DEVELOPMENT OF A FINITE ELEMENT MODEL OF THE TOTAL HUMAN MODEL FOR SAFETY (THUMS) AND APPLICATION TO INJURY RECONSTRUCTION

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ABSTRACT

A finite element model of a mid-size adult occupant has been developed in order to estimate overall injuries in traffic accident situations. Bones, ligaments, tendons, flesh, and skin are modeled using more than 80,000 elements. Several simulations were performed to validate impact responses of each body part. Detailed models of the head/face, shoulder, and individual internal organs have been also developed for more detailed analysis. The human model was used together with a model of a vehicle's internal structure to simulate a real-world accident situation and the simulations successfully reproduced gross motions and multiple injuries of an occupant.

Key words: Human Body, Finite Element Method, Biofidelity, Injuries, Accident Reconstructions

FIFTY-MILLION AUTOMOBILES are manufactured annually worldwide, and more than seven-hundred-million automobiles are currently registered. The number of fatalities in traffic accidents is estimated to be approximately five-hundred-thousand per year worldwide, and the number of persons injured every year is believed to have reached twenty- to thirty-million. Indeed, traffic accident injuries have become a leading cause of death and long-term complications among children and young adults. Reducing the number of these casualties, even if only a little, is a major issue confronting modern society.

In order to reduce the number of these casualties in real-world accidents, accident situations and injury outcomes need to be investigated. Researchers have been studying accident reconstructions to understand how accidents occur. Based on deformation of a vehicle, the position where it stopped, the tire skid marks etc. obtained by accident investigations, certain details of an accident such as impact speed, impact angles can be reconstructed. In addition, accident simulation software such as PC-Crash, CRASH3, and SMASH makes it possible to simulate the vehicle movement before, during, and after the impact and also to obtain accelerations or displacements of the vehicle (Steffan et al.,1996, Swider et al.,2000). On the other hand, the injury outcomes in real-world accidents have been investigated through support of clinical doctors. These injury data are described by the Abbreviated Injury Scale (AIS). Cause of death, medical expense and treatment period of injured persons are investigated. Using these data of accident situations and injury outcomes, statistical data analysis has been conducted (Morris et al.,1993 etc.). However, this approach is not enough to understand the relationship between accident situations and occupant injuries, which is necessary to protect occupants. It is important to estimate the occupant responses and injuries during impacts. Because occupant responses for impacts are not well known due to the high speed and complex phenomena.

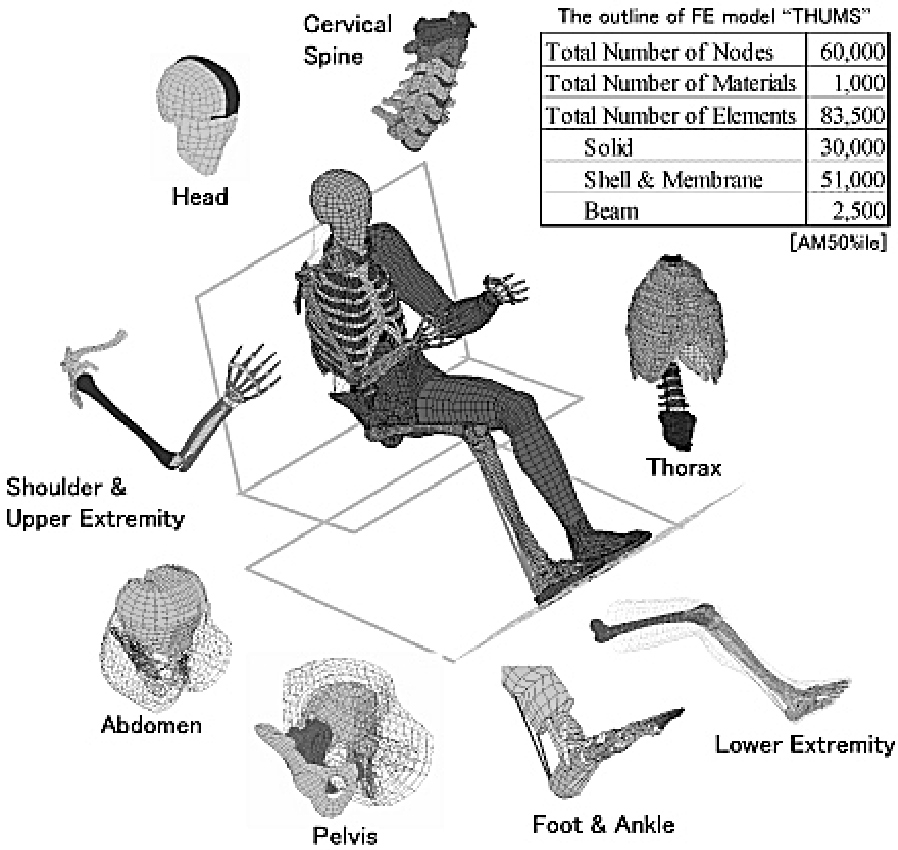
Over past decades, many researchers have studied occupant responses and injuries in impacts using human surrogates, dummies, and computer simulations. Until now, a large number of human surrogate tests such as volunteer tests, cadaver tests, and animal tests have been carried out and the research has made steady progress. A result of such research is the development of some crash dummies like Hybrid III, SID, BioRID etc., which are anthropomorphic test devices and are used to evaluate crash safety measures for vehicles. However, continued steady research and improvement are required to improve injury prediction. Since test dummies are made for repeated use, they have a different response compared to the human body (for example, Crandall et al., 1996). Another result of that research is human models, which can be used to run simulations on computers. MADYMO (TNO Automotive) have been recently used to simulate total human behaviors in impacts. Coley et al. (2001) validated the MADYMO mid-size male pedestrian model and reconstructed pedestrian kinematics in a real-world accident. This approach is useful because the analysis is fast and it is easy to change parameters for design of safety vehicle. However, the geometry of the human body is not so realistic and injuries of bones, joints, and soft tissues cannot be directly estimated. Therefore, human modeling approach using the finite element method has been adopted with the dramatic improvements in computer performance in recent years. Some researchers developed finite element (FE) models of each human body part, such as the lower extremity, thorax, neck, and head/brain. Kitagawa et al. (2001) developed a lower extremity FE model in order to elucidate injury mechanism of the ankle and tibia in frontal impacts. Aiman et al. (1999) developed a human head/brain FE model in order to estimate the brain/skull relative displacement magnitude due to blunt head impact. They used the models to understand local injury mechanisms. However, in real-world accidents, especially fatal accidents, many and various inputs for occupants may often cause multiple injuries through several body parts. For examples, occupants contact various components in the vehicles such as the steering wheel, windshield, side doors, instrumental panel and/or even an adjacent occupant during the crash sequence. As a result, occupants sustain multiple injuries, one of which sometimes leads to the death. Therefore, it is important to simulate gross motion and overall multiple injuries of the human whole body at the same time.

