DEVELOPMENT OF ADVANCED HUMAN MODELS IN THUMS

AUTHORS:

Masami Iwamoto, Yuko Nakahira, Atsutaka Tamura,
Hideyuki Kimpara, Isao Watanabe, Kazuo Miki
Toyota Central R&D Labs., Inc.

CORRESPONDENCE:

Masami Iwamoto
Toyota Central R&D Labs., Inc.
Nagakute, Aichi 480-1192, Japan
Phone: +81-561-71-8007
Fax: +81-561-63-6459
Email: iwamoto@mosk.tytlabs.co.jp

ABSTRACT

A finite element model of human body called THUMS has been developed to predict gross motions and multiple skeletal injuries of a whole human body during impacts. Recently, we have developed a head/brain model and thoracic/abdominal internal organ models to evaluate more severe injury risks for occupants and pedestrians in automotive accidents. The head/brain model was validated against some test data on translations and rotations of the head obtained from the literature. The internal organ models were validated against hub impacts for the thorax or abdomen. These models are currently attempted to predict severe injuries in the brain and liver, etc. Finally, we will show THUMS family including a small female, a large male, and a child, etc, which have been developed to investigate the effects of body size on impact responses and injuries.

KEYWORDS:

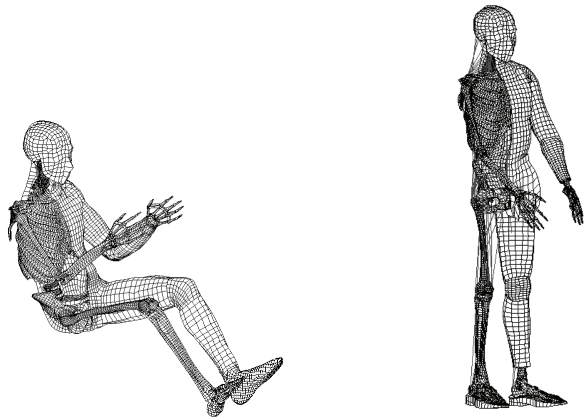
Impact biomechanics, FEM, Human body model, Injury prediction, Soft tissue

INTRODUCTION

Recent automotive accident data analysis demonstrates that some occupant restraint devices such as seatbelts and airbags contribute to reduce the fatality in Japan [1]. Contrary to reduction of the fatality, the number of injured persons tends to increase. To reduce the number of injured persons, we have to understand how injuries of occupants and pedestrians can occur. LS-DYNA [2] has good performance to simulate impact situations seen in automotive accidents. Therefore, if a human body model available in LS-DYNA exists, it is useful to investigate the injury mechanisms. In 2002, we developed a finite element model of the whole human body called THUMS [3]. The human model represents American male 50 percentile (here after referred to as AM50) occupant and includes bones, ligaments, and some soft tissues which are introduced for absorbing impact energy. The model was validated for frontal and/or lateral impacts to the thorax, abdomen, and hip. The responses showed good agreement with those of human bodies sustaining impact loads. In addition, the model appeared to have the possibility to predict skeletal injuries such as bone fractures and ligament ruptures, which are ranked to minor or moderate injuries. In order to see severe injuries, we have to predict injuries in the brain and internal organs. Thus, we have developed models with detailed structure of brain and internal organs. To evaluate injuries of occupants and pedestrians with different sizes, genders, and ages, we also have developed different types of human body models. In 2003, we reported on development of an occupant model with individual internal organs, 2D brain model, a small female model, and a pedestrian model [4]. However, those models have some problems on computational stability and accuracy in geometry, anatomical structure, and material properties. In this paper, we report on recent development of THUMS, especially, 3D brain model, internal organs, and different types of human body models such as American female 5 percentile (here after referred to as AF05), American male 95 percentile (here after referred to as AM95), and the 6-year old child.

THUMS-AM50

Figure 1 shows mid-size adult male occupant and pedestrian models of THUMS, which are called THUMS-AM50, with some soft tissues removed to expose the skeletal structure. These models represent the AM50 with 175 cm height and weighing 77 kg in a sitting posture. The THUMS-AM50 contains about 60,000 nodes and 80,000 elements. Each bone consists of cancellous bone modelled using solid elements and cortical bone modelled using shell elements. In joint articulations of the THUMS models, ligaments that connect the bones are modelled 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 modelled with solid elements. Internal organs and brain are modelled as continuum bodies with solid elements. The material properties of the tissues have been primarily taken from Yamada [5]. The occupant model was validated for frontal and/or lateral impacts to the thorax, abdomen, and hip [3]. The model was also validated for head-neck motions in flexion-extension, lateral bending, and rear end impact [6] and foot/ankle responses in a frontal impact [7]. The pedestrian model was developed by changing the posture of the occupant model to a standing posture, but it was newly validated against test data on lateral knee impacts and car-to-pedestrian impacts [4].

