IMPLEMENTATION OF REACTIVE HUMAN BEHAVIOR IN A NUMERICAL HUMAN BODY MODEL USING CONTROLLED BEAM ELEMENTS AS MUSCLE ELEMENT SUBSTITUTES

Adrian Prüggler
Philipp Huber
Andreas Rieser
Kurt Steiner
Virtual Vehicle Research and Test Center
Austria
Stefan Kirschbichler
Graz University of Technology, Vehicle Safety Institute
Austria
Arno Eichberger
Graz University of Technology, Institute of Automotive Engineering
Austria

ABSTRACT

The reduction of road casualties and injury risk is a major goal of automotive engineering. Manufacturers are confronted with increasing safety regulations, stricter exhaust gas pollution regulations and strong competition. Hence, cost efficiency is a significant concern of automotive industry. Furthermore the development of innovative safety systems such as adaptive restraints and collision avoidance systems calls for new methods for system design and evaluation beyond laboratory crash tests.

Cost efficiency is achieved with numerical simulations using Multibody System (MBS) or Finite Element Method (FEM) techniques partly substituting full vehicle testing. Focus has been on simulations of the crash phase but innovative safety systems call for consideration of the low g pre-crash phase. Therefore the use of crash test dummies and their numerical representations which are designed for higher loading, is not satisfying. The use of numerical human body models is a promising approach to further improve bio-fidelity. Nevertheless, for pre-crash simulations the influence of muscle activity on the passenger kinematics induced by the vehicle motion is no longer negligible for real life safety.

Hence the OM4IS ("Occupant Model for Integrated Safety") project was initiated by a large consortium including scientific partners (Virtual Vehicle Research and Test Center, Graz University of Technology, Bundesanstalt für Straßenwesen-BASt) and industry partners (Partnership for Dummy Technology and Biomechanis, Robert Bosch GmbH, Toyoda Gosei Europe, TRW Automotive, DYNAmore GmbH). The challenge is to identify human movement and behavior patterns (position and muscle activity) during pre-crash phase and implement these patterns into a suitable human body model. The present paper describes first results to implement muscle activity into a simplified version of the numerical model **T**otal **HU**man **M**odel for **S**afety (**THUMS**) developed by Toyota Motor Corporation and Toyota Central R&D Labs. This model represents a 50th percentile American Male (AM50) and is implemented into the explicit finite element software LS-Dyna.

As a starting point, the reactive behavior of humans in two distinct load cases, an emergency braking maneuver and a single lane change are investigated. Movement and behavior patterns as well as muscle activity are analyzed by volunteer tests on sled and full vehicle level. An infrared based 3D motion capturing system and an electromyography measurement (EMG) system are used. Methodology and results of this behavior pattern analysis is presented in a separate paper.

A simplified FE model that qualitatively reproduces human motion patterns in the selected load cases is developed. The first version of the model features a simplification of the THUMS model replacing the deformable parts by rigid body parts and using kinematic joints. Major muscle groups are implemented as beam elements which can be controlled using coupling of LS-Dyna software and Matlab/Simulink. The model should be able to reproduce volunteers' movements for two load cases (acceleration in frontal and lateral direction) and in the second modeling step identified human movement and behavior pattern should be implemented qualitatively which is presented in a separate publication.

At this stage computing time efficiency, numerical stability and implementation in the automotive development process were not of first priority. Furthermore the study concentrates on occupants' acceleration induced reactions and not on active movements.

INTRODUCTION

Basically, there are two methods of modelling the real system, namely Multi Body (MBS) and Finite Element Method (FEM). MBS represents the real system via rigid segments, the so-called bodies. These bodies are connected via kinematic joints with a defined number of degrees of freedom (DOF). Centre of gravity, inertial properties and a local coordinate system are assigned to each of the segments. Professional simulation software automatically generates the equations of motion for the system. Using the boundary conditions and a numerical solution approach the equations of motion are solved [1]. For contact definitions between the bodies, simple, non-deformable geometric elements are dedicated to the bodies. Due to the simplicity of this approach the computing power needed is low and it can be used for parameter variations.

