulate a human head that sustains angular acceleration. As shown in Figure 4(b), the prescribed angular acceleration was applied on the skull with the mass center of the head as the center of rotation so that skull rotates in axial plane. The peak value and the duration of the step-shaped pulse of the angular acceleration were 5000 rad/sec^2 and 5 msec, respectively. Figure 5 shows comparisons of peak 1st principal strain sustained by the white matter and gray matter between the two types of models. The peak value of the white matter’s strain predicted by the “with-sulci” model are larger than that predicted by the “without-sulci” model. The maximum ratio of the peak 1st pricipal strain obtained from the “with-sulci” and that obtained from “without-sulci” model is up to 1.25. We conclude that modeling of sulci of the cerebrum can affect the prediction of occurrence of brain injury. In the future, further study will be performed to determine if the other factors described above affect prediction for occurence of DAI. Then, a 3-D brain model will be developed based on these simulation results.



(a) 2-dimensional head/brain model (b) Prescribed angular velocity

Figure 4 2-Dimensional Head Model and a simulation set-up with prescribed angular velocity

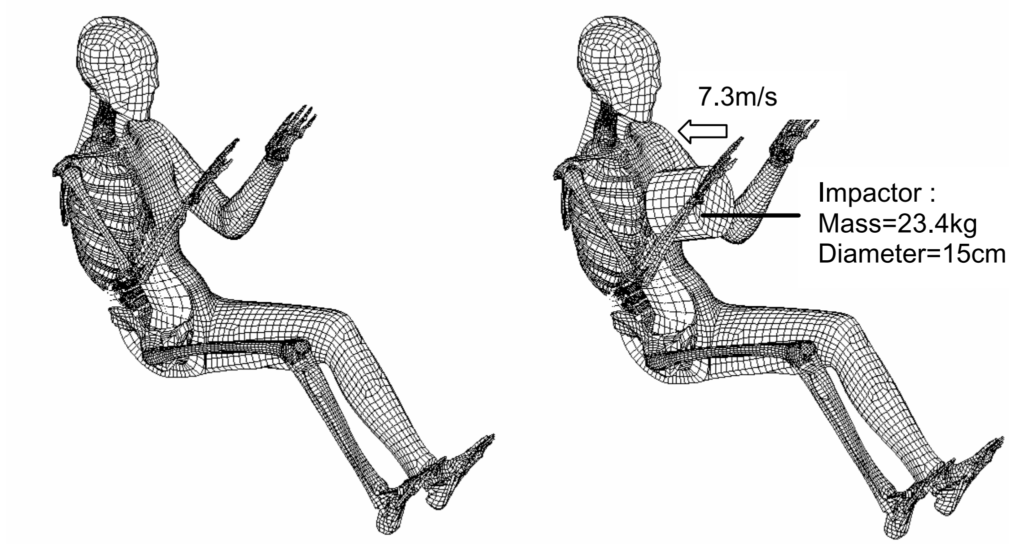


(a) White Matter (b) Gray Matter

Figure 5 Peak 1st principal strain sustained by the white matter and gray matter

Small Female

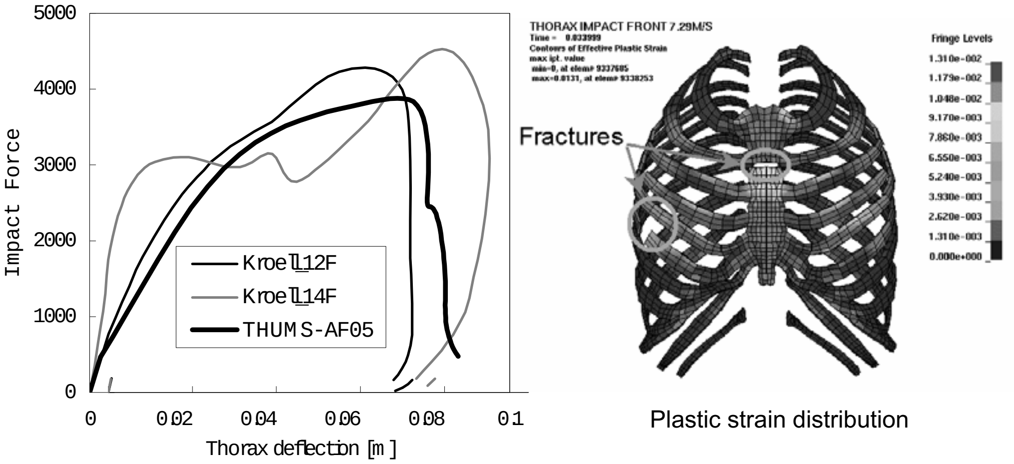
This section describes development and validation of a finite element model of a small female occupant with 152cm height and weighing 46.4kg, which is called THUMS-AF05. Figure 6(a) shows THUMS-AF05. Anthropometric data of the small female occupant were obtained from AF05 (American Female 5%ile) data defined at the university of Michigan [8]. The head, neck, spine and extremities of the model were obtained by scaling down THUMS-AM50. According to anatomical texts, there are significant differences on the geometry of thoracic and pelvic regions between males and females. Therefore, thoracic and pelvic regions were newly developed in order to reproduce geometric features of the female skeletal parts. Skeletal parts and soft tissues were modeled by using the same way as THUMS-AM50.