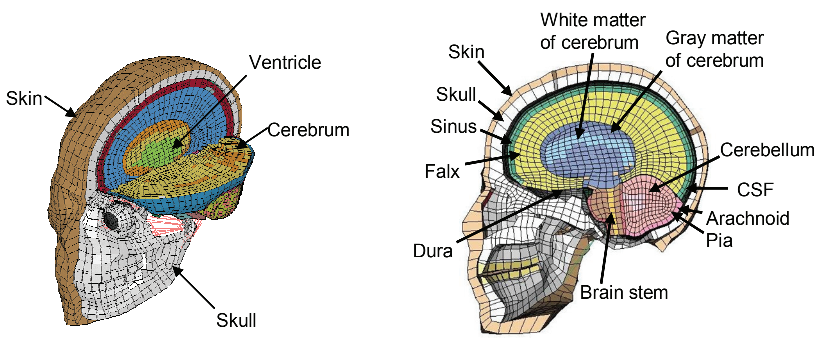


(a) Occupant (b) Pedestrian

Figure 1: THUMS-AM50 occupant and pedestrian models with some soft tissues removed to expose

HEAD/BRAIN MODEL

A head/brain model was developed to investigate head/brain injury mechanisms during impacts. Figure 2 shows the head/brain model. The head/brain model consists of the skull, brain, and skin. Basic anthropometric data of the skull and brain model were partially obtained from available anatomical data sets (Viewpoint Datalabs, and Visible Human Project, USA) and were modified based on the anatomical references [8]. The skull model includes cortical bone modelled by solid elements and spongy bone modelled by shell elements. The brain model consists of all hexagonal solid elements representing the cerebrum, cerebellum, brainstem with distinct white and gray matter, and cerebral spinal fluid (CSF). Additionally, solid elements were used to represent the sagittal sinus and shell elements to represent the dura, pia, arachnoid, meninx, falx cerebri, and tentorium. The minimum mesh size (length, width, and height) was determined as 2 mm to accomplish a reasonable time step. The head/brain model consists of 49,700 elements (24,100 solid, 25,200 shell and 400 seatbelt elements) and has a mass of 4.39 kg. The interface between the brain and the skull is the most important to represent accurate brain motions. Since the fluid called CSF exists between the brain and the skull, the brain can slide along the interior surface of the skull with a weak connection to the skull through the arachnoid. Although the interface with CSF should be represented by using fluid-structure interaction, it is still difficult to solve the problem in LS-DYNA. Therefore, some techniques were introduced to represent the interface. The CSF was modelled by hexagonal solid elements with material properties of the cerebral spinal fluid. Tiebreak interfaces available in LS-DYNA were used for representing contacts between the skull and the CSF. The tiebreak interfaces can be used to simulate frictional sliding between two adjacent surfaces. Material properties for the head/brain model were determined based on published literature. The skull was modelled with elastic-plastic material models with failure (MAT24/105). The brain was modelled using a viscoelastic material model with incompressibility (MAT5) according to Galford and McElhaney [9].



(a) Oblique view (b) Lateral view

Figure 2: Head/Brain Model

The head/brain model was validated against three series of head impact tests [10]. In this paper, we describe one of the validation results using test data reported by Trosseille et al. [11]. A simulation condition was carefully determined as to reproduce the test setup. An impactor with a mass of 23.4 kg and a shape similar to that of a steering wheel was directed to the facial region at an impact velocity of 7 m/s in the anterior-posterior direction. As a result, a translational acceleration of 1000 m/s^2 and a rotational acceleration of 7600 rad/s^2 were applied to the center of gravity (CG) in the head of a human body in a sitting posture. The intracranial pressure and acceleration measured in the experimental tests were compared with those calculated in the simulations. The simulation setup is shown in Figure 3. The position of intracranial pressure transducers, accelerometers, and center of gravity (CG) were indicated with dark, gray, and white colored dots, respectively. In the simulations, the material model for the skull was changed from deformable material to the rigid one in order to setup the CG on the center of rotation of the head model. Figure 3 also shows the time history curves of the intracranial pressure at frontal and occipital regions and the acceleration time history curves at the local regions of frontal and occipital brains. Solid lines and dashed lines represent predicted results and experimental data, respectively. The predicted pressure and acceleration of the model reasonably agreed with those of the experimental data. Validations using three series of test data suggest that the head/brain model has adequate biofidelity and computational stability. The head/brain model was incorporated into the THUMS-AM50 pedestrian model and used for the brain injury predictions during SUV-to-pedestrian impacts [12].