The purpose of this study is to develop a FE model of the entire human body in order to estimate total behaviors and overall injuries in traffic accident situations. In this paper, a FE model of Total HUman Model for Safety (here after, it is called THUMS) has been developed and validated against some impacts for each body part. Next, detailed models of the head/face, shoulder, individual internal organs such as the heart, lungs, liver, kidney, etc., have been developed and validated for impacts. Finally, one of the methods to reconstruct injuries in real-world accidents was suggested by using THUMS. Using this method, gross motions and multiple injuries of an occupant in a real-world accident situation were reconstructed.

MODEL DESCRIPTION

THUMS is a FE model of the mid-size adult male occupant. It consists of all deformable human body parts with anatomical geometry and biomechanical properties (Fig.1). It can be analyzed using the explicit FE analysis codes of PAM-CRASH (ESI Group) and LS-DYNA3D (LSTC). Basic geometry data of THUMS was based on commercial data packages and anatomical texts of the human body (Viewpoint Datalabs and Gray, 1973 etc.). The geometry was scaled to fit a 50th percentile American male occupant according to data reported by Schneider et al. (1983). Each element of THUMS was created so that the time steps should be more than 1 micro second by adjusting the size and shape of each element of the model. This method can assure reasonable CPU time while using current computers (Workstation level), in spite of more than 80,000 total elements.

Each bone except the thoracic and lumbar vertebrae consists of outer cortical bone and inner spongy bone. The cortical bone was modeled as isotropic elastic plastic material using shell elements while the spongy bone was modeled as the same material using solid elements. Each joint in the whole body was modeled anatomically by bone-to-bone contacts with major ligaments and without any mechanical joint. Each ligament was modeled as tension-only elastic material using membrane or bar elements. Soft tissues such as the brain, internal organs, abdomen, flesh and fat were modeled as viscoelastic material using solid elements while the skin was modeled as elastic material using shell elements. Muscles and tendons were modeled as tension-only elastic material using bar elements



Total Number of Nodes	60,000
Total Number of Materials	1,000
Total Number of Elements	83,500
Solid	30,000
Shell & Membrane	51,000
Beam	2,500

Fig.1 - THUMS overview (Base Model)

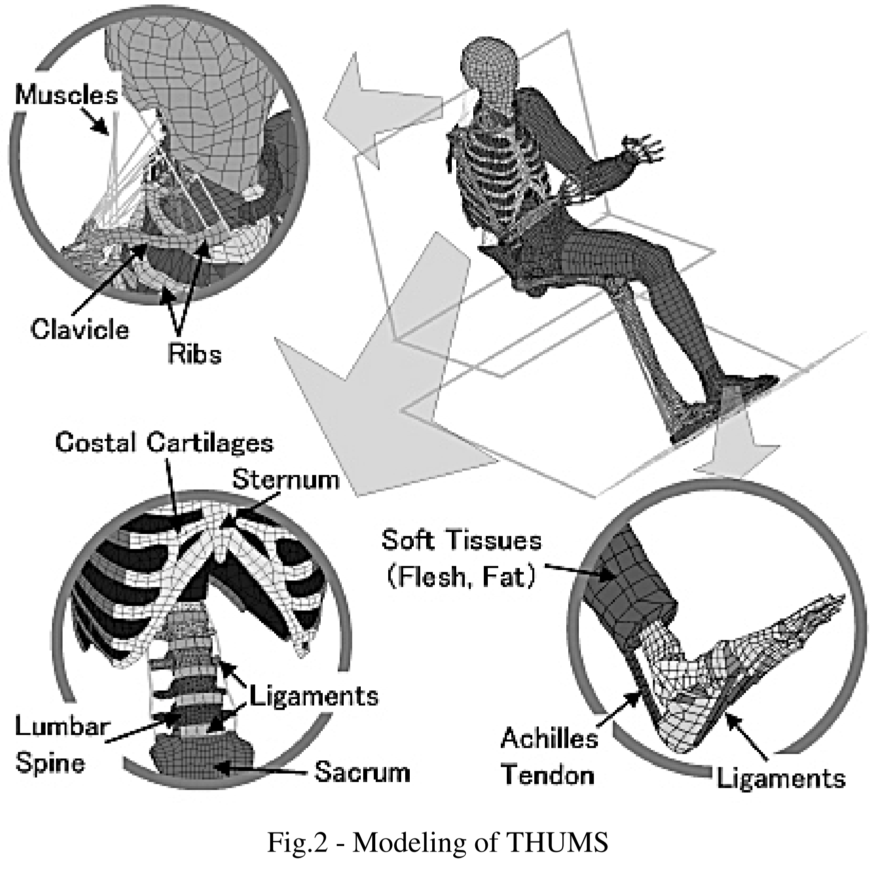


Fig.2 - Modeling of THUMS

(Fig.2). The muscles around the neck can be flexed in order to simulate the effects of an occupant's neck muscles for rear-end impacts. Material properties of the density, Young's modulus, Poisson ratio, stress-strain curve, stiffness, ultimate stress and strain of the bone and soft tissues in THUMS were based on available literature (Yamada, 1970, Abe et al., 1996, etc.). Therefore THUMS can simulate deformations caused by contacts with objects and stress or strain distributions on the bones and soft tissues in any part of the human body.