The basic principle of FEM is to divide a continuous body into discrete small elements with simple geometry. The adjacent elements are connected on the nodes of the element. The system of nodes and elements is called a mesh. Properties are assigned to the nodes. The solid mechanics problem of the body is solved by using approximating functions. To relate deformations to internal forces a constitutive material law is used (e.g. [2], [3]). Therefore the FEM approach offers the chance to investigate the displacements and stresses in a structure. Due to discretization and the complexity of solving the differential equations of the system, the needed computing power is considerably higher than a comparable system using the MB modelling technique. For simulations of the pre-crash phase the deformations of vehicle structure and the deformations of the occupant are not the primarily concern. Hence the use of FE models for pre-crash applications is not very widespread. Especially for the crash phase, FE simulations have become an important development tool. Two main aims are defined in the OM4IS project: The characterization of reactive behavior in low load pre-crash phase and the implementation of reactive behavior into numeric human body models. In the last decades passive and active safety of automobiles have been developed more or less separately, nowadays as the consideration of the pre-crash phase gains importance the simulation of this phase also becomes relevant. Using a MBS model for the pre crash phase and a FE model for the crash phase causes costs and the transfer of model kinematics from pre crash to crash phase simulation is difficult. Using an "integrated" FE model for pre crash and crash phase would decrease cost and may simplify the transfer of kinematic results from pre crash to crash phase. Hence the basis for the OM4IS is a FE human body model, namely the **T**otal **HU**man **M**odel for **S**afety (**THUMS**) developed by Toyota Motor Corporation and Toyota Central R&D Labs. As a starting point for identifying human behavior and movement patterns, the OM4IS consortium has agreed on two maneuvers. The first one is an emergency braking maneuver and the second one is a single lane change maneuver. For both maneuvers the acceleration level in longitudinal as well as in transversal direction vehicle is in the range of 1g.

METHODS

Testing

Sled tests were carried out at the Vehicle Safety Institute of Graz University of Technology. All in all eleven males which were close to the 50th percentile male have been tested. For all tests, a reference seat mounted on a sled has been used. This seat has been a serial production seat with removed cushions which were replaced by wooden plates mounted on seat and back rest. These wooden plates have been covered with leather to increase friction between the volunteer and the seat. The modifications have been done in order to eliminate the influence of the deformable seat cushion and therefore simplify the boundary conditions for the numerical simulation. Due to the fact that the sled acceleration can only be controlled in a single direction and the aim of the investigations was to simulate a braking and an evasive maneuver, the seat has been either mounted backwards to simulate the braking maneuver, or for evasive lateral maneuver, the seat has been mounted perpendicular to the acceleration direction. Figure 1 shows a principle setup of the sled tests for simulation of the braking maneuver.

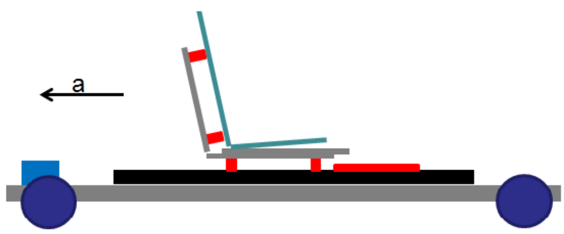

Figure 1. Principle sled test setup. Symbol a is the sled acceleration during the test.

For further information concerning the test set up and the results refer to [4].

Simulation

<u>Muscles</u> The human body consists of more than 300 muscles. For detailed simulation of human kinematics and to gain insight into the resulting stresses in the human body it is necessary to implement the muscles in a realistic manner. There are basically two approaches- the biophysical cross-bridge model of Huxley [5] and the phenomenological Hill model [6]. The Huxley model is based on the attachment and detachment of action and myosin filaments. The model describes the muscle activity on a microscopic level and takes the chemical and physical processes within the sarcomere into consideration [5]. The Hill model describes the muscle as a combination of springs and non linear contractile elements. Due to the fact that the Huxley model describes the muscle activity on microscopic level, this model is more complex than the Hill model. Hence the Hill model is usually the preferred approach for muscle modeling. In the present project another approach was chosen. The first focus of the OM4IS project is on the identification of human behavior patterns and its implementation into a numeric human body model. The accuracy of resulting stresses is in this phase of lower priority. An application of Hill model is therefore not essential. The approach described below simplifies also the fulfillment of another project requirement: it should be applicable to other human body models.

