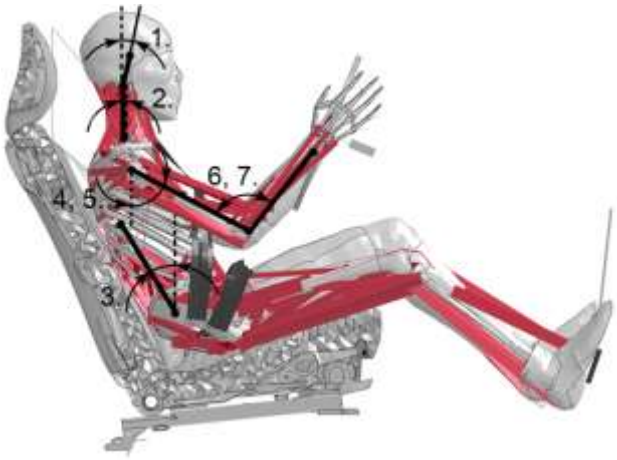
Active human body models for virtual occupant response, step 2



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FFI in short

FFI is a partnership between the Swedish government and automotive industry for joint funding of research, innovation and development concentrating on Climate & Environment and Safety. FFI has R&D activities worth approx. €100 million per year, of which half is governmental funding. The background to the investment is that development within road transportation and Swedish automotive industry has big impact for growth. FFI will contribute to the following main goals: Reducing the environmental impact of transport, reducing the number killed and injured in traffic and Strengthening international competitiveness. Currently there are five collaboration programs: **Vehicle Development, Transport Efficiency, Vehicle and Traffic Safety, Energy & Environment and Sustainable Production Technology.**

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1. Executive summary

The risk for a vehicle occupant to sustain an injury in a crash is reduced in vehicles that are equipped with systems that autonomously brake the vehicle before a crash. Hence, the reduced impact velocity results in a reduced injury risk. Additional occupant protection can be achieved if also occupant restraints are initiated in situations in which the vehicle autonomously brakes. Such initiations can be to pre-tense the seat belts, to help keep or put the occupant in a good position for the protection systems. In an emergency braking sequence the vehicle occupant can interact with the vehicle interior by resisting the forward motion by tensing the muscles in the body.

To develop occupant protection systems that interact with the occupant before the impact there is a need to also take the muscle response of the occupants into account. However, such tools are not available.

Therefore in this project a mathematical (finite element) human model with active muscles was developed. The model can predict the kinematics of a vehicle occupant, both driver and passenger, in an emergency braking (autonomous braking) vehicle up to 2 seconds braking of the vehicle prior to potential impact.

To develop and validate the active human body model, volunteer tests (20) in braking vehicles were carried out to collect necessary data. Both autonomous braking and voluntary braking tests were carried out. Drivers as well as passengers were included. A significant amount of data was collected, such as video recordings of the motion of the occupants, forces in the steering wheel, force in the brake pedal and force in the foot rest. To model muscle tensing of occupants during vehicle braking, the activity of selected muscles of the volunteers were recorded using Electromyografi (EMG) measurements.

The model will be used to predict and evaluate the motion and loads of an occupant in a frontal impact sequence including a preceding braking event. Automatic braking by vehicle integrated systems can be simulated, hence helping to develop collision avoidance/mitigation by braking types of systems. Additionally, the model serves an important part when developing integrated protection systems where information from the car's sensors (supplied from the automatic braking system) can be used to improve occupant restraints.

2. Background

Human Body Models (HBM) are valuable tools to simulate the pre-crash and in-crash occupant response in order to develop advanced restraint systems and reconstructions of real life crashes. Also, HBM offer possibilities to understand injury mechanisms on a detailed level and to determine injury criteria. These criteria can be used to develop assessment methods of new restraint systems. As compared to physical and virtual crash test dummies, HBM can more easily have a biofidelic sensitivity to different loading directions and differences in g-levels. HBM's can represent different occupant sizes, gender, anthropometry and muscle tonus.

In a previous project (SAFER project: B8 Development of active HBM in frontal impact situations, step 1), the partners of this project had initiated the research on active human body models that can simulate muscle tonus. Results confirmed that feedback control was a feasible approach to simulate active muscle contraction for vehicle occupants in autonomous braking events. An active HBM, the Beta version of the SAFER A-HBM, was developed and compared to 0.7 g volunteer autonomous braking. However, it was limited to sagittal plane motions and required further validation. Validation data including volunteer muscle activity as well as kinematics and boundary forces for vehicle occupants were lacking.