MODEL CONSTITUTION

THUMS consists of a base model and specially developed detailed models. As shown in Fig.1, the base model has a detailed structure for the cervical spine, thorax, spine, pelvis, and lower extremity, which could affect total human behavior, with simple structure for the head/brain, shoulder/upper extremity, and internal organs. As shown in Fig.3, specially developed detailed models of the head/face, shoulder, individual internal organs can be integrated with the THUMS base model and used according to user's purpose. The detailed head/face model can be used to reproduce skull and facial bone fractures. However, currently it does not include the detailed brain model yet. The shoulder model can be used to reproduce the shoulder and thoracic injuries in side impacts. The individual internal organs can be used to reproduce the detailed internal organ injuries.

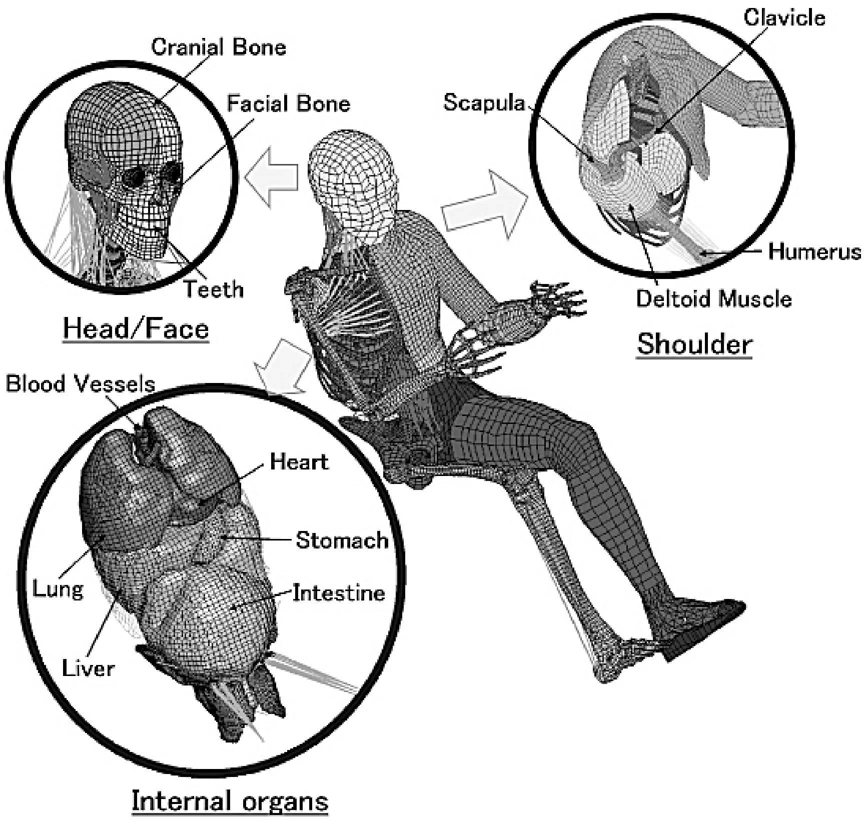


Fig.3 - THUMS with detailed models of the head/face, shoulder, and internal organs

MODEL VALIDATION

Each body part of THUMS was selectively validated against published human cadaveric test data. In this paper, all simulations of THUMS were performed using PAM-CRASH. The thorax and spine model was validated for frontal and side impacts using cadaver test data published by Bouquet et al. (1994). Fig.4 shows the simulation setup for side impact and the simulation result with cadaver test corridors (Furusu et al., 2001). The simulation result fell within the corridors. The lower extremity model was validated for cadaver test data published by Manning et al. (1998). Fig.5 shows the simulation setup and result with test data (Tamura et al., 2000). The tibial force and moment was obtained at the center of the bone shaft. Simulation results showed good agreement with test data. Using this lower extremity model, analysis and research have been carried out to clarify the influence of the amount and velocity of toe board intrusion (including rotation) on the bone fracture mechanism of the diaphysis of the tibia in a frontal crash (Tamura et al., 2001). In addition, the model was also used to estimate the effectiveness of the Tibia Index under dynamic axial load (Iwamoto et al., 2000). These results for each body part indicate that THUMS has adequate biofidelity to simulate human responses in impacts.