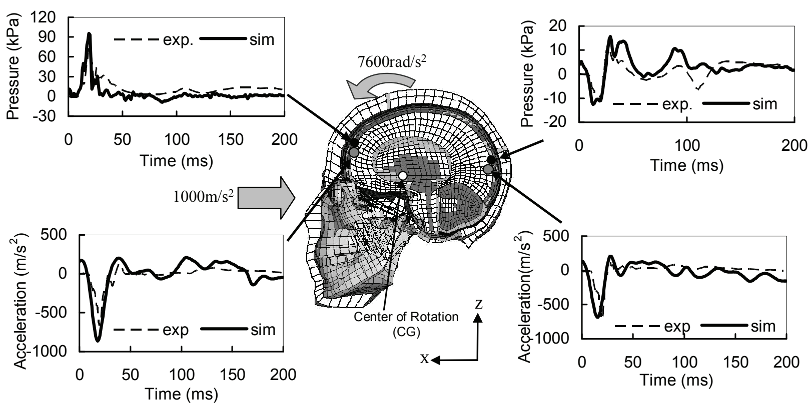
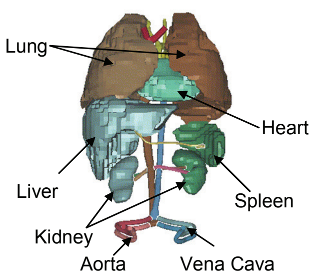


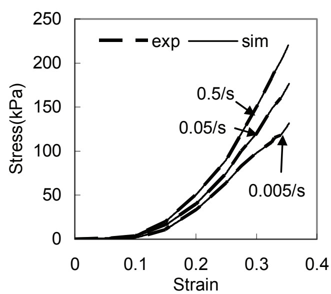
Figure 3: Intracranial pressure and acceleration at frontal and occipital sites

INTERNAL ORGAN MODELS

Fatal and severe injuries in real-world automotive accidents include injuries in internal organs such as the lung, heart, liver, spleen, kidney, and aorta. We developed individual internal organ models to predict injuries of such organs [4]. Figure 4(a) shows some internal organ models. The total internal organ model contains 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. Solid organs of the liver, spleen, pancreas, and kidney are modelled 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 modelled 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 is fixed with soft tissue of buttock while the rear part of it is fixed with the lumbar spine using bar elements. Most of organs were modelled as nonlinear elastic materials and the material properties were obtained from the literature [5]. In particular, some abdominal organs of the liver, spleen, and kidney were modelled as a rubber like material (MAT_181) and those material properties were obtained from Tamura et al. [13] as shown in Figure 4(b). The internal organ models were integrated with the THUMS-AM50 occupant model. Then, the models were validated against some test data on frontal and lateral impacts to the thorax and frontal impacts to the abdomen. In this paper, we describe two series of validation results of frontal impacts to the thorax and the abdomen. Simulation setups in these validations were carefully determined as to reproduce the test setups reported by Kroell et al. [14] and Nusholtz [15] et al. A hub impactor with a mass of 23.4 kg was applied to the thoracic region in the antero-posterior direction. Figure 5 (a) shows a deformation image of the THUMS-AM50 occupant at 40 ms after impact. Figure 5(b) shows a comparison of impact force-displacement curves between simulation results and test data obtained from Kroell et al. An impactor with a mass of 18 kg and a shape similar to that of a steering wheel was directed to the abdominal region at an impact velocity of 10 m/s in the anterior-posterior direction. Figure 6(a) shows a deformation image of the THUMS-AM50 occupant at 40 ms after impact. Figure 6(b) shows a comparison of impact force-displacement curves between simulation results and test data obtained from Nusholtz et al. These simulation results are almost the same as test data. Validations using these test data suggest that the internal organ models have adequate biofidelity and computational stability.