3. Objective

The objectives were:

- To improve the methodology to simulate active muscle response in human body models, developed in the Beta version of the SAFER A-HBM;
    - To account for bracing and
    - To increase the applicability to load cases beyond the braking, such as lane change manoeuvres.
- To provide validation data for active HBM in autonomous braking events.
- To develop an active human body model, validated for prediction of driver and passenger motion during heavy braking cars

4. Project realization

The project was a cooperation between academia and industry. It has contained both mechanical volunteer testing and development of mathematical models, beside development of methodology for active muscle responses. The project included three industrial partners and one academic partner, involving senior engineers and researcher as well as two Ph.D. students.

One of the Ph.D. students was mainly involved in planning and carrying out the mechanical volunteer tests with support from the industrial partners Volvo Cars and Autoliv. For the tests, Volvo Cars supplied the vehicle used for testing and supported the installation of the test equipment in the vehicle. Autoliv supplied the restraint systems used in the tests and also supported the installation. In total, 20 Volunteer tests were carried out and analysed. The results were used in the development and validation of the mathematical model. The other Ph.D. student was mainly involved in analysing volunteer tests carried out at “University of Vancouver”. Both students were involved in the development and validation of the mathematical human body model.

5. Results and deliverables

Within this project, Jonas Östh completed a doctoral degree and Jóna Marín-Ólafsdóttir completed a licentiate degree at Chalmers University of Technology. In total 9 publications in peer review journals.

The Beta version of the SAFER A-HBM was further developed to enable simulation of bracing in autonomous and driver voluntary braking; and to simulate postural control for events with a lateral component. To enable this, a number of further developments were identified and implemented. The main results were:

1. To simulate driver interaction with the steering wheel, muscles with active postural control were implemented for the upper extremities. The active muscle models for the spine and upper extremities were merged into the SAFER A-HBM. To simulate driver braking, lower extremity muscles were implemented in the SAFER A-HBM. (Blomgren et al. 2013). The updated SAFER A-HBM with controller angles is illustrated in Figure 1.

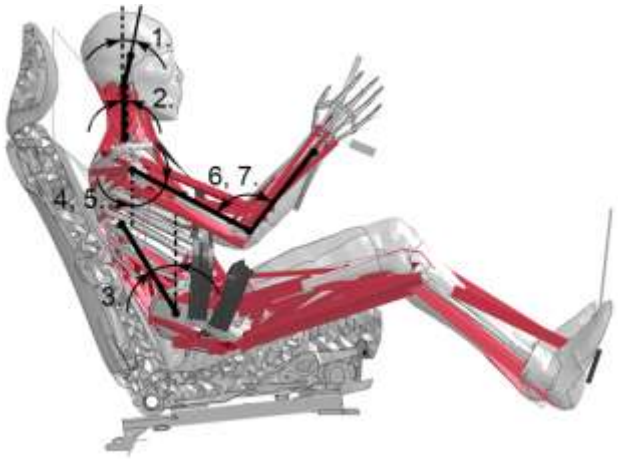

Figure 1. The SAFER A-HBM with active muscles to control spine, upper and lower extremities. The controller angles for the (1) head, (2) neck, (3) lumbar spine, (4) left and (5) right shoulder all use the angle of the body part with respect to the vertical axis. The (6) left and (7) right elbow controllers utilize the relative angle between the humerus and ulna. Soft tissues of the trunk, neck, and upper extremities and half the seat are not shown to disclose the musculoskeletal structure of the model.

2. To provide validation data, a set of volunteer experiments were carried out. 20 volunteers (11 male, 9 female) were subjected to autonomous and driver braking as drivers and passengers, with two seat belt systems in a Volvo V60 driving on rural roads in the Gothenburg area. Prior to testing, the volunteers were instrumented with surface electromyography (EMG) and the maximum voluntary contractions (MVC) were measured. During braking data collected were: vehicle accelerations, occupant kinematics from video data, surface EMG normalized to the MVC, steering column forces, seat indentation, foot-well and braking forces, seat belt forces and payout. The driver response to autonomous braking was significantly different from driver braking. Shoulder belt pre-tension before braking induced muscle activity in the upper extremities, this was most prominent for females. (Östh et al. 2013, Ólafsdóttir et al. 2013)
3. The SAFER A-HBM was validated with regard to the volunteer data for autonomous braking. Selected results from the simulations of autonomous braking interventions are shown in Figure 2. (Östh et al. 2104a)