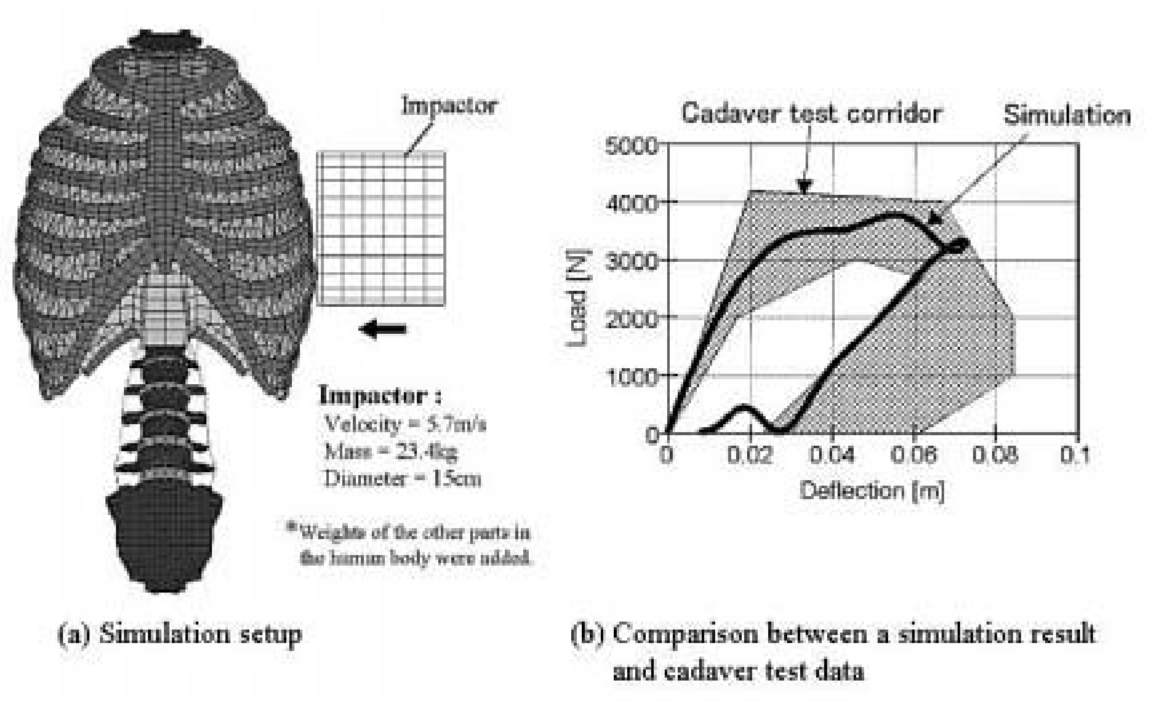


Fig.4 - Validation of the thorax and spine model

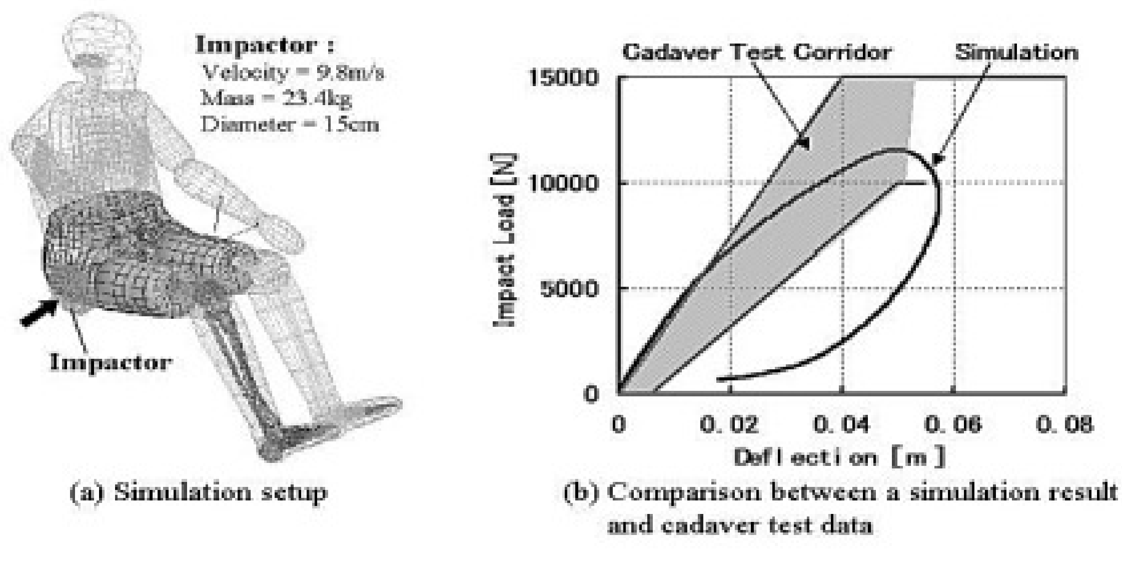
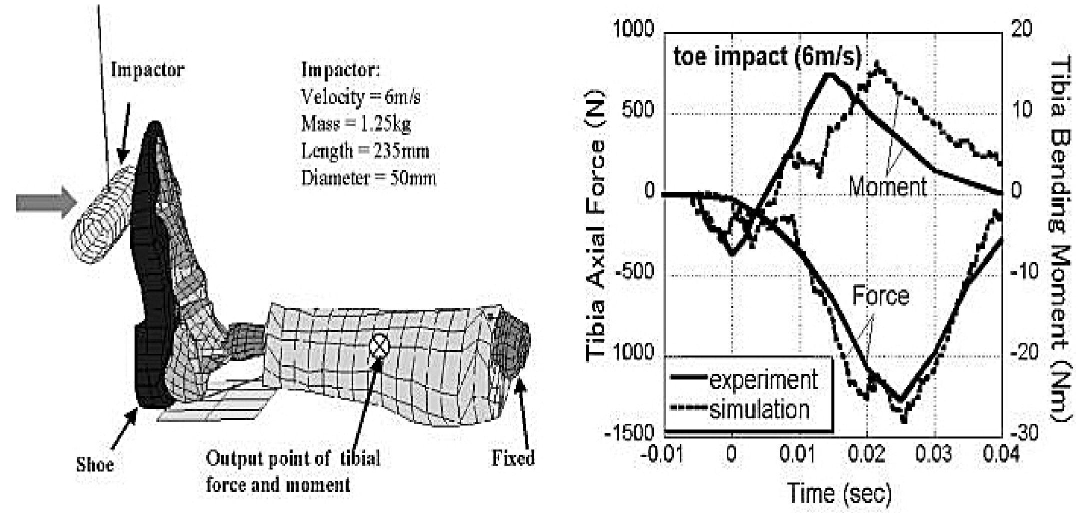