<u>Controller and Co-simulation</u> A promising approach which fulfills the project's requirements is the use of a coupling between Matlab/ Simulink and the explicit FE solver LS-DYNA. The concept is shown in Figure 2. As it can be seen there are two blocks. The first one is the explicit FEM solver block named "LS-DYNA" and the second one is the "Matlab, Excel" block. The two blocks communicate via an interface. . LS-DYNA provides the translational and rotational values of predefined nodes for the Matlab, Excel block. On basis of this values and the chosen controller concept the controller software (Matlab, Excel…) calculates force values and sends them back to LS-DYNA. Those force values are applied on predefined bar elements in axial direction. The time increment for data exchange can be determined by the user. It depends on the time step as used in the FE calculation. Theoretically, the information could be exchanged after each FE time step. In order to increase the speed of calculation the exchange interval can be increased. The exchange parameters are then frozen [7].

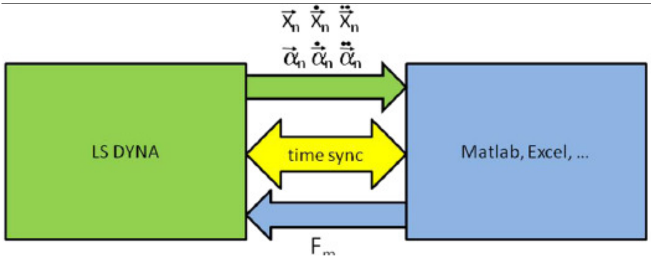

Figure 2. Coupling Exchange parameters

Modeling

After having defined how to implement muscle activity into the numeric human body model the method has been investigated. This first two modeling steps had two main objectives. The first objective was to validate if the coupling approach (Coupling between Matlab/Simulink and Explicit FE solver) could be used for this field of application. The second objective was to find a modeling technique which allows a fast adjustment of the controller when using another Finite Element model. First simulations to validate the coupling have been carried out on basis of a simple model equivalent of the lower extremity. Foot, shank and thigh have been modeled as rigid shell elements connected via revolute joints. Muscles have been included using controlled beam elements. Origin and insertion of the muscle elements was not anatomically correct.

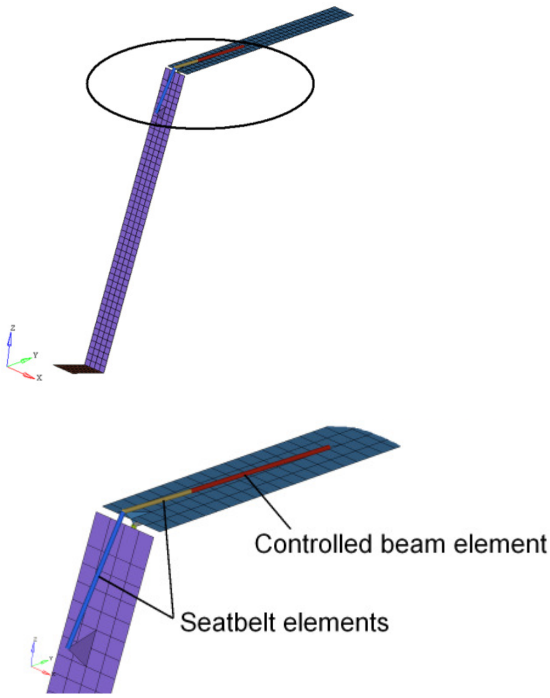

Figure 3. Leg model substitute, detail muscle modeling with seatbelt elements and controlled beam element

Simulations showed that a muscle modeling approach with seatbelt and controlled beam elements works sufficiently. For further controller development controlled beam elements connecting directly the two body parts would also be adequate. Modeling approaches using seatbelt, slipring and controlled beam elements could be used in a later project phase. Further simulations showed that the use of the coupling between Matlab/Simulink and the explicit FE solver is very sensitive in terms of the Matlab/Simulink release. Due the fact that this coupling was one essential part for the further work we have decided to simplify coupling process. Matlab/Simulink was substituted by a C++ code. The control algorithms have therefore been modeled in C++ which offers two chances. The first one is the desired independence of software releases and the second advantage is the simplification concerning automation (for initializing and parameter calculations, loops can be used).