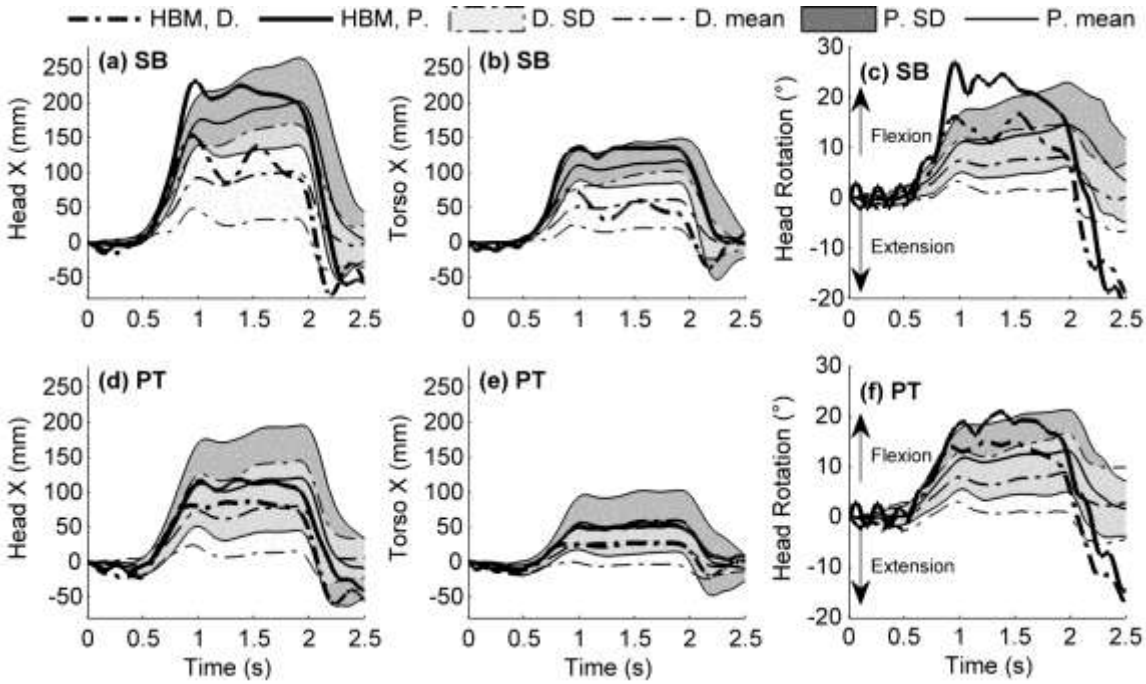

Figure 2. SAFER A-HBM head and torso kinematics in comparison with volunteer with volunteer mean ± one SD (Östh et al. 2013; Ólafsdóttir et al. 2013) in the validation simulations. The torso displacements were measured for the sternum in the driver (D) position (dashed lines), and for the T1 vertebra in the passenger (P) position (solid lines). Plots (a–c) are Standard Belt (SB); (d–f) are Pre-Tensioned belt (PT).SD = standard deviation (shaded areas).

4. Anticipatory postural responses were implemented with feed forward control of the active muscle elements and the response was compared to the volunteer data for driver braking (Figure 3). (Östh et al. 2014b)

Figure 3: The SAFER A-HBM (red) compared to one volunteer (blue) , the mean volunteer response (grey) and one standard deviation corridor (light grey area).

5. To define a modeling methodology of lateral postural control, muscle recruitment strategies were studied by analyzing the cervical muscle activity of volunteers subjected to perturbations in eight different directions. It was found that the activation patterns varied with direction (Figure 4). Anterior muscles (SCM and STH) were most active during forward (0°) and forward oblique (±45°)

perturbations whereas posterior muscles, aside from SPL, were most active during rearward (180°) and rearward oblique (±135°) perturbations. A combination of anterior and posterior muscles was active during lateral (±90°) perturbations. (Ólafsdóttir et al. 2014)

6. A strategy to implement lateral posture control with closed loop control was defined. A first version of the lateral control tested for the cervical muscle, indicate that multiple controllers are needed at each location.