Fig.5 - Validation of the lower extremity

DETAILED MODELS

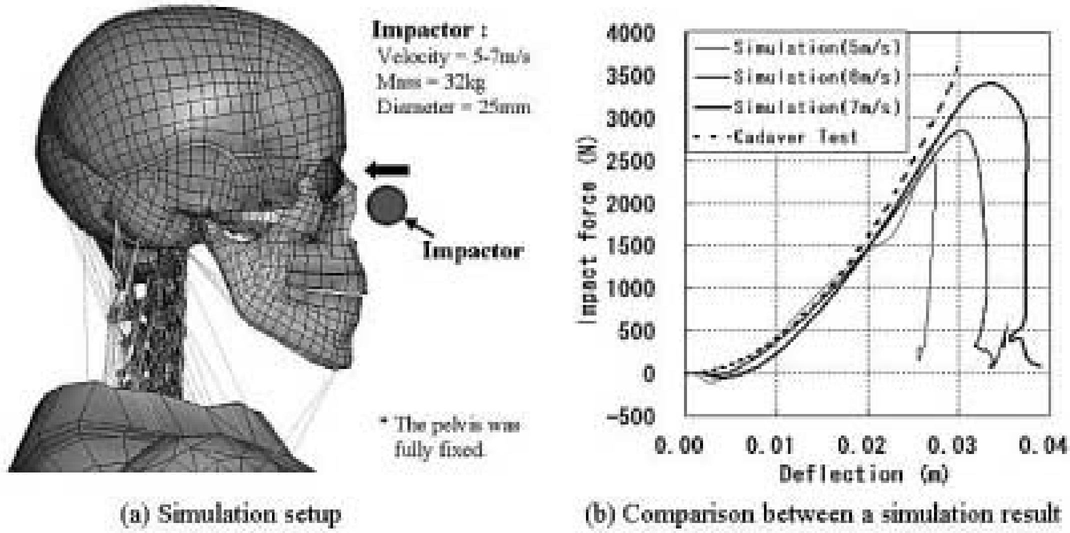
HEAD/FACE: The head/face model consists of the cranial and facial bones, ligaments, and muscles with the simple brain model as shown in Fig.3. The model was validated for cadaver test data published by Nyquist et al. (1986). Fig.6 shows the simulation setup and results with cadaver test data. Cadaver test data shown in Fig.6 includes data for impact velocities ranging from 5 to 7m/s. Therefore, simulations were performed for three initial velocities of 5, 6, 7m/s (Watanabe et al. 2001). Simulation results show good agreement with test data. In this simulation, bone fractures were observed around the nose as well as the test data.

SHOULDER: The shoulder model consists of bones (the scapula, clavicle, humerus), ligaments, muscles, fat and skin as shown in Fig.3. This model was developed using the technique acquired by author's previous study (Iwamoto et al., 2000). The shoulder model was validated for cadaver test data published by Bendjellal et al. (1989). Fig.7 shows the simulation setup and result with cadaver test data. MS202, 203, and 204 represent cadaveric test number. Simulation result fell within cadaver test corridors.



(a) Simulation setup (b) Comparison between a simulation result and cadaver test data

Fig.6 - Validation of the head/face model



(a) Simulation setup (b) Comparison between a simulation result and cadaver test data

Fig.7 - Validation of the shoulder model

INTERNAL ORGANS: The internal organ models consist of the heart, lungs, liver, kidneys, pancreas, spleen, stomach, diaphragm, intestine, and blood vessels as shown in Fig.3. The geometry of the individual internal organs was basically constructed using cadaveric tomogram data from the Visible Human Project (National Library of Medicine). The model was validated for cadaver test data published by Cavanaugh et al. (1986). Fig.8 shows the simulation setup and results with cadaver test data. Simulation results show good agreement with test data.

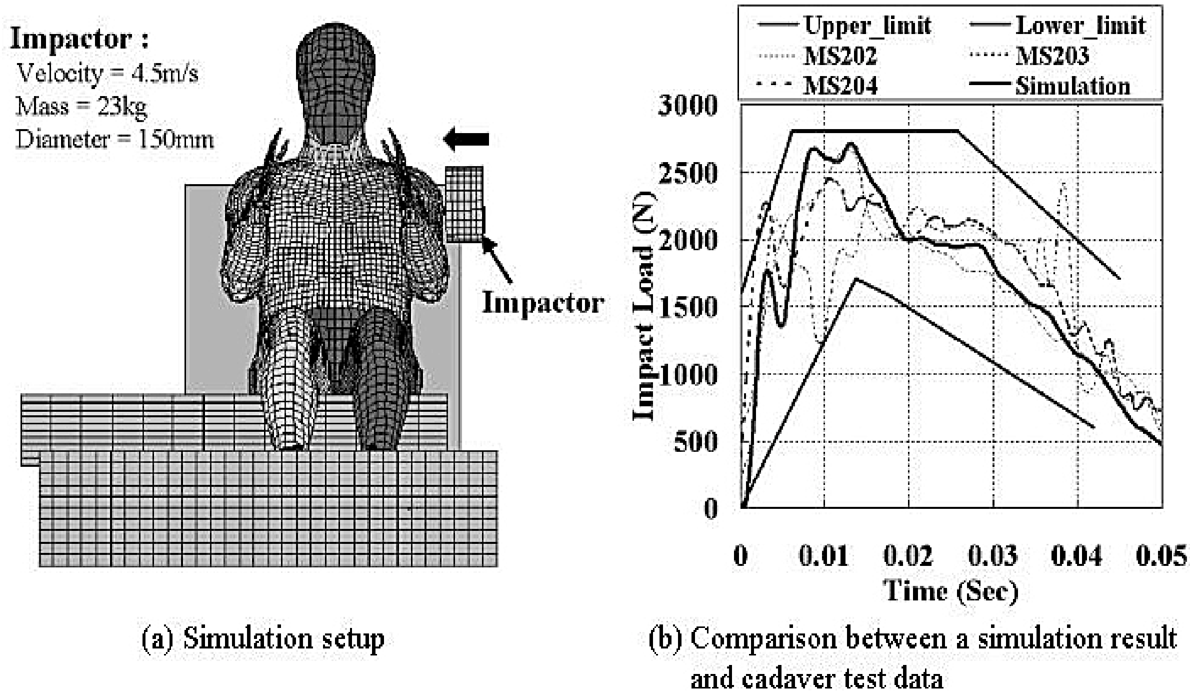


Fig.8 - Validation of the internal organs

APPLICATION TO INJURY RECONSTRUCTION

Technology to reconstruct the injuries that are caused in real accidents is necessary for appropriate casualty reduction measures to be implemented. In order to verify the accuracy in reconstructing occupant injuries on the computer, an example of an actual accident where an occupant sustained multiple injuries was selected.