(a) THUMS AF05 occupant model (b) A simulation set-up

Figure 6 THUMS AF05 occupant model and a simulation set-up for a frontal impact.

The model was validated for frontal impact cadaver test data conducted by Kroell et al.(1971) [9]. Kroell et al. conducted a series of cadaver tests for thoracic frontal impacts. Their tests included two cadavers of which the anthropometric data were similar to those of AF05. In simulations, a 23.4 kg impactor hit frontal surface of the thorax at a speed of 7.3 m/s in order to reproduce the experimental set-up (Figure 6(b))[10]. Thoracic deflection was obtained from the distance between an impactor surface and a thoracic posterior surface. Figure 7(a) shows the comparison of thoracic force-deflection curves between a simulation result and test data. The simulation result shows good agreement with test data. Figure 7(b) demonstrates that the model predicted bone fractures in the ribs and sternum, which were observed in cadaver tests. Future work will include further development of internal organs for a female and pregnant, and further validation for reproducing global behaviors and injuries of small female occupants.

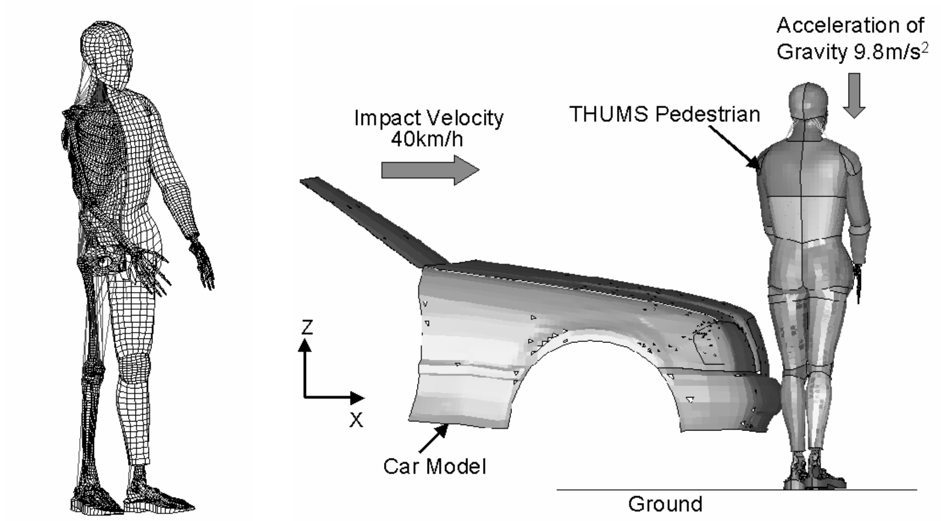


(a) Force-deflection curves (b) Prediction of bone fractures

Figure 7 Impact force-deflection curve and bone fractures predicted in the simulation.

Pedestrian

A pedestrian model was first developed and validated using PAM-CRASH [11]. The model was modified to simulate using LS-DYNA ver.960. Figure 8(a) shows a mid-size adult male pedestrian model with some soft tissues removed to expose the skeletal parts. This model was used to simulate a car-to-pedestrian impact with initial velocity of 40km/h. Figure 8(b) shows a set-up used in this simulation. Although a car was modeled as a rigid body using shell elements, the simulation set-up is almost the same as that of a cadaver test conducted by Schroeder et al. (2000)[12]. Figure 9 shows motions of the pedestrian model during the impact. After the impact, the bumper of the car hit the lower part of the knee and the human body was thrown up on the hood as observed in the cadaver test. Figure 10 shows bone fractures predicted in the lower extremities in the car-to-pedestrian impact simulation. The sites of bone factures predicted in the simulation were almost the same as those in the cadaver test. In the future, more muscles will be added to the pedestrian model and activated in order to investigate the differences in gross motions of pedestrians for impacts between non-activated models like cadavers and activated model like living human bodies.



(a) THUMS AM50 pedestrian (b) A simulation set-up for a car-to-pedestrian

Figure 8 THUMS AM50 pedestrian model and a simulation set-up for a car-to-pedestrian impact.