The next model of higher complexity consisted of parts of the H3 Dummy model and the BIORID II model. Similar to the first model, joints have been modeled as kinematic joints with one DOF. The extremities as well as the spine were modeled as rigid bodies.

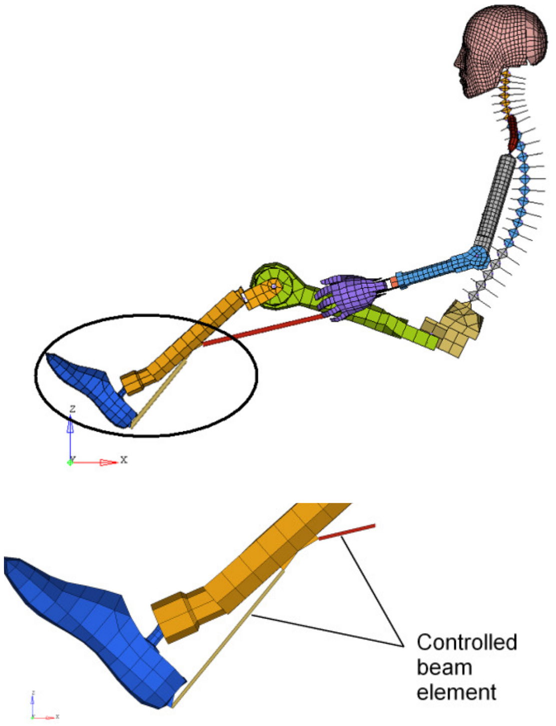

Figure 4. Model consisting of BIORID II and H3 dummy parts, detail muscle implementation

The model was also equipped with beam muscle elements which could be directly controlled. Again the focus of this modeling step was on control of the lower extremity of the model. Hence the hip, the spine as well as the head and the upper extremities have been fixed. The aims of this step were to work on a model with more realistic geometry, to find a muscle modeling approach which could also be used for the upper parts of the human body and to find a suitable modeling approach which allows also a change of the FE model without having too much adaption effort. Figure 4 shows the model. The most promising modeling approach was to directly use nodes of the FE model for muscle origin and insertion. The muscle element directly connects the shank with the thigh. Results of the first sled tests showed that the movements of occupants' lower extremities are negligible. Further simulations therefore focused on the kinematics of occupants upper body parts. Figure 5 shows the model response to a 50 ms 4 g square pulse, applied at time zero. The aim of this investigation was to check if the model is able to return to initial position after being exposed to a single perturbation in x direction. Gravity has not been included.