ACCIDENT DETAILS: The occupant is a 25-year-old male, 168cm tall and weighing 66kg. As shown in Fig.9(b), the occupant's injuries included multiple rib fractures with hemothorax and pneumothorax, traumatic hernia in the left diaphragm, skull fracture, and an open wound at the knee etc. The vehicle's behavior, such as the impact speed and the impact angle, were estimated based on the deformation of the vehicle, the position where it stopped, the tire skid marks, etc. As shown in Fig.9(a), the vehicle deviated from a lane during moving straight at an estimated impact speed of 70km/h. After it hit a pole and wall without any operation for avoidance, it turned right against the traveling direction and then stopped. This data was provided by ITARDA (Institute for Traffic Accident Research and Data Analysis, JAPAN).

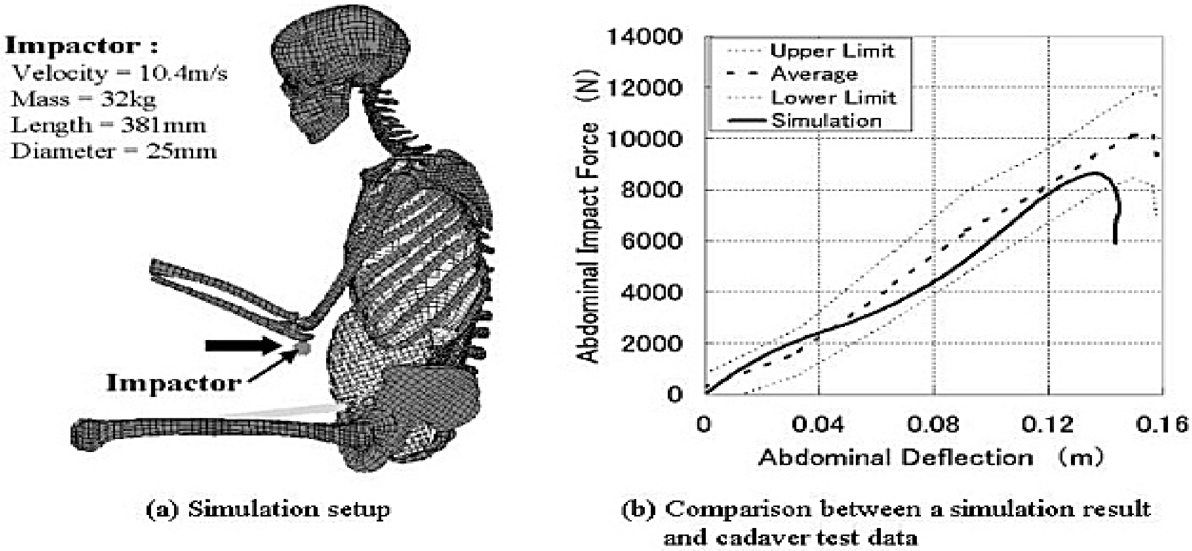


Fig.9 - Accident data and occupant injury (Data provided by ITARDA)

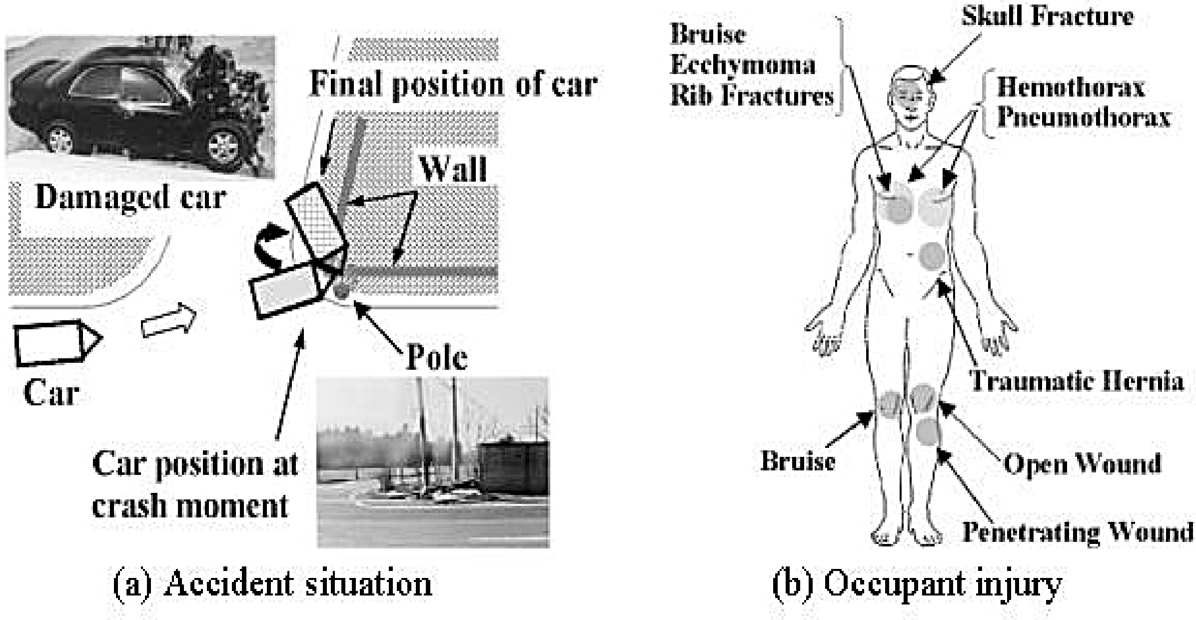
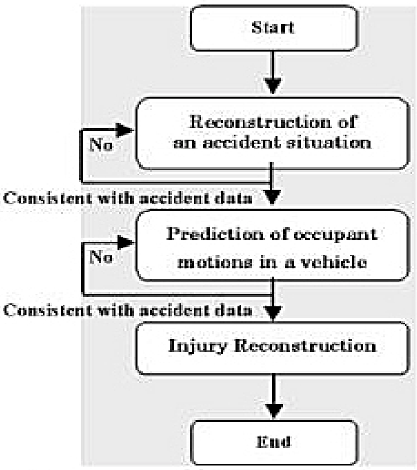
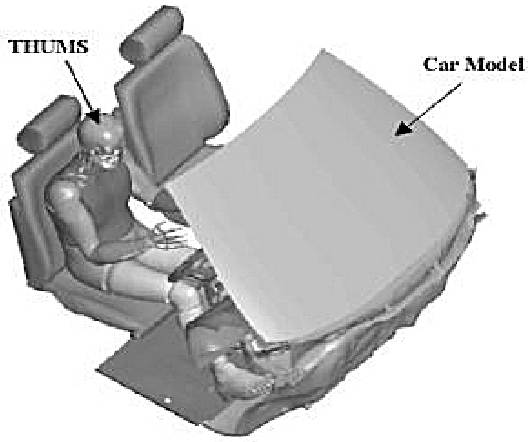