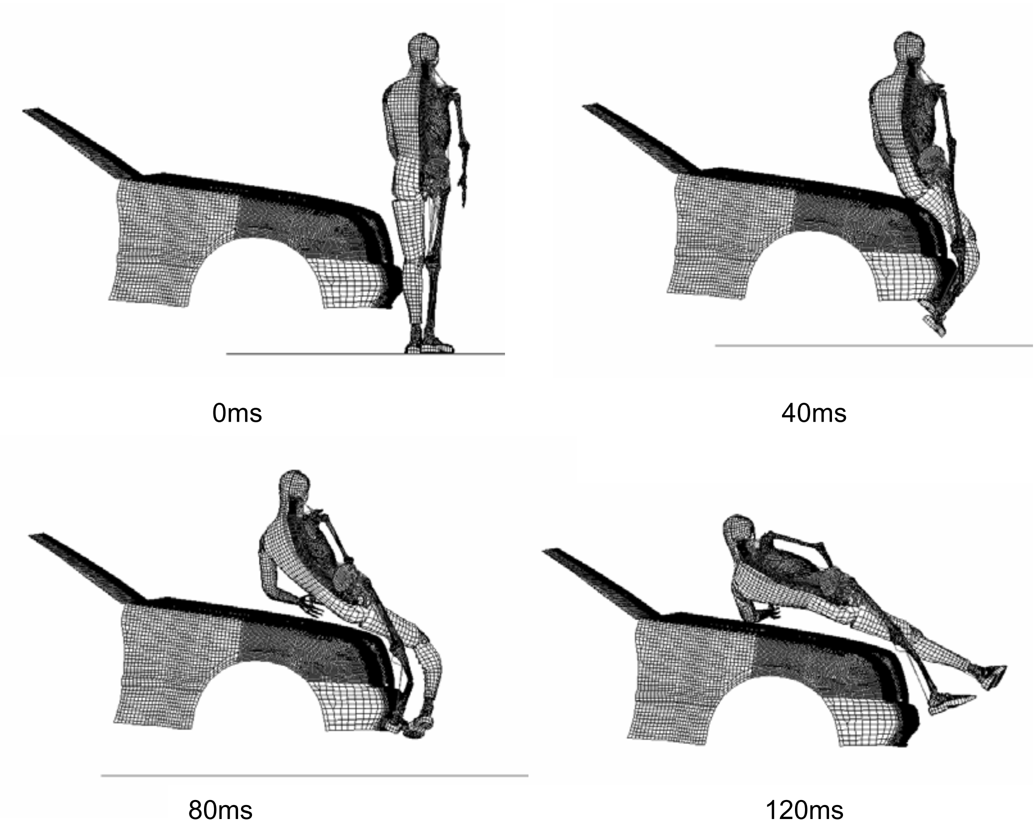


Figure 9 Motions of THUMS pedestrian model during a car-to-pedestrian impact

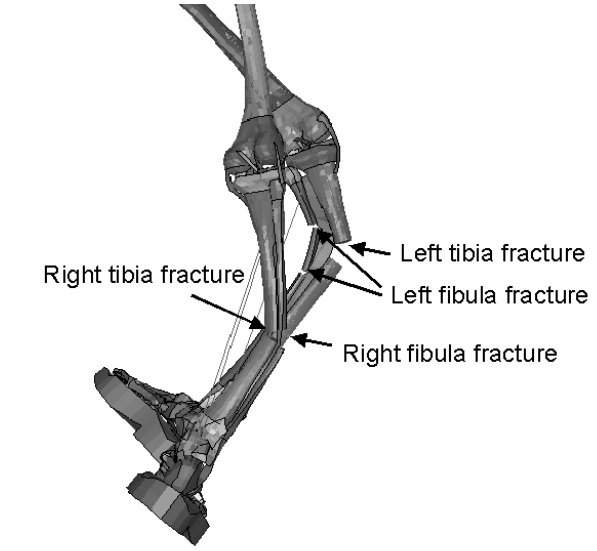


Figure 10 Bone fractures in the lower extremities predicted in the car-to-pedestrian impact simulation (45ms after impact)

Summary and Conclusions

THUMS AM50 occupant model has been developed with new features in order to perform more detailed investigation on human body responses and injuries for impact loads. These include individual internal organ models and a detailed brain model, which are modeled by reproducing their complicated structures as faithfully as possible and defining necessary connections and sliding interfaces which associate each componet with the others. These models have been used for investigating if they are enough models to predict responses of the internal organs or the brain for impact loadings. However, in the current model, the internal organs are modeled using non-linear elastic material without viscosity and the brain is modeled using liner viscoelastic material, although soft tissues of the internal organs and brain are actually non-linear viscoelastic material. Additionally, the assumed material properties were assigned to some components of the current models due to the lack of experimental data, especially on strain rate dependency. Therefore, furthur study would be needed to model soft tissues of the internal organs and brain, and to obtain experimental data on material properties of these soft tissues. In addition to the mid-size male occupant model, a small female occupant model and a mid-size male pedestrian model have been also developed and validated in order to simulate impact responses of female occupants and male pedestrians. In the simulations, some bone fractures in the ribs and sternum of the small female occupant model and in the lower extremities of the mid-size male pedestrian model were reproduced as observed in experimental cadaver tests. Future work will include further study on effects of muscle activity and blood flow, and further development of a large male occupant, pregnant, child, and elderly person model.

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