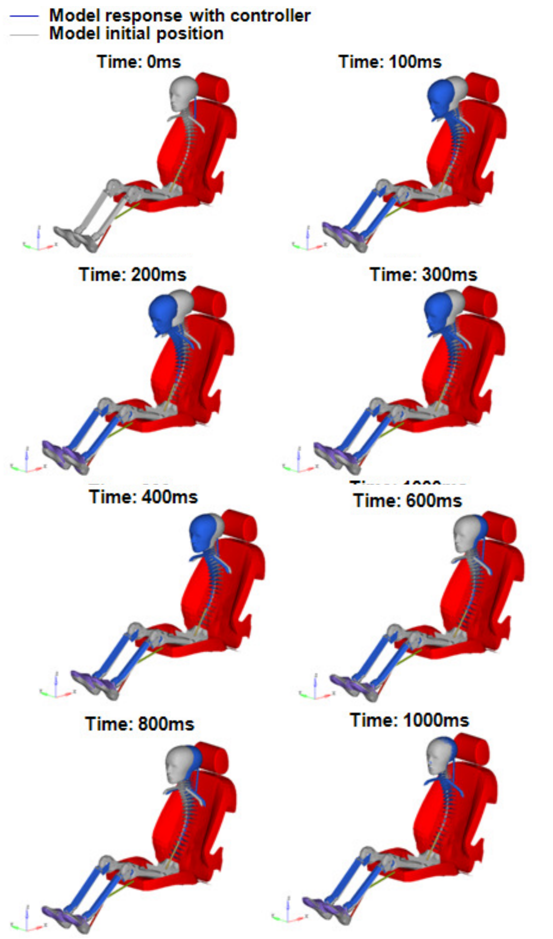

Figure 5. Model response to a 50 ms 4 g square pulse

After 1000 ms the models reaches its initial position.

THUMS model and necessary model simplifications

As already mentioned the THUMS model should serve as basis for research. THUMS is an advanced simulation model that has been developed to estimate injury mechanisms and injuries in traffic accident situations. It 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 [8], [9]. While the first versions of the THUMS model were initially developed for the explicit finite element code PAM-CRASH (ESI Group), it is now solely developed for the software LS-DYNA (LSTC). The THUMS version of 2002 had more than 80.000 total elements [8]. The latest version of THUMS which is called THUMS4 has more than 1.7 million elements. According to [10] the model offers Toyotas' accident researchers more than 14 times more information than the previous THUMS version. Obviously one of the disadvantages of a finite element model is the high calculation time compared to a multi-body model.

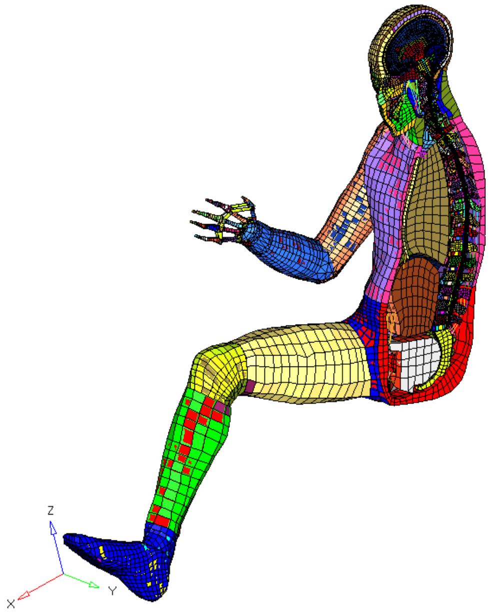

Figure 6. Section cut of THUMS

The development of a controller strategy demands a high number of iterations and this is why the use of the original THUMS would cause calculation time and costs, which is not satisfying in practical application. Therefore, the original THUMS had to be modified. The bones of the model have been extracted. After extraction, the bones have been set rigid and additional masses have been added to the bones to fit the masses and inertias of the new model to the original THUMS. In case of the original THUMS, joints are modelled via contacts. For the described bone model the joints have been modelled as kinematic joints. All in all 12 joints have been defined. Two for the left and right ankle, two for the left and right knees, two for the left and right hip, one for lumbar vertebrae, one for the cervical vertebrae, two for left and right shoulder, two for left and right elbows, see Figure 7. For all joints except the shoulder and hip joints muscles have been included. Due to the fact, that the models rotational and translational DOF's have been locked in pelvis region and the kinematics of upper region has been in focus of interest, muscles have only been defined for the two vertebrae joints. The muscle origins and insertions have been adjusted to joint locations and are therefore not anatomically correct. In contrast to real muscles which can only contract, the muscle elements can contract as well as elongate to control the movement of upper body region.