Fig.10 – Method of injury reconstruction

INJURY RECONSTRUCTION: Injury reconstruction was performed according to a flowchart as shown in Fig.10(a). To reconstruct the accident situation, the vehicle's movement was estimated by PC-Crash (MEA[MacInnis Engineering Associates]) and FE analysis of the vehicle model with try and error until it agreed with actual accident data. The vehicular barycentric displacements and rotations obtained from the vehicle's movement were input in the vehicular internal structure model which consisted of a seat, dashboard, windshield, and steering wheel etc. as shown in Fig.10(b). In this case, the main injuries were multiple rib fractures with hemothorax/pneumothorax (AIS5) and skull fracture (AIS3). It is estimated that these injuries were caused by the impact on the occupant's thorax when it hit the steering wheel and an impact of the occupant's head with the windshield, respectively. Thus, THUMS with the detailed head/face model was used as the occupant model. In addition, any deformation of the vehicle was not added because the intrusion was very small.





(a) Procedure of injury reconstruction **(b) Simulation model for injury reconstruction**

Fig.11 - Occupant behavior during the accident

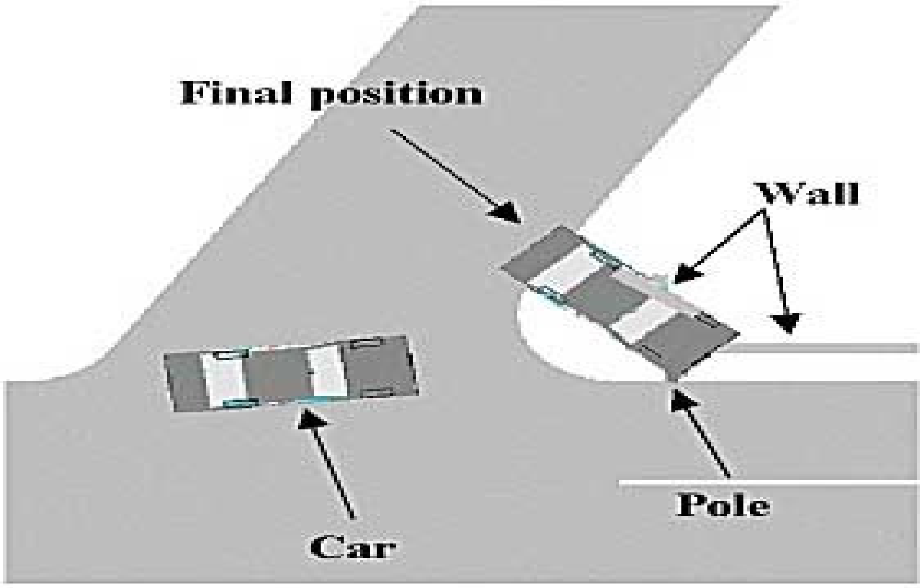


Fig.12 - Injury reconstruction of the thorax (Accident data provided by ITARDA)

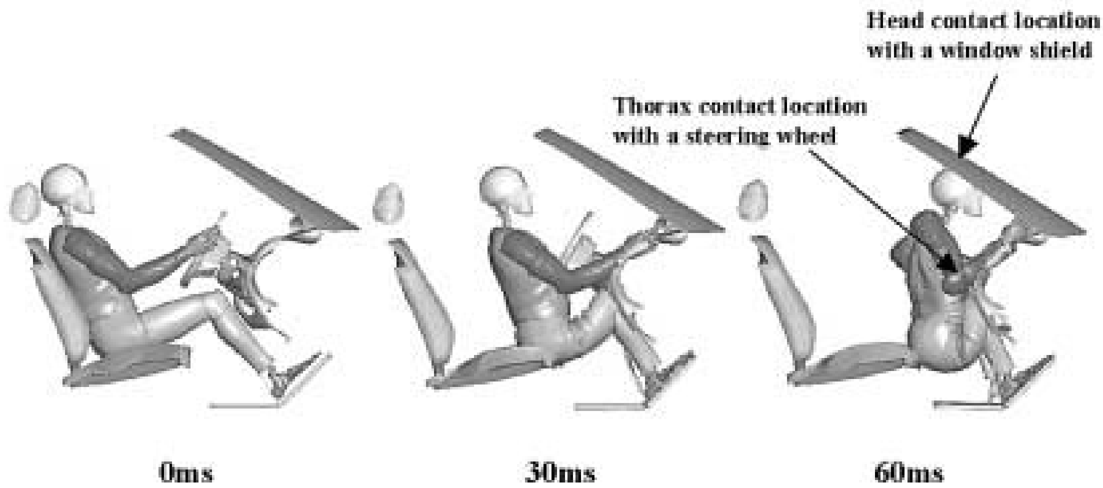


Fig.13 - Injury reconstruction of the head (Accident data provided by ITARDA)