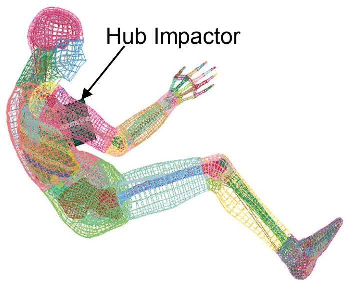


(a) Some individual organ models

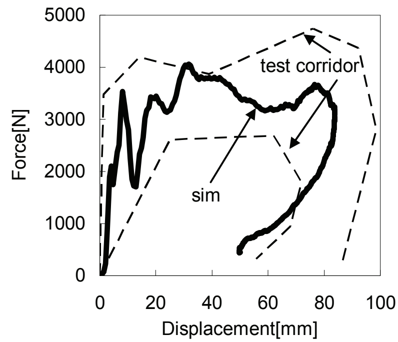


(b) Material properties of kidney model predicted by MAT_181

Figure 4: Internal organ models

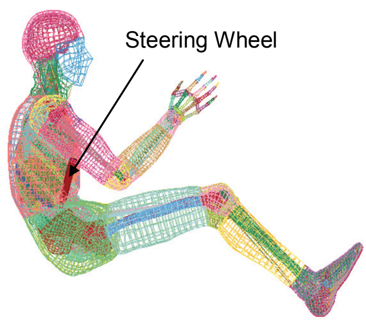


(a) Deformation at 40 ms after impact

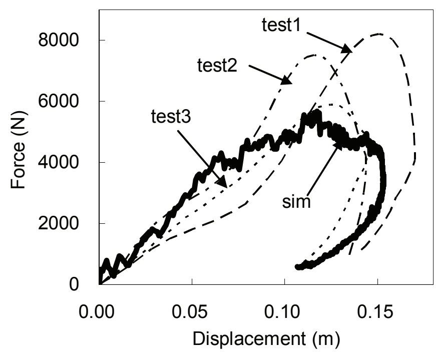


(b) Impact force-displacement curves

Figure 5: Frontal impacts for the thorax



(a) Deformation at 40 ms after impact



(b) Impact force-displacement curves

Figure 6: Frontal impacts for the abdomen

THUMS FAMILY

THUMS-AM50 has been developed to predict skeletal and brain/internal organ injuries in impact situations. In real-world automotive accidents, however, various sizes, ages, and genders of occupants and pedestrians are caught in accidents and sustain injuries.

Therefore, different sizes, ages, and genders of human body models are needed to investigate injury mechanisms in automotive crashes. In a THUMS project, we have been developing some types of human body models: AF05, AM95, 6-year old child, Japanese elderly male, and pregnant. Figure 7 shows two types of occupant models: AF05 and AM95, and two types of pedestrian models: AF05 and 6-year old child. The AF05 occupant model was developed based on anthropometric data obtained from the University of Michigan [16] and scaling techniques using THUMS-AM50. However, thoracic and pelvic regions of the AF05 model were newly developed to represent geometric features of the female skeletal parts. The AF05 model was validated for several test data and the predicted results by the model showed good agreement with test data [17]. The AM95 model was developed by scaling the AM50 model based on the anthropometric data [16]. However, validations are not conducted yet due to the lack of test data using AM95. The 6-year old child model was also developed by scaling the AM50 model. However, the model is not yet validated due to the lack of enough material properties and impact test data.