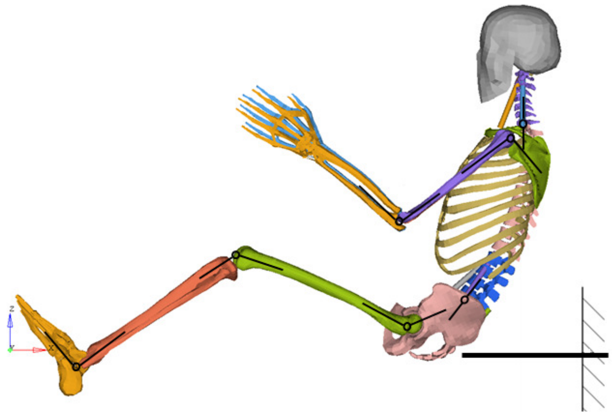

Figure 7. Extracted bone model for controller development

Figure 8 shows the sled acceleration characteristics for one volunteer in 3 different trials, which is needed to reproduce the occupants sled test kinematics. As it can be seen, the characteristics is similar for the second and third trial, the first trial shows a small offset of approximately 50 ms. For an implementation of the acceleration pulse into the simulation a mean acceleration pulse has been created. For the simulation the acceleration up to about 700 ms was used.

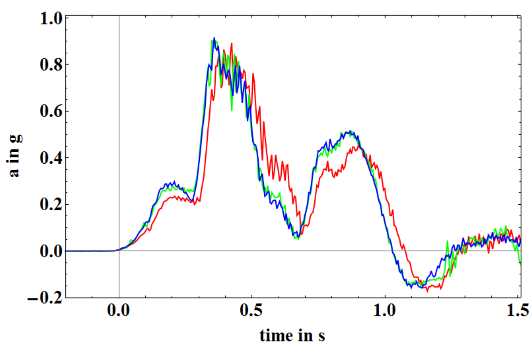

Figure 8. Acceleration pulses for one volunteer (3 trials: red=first, green= second and blue= third trial)

RESULTS

Figure 9 shows the first simulation results using the simplified THUMS model and the sled test acceleration pulse. Blue is volunteers' lumbar angle during the sled test. Red is the calculated lumbar angle during simulations. As it can be seen the angles show a good accordance up to 500 ms. At this point in time one can see that the acceleration depicted in green is already decreasing. Further work will concentrate on the adjustment of the controller in order to be able to simulate volunteers kinematics up to about 1000 ms.

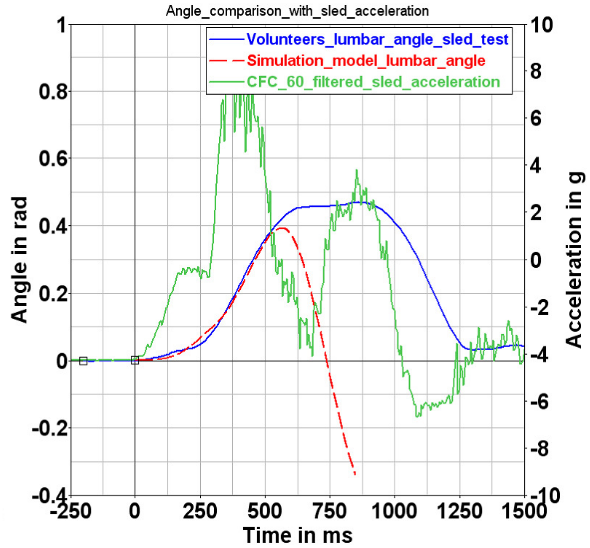

Figure 9. Sled test acceleration and volunteer lumbar angle in during sled test and simulation

DISCUSSION AND CONCLUSION

The current paper presents the aim and the first modeling approaches of a research project of a large consortium called OM4IS. This project focuses on the modeling of kinematic reactive behavior of an occupant during pre crash phase especially for two defined maneuvers. A frontal emergency braking and a single lane change maneuver. First simulations started with a simple substitute of the lower extremity. Muscle modeling approach has been tested using a model consisting of parts of BIORID II and H3 dummy model. For current controller development a FE human body model developed by Toyota Central R&D Lab serves as a basis. The reasons for choosing a FEM model instead of a MBS model are that the level of detail of FE models compared to MBS models is very high and using a FE model also for pre crash phase reduces the number of used models and may lead to a simplification of the development process. On the other hand the use of such a model especially in pre crash leads to two problems. The first one is that the use of a FE model instead of a MBS model increases the calculation time and the second is the numerical stability during the long pre crash phase (up to 1.5 s) compared to the collision phase. In order to reduce the calculation time and to have a stable numeric model for controller development the FE human body model has been modified in that way that it is similar to a MBS.