Next, an initial occupant position was estimated with try and error by changing the position in THUMS and confirming the contact between the human model and the vehicle internal structure model. In this case, the deformation of the steering wheel and the contact position of the head with the windshield predicted by the analysis were compared with the actual deformation of the steering wheel in the vehicle and the actual contact position of the driver's head with the windshield, respectively (Kisanuki et al., 2001). Finally, the occupant motion and injuries were reconstructed using PAM-CRASH with vehicle's movement and the initial occupant position determined above. Fig.11 shows the occupant behavior at the time of impact. Fig.12 shows the comparison on thoracic injuries between simulation results and clinical data. It is seen that rib fractures occurred at almost the same locations as clinical data. Fig.13 shows the comparison of head injuries between simulation results and clinical data (Kisanuki et al., 2002). In the simulation, bone fractures were estimated to occur at almost the same locations as clinical data. In addition, when the lower extremities hit the instrumental panel at the knees, bone fractures around the knees were not observed in this simulation, which was the same as the actual accident. Therefore, it is confirmed that this injury reconstruction using THUMS is a promising tool for reconstructing bone fracture injuries.

DISCUSSION

In order to estimate total behavior and overall injuries in traffic accidents, a FE model of the human body called "THUMS" has been developed. THUMS consists of a base model and several detailed models. The base model has been developed to simulate total behavior of the human body and detailed injuries to the cervical spine, thorax, pelvis, and lower extremity. The detailed models of the head/face, shoulder, and internal organs have been also developed to estimate detailed injuries to these regions. In human model like THUMS, verification of biofidelity is one of the most important things. Each body part of THUMS such as the head, neck, thorax, abdomen, pelvis, and lower extremity was validated in more than one impact situation such as frontal, side or rear impacts, while each detailed model of the head/face, shoulder, and internal organs with the THUMS base model has currently been validated in only one impact situation. In THUMS, bones were modeled as isotropic elastic-plastic material without any strain rate dependency while either strain rate dependency or nonlinear property was represented in soft tissues. This paper indicates that the model response showed good agreement with cadaver test data under some limited conditions. However, actual bones and soft tissues such as ligaments, muscles, fat, skin and internal organs have non-linear anisotropic characteristics and strain rate dependency (Fung, 1993). Therefore, the model still need more validations for various impact directions and impact speeds in order to be further improved and refined.

The limited number of available published cadaver test data is useful for validation of the model, but it is not enough to estimate occupant behavior and injuries in complicated real-world accidents. Thus, it is important to reconstruct injuries in real-world accident situations using the model. In this study, a real-world accident with occupant injuries was reconstructed using THUMS. To estimate the occupant behavior in the accident, vehicle data, such as the barycentric accelerations of a vehicle, is necessary. Commercially available accident simulation program "PC-Crash" was used for calculating displacements and rotations of a vehicle in an accident. Before PC-Crash was actually used for the accident reconstruction, the accuracy of results estimated by PC-Crash was verified by comparing the simulation result with test data for a full-lap crash test. The simulation result generally showed good agreement with test data (Kisanuki et al., 2001). However, it was found that PC-Crash alone was not adequate to reconstruct the vehicle movement for some accident cases such as offset frontal impacts. Therefore, in this study, FE analysis of a vehicle model was also used to estimate the vehicle movement in detail. On the other hand, THUMS represents an adult male of average size. However, those killed and injured in actual accidents range from children to the elderly, and there is a wide distribution of body types as well. In this study, the locations of the skull fractures and rib fractures estimated by THUMS are almost the same as those in actual injury data, although the occupant was a little smaller and lighter than THUMS. However, generally, this model should not be used for too large and too small people, female, and children. Modeling of a variety of body sizes is planned in order to make wider use of human models. These include the child model (6-year-old) as well as a small female (AF05). As for the injury evaluation, in this study, it is assumed that bone fractures could occur when stress or strain in any element of each bone exceeds the ultimate stress or strain of each bone as obtained from the literature (Yamada, 1970 etc.). Such elements in some parts of the model, for example, the ribcage, can be eliminated as shown in Fig.12(b). This assumption successfully reconstructed bone fractures in the accident studied. However, as mentioned above, the bone has non-linear anisotropic characteristics and strain rate dependency. Therefore, further improvement would be needed to reproduce bone fractures in various accident types. On the other hand, injuries in accidents are not limited to bone fractures, but also include a broad range of injuries, such as brain injuries and injuries to the internal organs of the thorax and abdomen. In order to account for and predict these injuries, detailed brain and individual internal organ models should be incorporated into THUMS and used for injury reconstruction in real-world accidents.

Although THUMS was well validated in several impact situations, at this stage, it is not so easy to utilize the model for practical purposes, such as in designing safety vehicles and development of effective restraint systems. Since the total number of the elements in the THUMS base model and the base model with detailed models of the head/face, shoulder, and internal organs is approximately 83,500 and 216,500, respectively, when THUMS is used with a total vehicle model for purposes of safety vehicle designs, the result would be a large-scale model that would take considerable time to run on current computers. Even though computer performance has improved dramatically, it is still inadequate to do the analysis in a reasonable amount of CPU time. Therefore, it is currently better to use both actual crash test dummies and computerized human models like THUMS and exploit their mutual advantages for automotive safety designs.

CONCLUSIONS

A finite element model of a human called THUMS has been developed in order to estimate total human behavior and overall injuries in traffic accidents. Each body part of the model has been validated for some impacts using published cadaver test data. Simulation results showed good agreement with test data in all cases used in this study. The detailed models for the head/face, shoulder, and individual internal organs have been newly developed and currently validated for one impact situation in order to estimate more detailed injuries in these body regions. Additional validation using THUMS whole body model was conducted using real-world accident data. As a result, bone fractures of the ribcage and head were successfully reconstructed. Although more validations and accident reconstructions using the whole body would be needed to improve and refine the model, it is confirmed that the model is a promising tool for reconstructing occupant multiple injuries in real-world accidents.

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