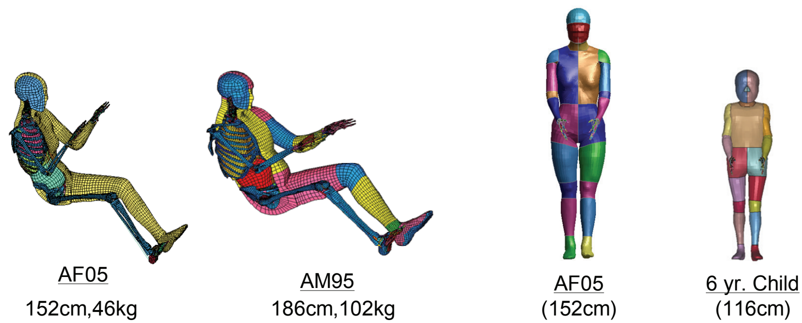


Figure 7: THUMS family

SUMMARY AND CONCLUSIONS

A computational human model of THUMS has been developed to investigate injury mechanisms during automotive accidents. The human model has the possibility to predict the risks of bone fractures and ligament ruptures. Recently a head/brain model and internal organ models, which can be integrated with THUMS-AM50 occupant model, have been developed in order to predict severe injuries in the brain and internal organs and investigate the injury mechanisms. The head/brain model was validated against three series of test data, in which translational and rotational accelerations were applied to the CG of the head. The model responses showed good agreement with test data. The internal organ models were validated against frontal and lateral impacts for the thoracic and abdominal regions. The model showed almost the same responses as test data. Therefore, these head/brain and internal organ models are currently attempted to predict severe injuries in automotive accidents. In addition to THUMS-AM50 models, THUMS family including AF05, AM95, 6-year old child models has been developed and partially validated against test data. The validations of these human models are not complete yet because of the lack of test data of such sizes, ages, and genders. Future work will include further study on the effects of muscle activity and development of more accurate injury evaluation methods.

ACKNOWLEDGEMENT

This study was conducted in part under a collaboration research with Toyota Motor Corporation. The authors would like to thank Wayne State University for providing good references on modelling the human head and thorax. We also wish to appreciate Toyota Technical Development Corporation for their supports in developing THUMS models.

REFERENCES

1. National Police Agency of Japan, A Report on Traffic Accidents, 2003 (in Japanese)

2. Hallquist, J. O., LS-DYNA. Keyword User's Manual. Version 971, Livermore Software Technology Corporation, Livermore, 2007.

3. Oshita, F. et al., "Development of a Finite Element Model of the Human Body", 7th International LS-DYNA Users Conference, Detroit, 2002.

4. Iwamoto, M. et al., "Recent Advances in THUMS: development of individual internal organs, brain, small female, and pedestrian model", 4th European LS-DYNA User Conference, Ulm, 2003.

5. Yamada, H., Strength of Biological Materials, Williams & Wilkins Company, 1970.

6. Iwamoto, M. et al., "Recent Advances in THUMS: development of the detailed head-neck and internal organs, and THUMS family", LS-DYNA & JMAG User Conference, 2003, Japan (in Japanese).

7. Iwamoto, M. et al., "Ankle Skeletal Injury Predictions Using Anisotropic Inelastic Constitutive Model of Cortical Bone Taking into Account Damage Evolution", Stapp Car Crash Journal, 49, 2005, pp. 133-156.

8. Clemente, C.D.; ed. Gray's Anatomy, 30th American Edition of the Anatomy of the Human Body by Henry Gray, Lea & Febiger, PA, 1985, pp. 1825-1861.

9. Galford, J.E., and McElhaney, J.H., "A viscoelastic study of scalp, brain and dura". Journal of Biomechanics 3, 1970, pp. 211-222.

10. Kimpara, H. et al., "Investigation of Anteroposterior Head-Neck Responses During Severe Frontal Impacts Using a Brain-Spinal Cord Complex FE Model", Stapp Car Crash Journal, 50, 2006, pp. 509-544.

11. Trosseille, X., Tarriere, C., Lavaste, F., Guillon, F., and Domont, A., "Development of a FEM. of the human head according to a specific test protocol", Proc. of 36th Stapp Car Crash Conference, SAE Paper No.922527, 1992.

12. Tamura, A. et al., " The Influence of the Traction Force Due to Inertia of the Brain Mass on Traumatic Brain Injury During SUV-To-Pedestrian Impact", IRCOBI conference, 2006, pp.361-364.

13. Tamura, A. et al., "Mechanical Characrerization of Porcine Abdominal Organs", Stapp Car Crash Journal, Vol.46, 2002, pp.55-69.

14. Kroell C.K., et al., Impact Tolerance and Response of the Human Thorax, Stapp 710851, 1971.

15. Nusholtz, G.S., Kaiker P.S., Lehman R.J.; Steering System Abdominal Impact Trauma, MVMA, Report UMTRI-88-19, 1988.

16. Schneider, L.W., Robbins, D.H., Pflug, M.A., and Snyder, R.G., "Development of anthropometrically based design specifications for an advanced adult anthropomorphic dummy family", Volume 1. UMTRI-83-53-1, NHTSA, 1983.

17. Kimpara, H. et al., "Development of a Three-Dimensional Finite Element Chest Model for the 5th Percentile Female", Stapp Car Crash Journal, 49, 2005, pp. 251-269.