For the implementation of human muscle activity, actively controlled beam elements have been included. The beam elements are controlled using a coupling between Matlab/Simulink respectively a C++ routine and the explicit FE controller. This modeling approach splits the controller with its intelligence and the model information. It offers the chance to change the model without losing or destroying parts of the controller. In order to develop a method which could also be used for other FE models and also for MBS models the controller intelligence has been excluded from the FEM code. As described, the current model has only been used for the simple test data and with focus on the frontal braking maneuver. Future work will concentrate on simulation of full vehicle maneuvers which were carried out in November 2010. The presentation of the results and a more detailed description of the controller concept will be subject of future publications.

ACKNOWLEDGEMENT

The authors would like to acknowledge the financial support of the "COMET K2 - Competence Centres for Excellent Technologies Programme" of the Austrian Federal Ministry for Transport, Innovation and Technology (BMVIT), the Austrian Federal Ministry of Economy, Family and Youth (BMWFJ), the Austrian Research Promotion Agency (FFG), the Province of Styria and the Styrian Business Promotion Agency (SFG).
We would furthermore like to express our thanks to our supporting industrial and scientific project partners, by names in alphabetical order: Bundesanstalt für Straßenwesen-BASt (DI Andre Eggers), Robert Bosch GmbH (Dr.-Ing. Gian Antonio D'Addetta), DYNAmore GmbH (Dr.-Ing. Dirk Fressmann), Daimler AG (DI Christian Mayer), BMW Group (Dr. Katja von Merten; DI Philipp Wernicke), TRW Automotive (DI(FH). Thomas Herpich; DI Simon Kramer), Toyoda Gosei Europe (Dr.-Ing. Jörg Hoffmann; DI Michael Freisinger), Partnership for Dummy Technology and Biomechanics (Dr. Norbert Praxl); Graz University of Technology, Vehicle Safety Institute (DI Dr.techn. Wolfgang Sinz), Ludwig-Maximilians-Universität Munich (Dr.-Ing Steffen Peldschus).

REFERENCES

[1] MADYMO (2004). MADYMO Theory Manual Version 6.2.1 TNO Road Vehicles Institute, Delft, The Netherlands.

[2] Bathe, K. J: “Finite-Elemente-Methoden.” Springer, Berlin; Auflage: 2, 2007

[3] Steinke, P: “Finite-Elemente-Methode.” Rechnergestützte Einführung. Springer-Verlag GmbH & Co. KG, 2.Auflage ,2007

[4] Kirschbichler. et al. 2011. “Detailed Analysis of 3D Occupant Kinematics And Muscle Activity During The Pre-Crash Phase as Basis For Human Modeling Based On Sled Test .”.Manuscript to be submitted to the 22nd International Conference on the Enhanced Safety of Automobiles Conference, June13-16. Washington, USA

[5] Huxley, A. F. 1957. “Muscle structure and theories of contraction.” Prog. Biophy. Biophy. Chem. 7, 255-318.

[6] Hill AV. 1938. “The heat of shortening and the dynamic constants of muscle.” Proc. R. Soc. Lond.
B. 126:136–195.

[7] Cresnik, R. et al. 2009. “Dynamic Simulation of Mechatronic Systems.” 7th European LS-Dyna Conference, Graz, Austria

[8] Iwamoto, M. et al. 2002. “Development of a Finite Element Model of the Total Human Model for Safety (THUMS) and Application to Injury Reconstruction.” International IRCOBI Conference on the Biomechanics of Impact, September 18-20. Munich, Germany

[9] Article published on 08-02-2010. “ Total Human Model for Safety (THUMS).” URL-http://www.toyota.com/esq/articles/2010/THUMS.html, Accessed on 10-12-2010

[10] Article published on June 9 2010. “THUMS 4 -Toyota optimiert seine virtuellen Crashtest-Dummys.” URL-http://www.unfallzeitung.de /zeitung/thums-4-toyota-optimiert-seine-virtuellen-crashtest-dummys, Accessed on 15-01-2011