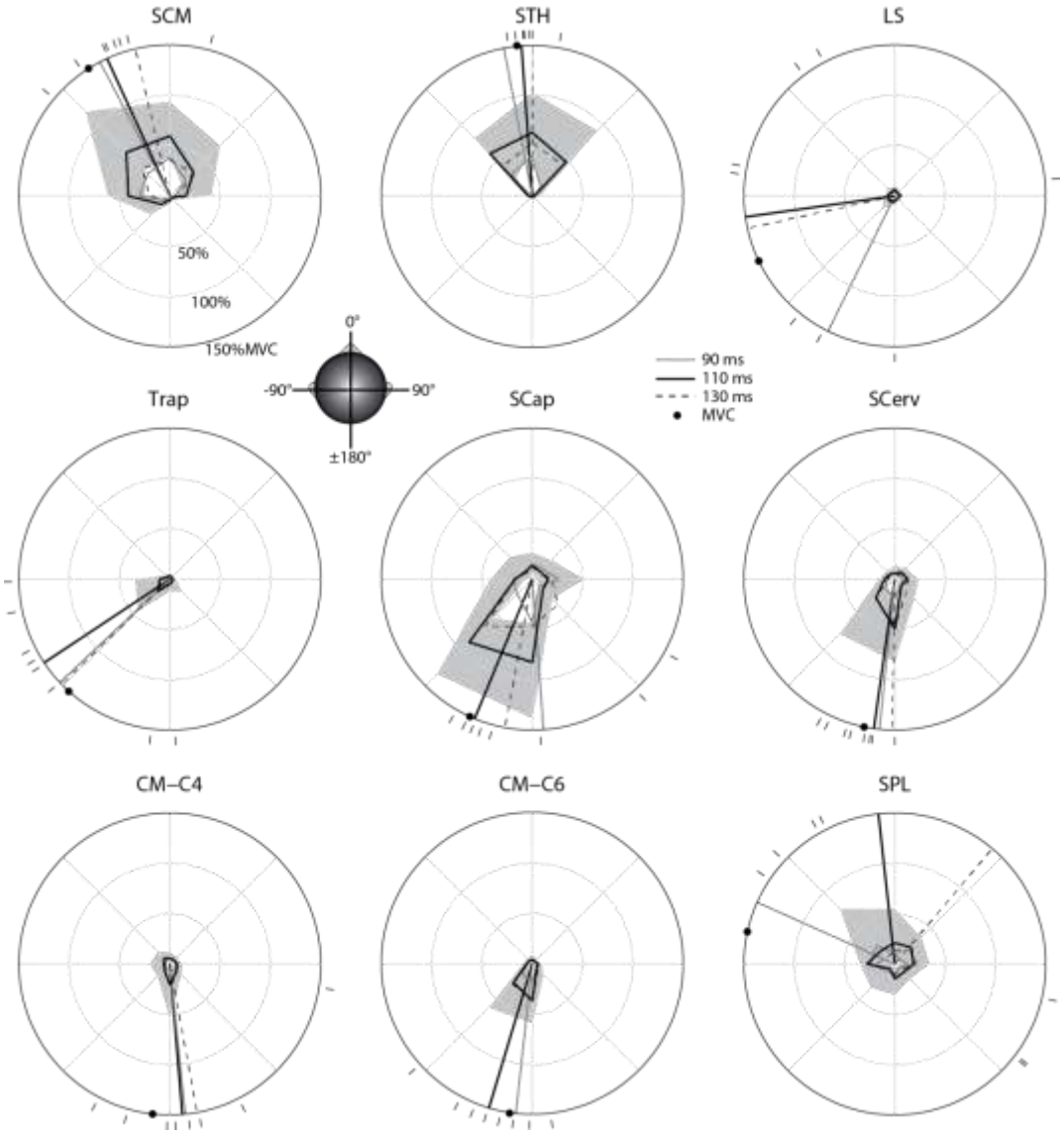

Figure 4. Median dynamic spatial tuning patterns of normalized RMS EMG at 90, 110 and 130 ms. The shaded area represents the interquartile range at 110 ms. Median preferred directions are shown for the dynamic responses (radial lines), MVCs (black dots), and subject-specific responses (perimeter ticks) at 110 ms. SCM: sternocleidomastoid, STH: sternohyoid, LS: levator

scapulae, Trap: trapezius, SCap: semispinalis capitis, SCerv: semispinalis cervicis, CM-C4: cervical multifidus C4/C5 level, CM-C6: cervical multifidus C6/C7 level, SPL: splenius capitis.

The model has taken steps into industrial applications and is being adjusted to be used within the industrial process at Autoliv and Volvo Cars. Significant challenges have been overreached and the industrialization is a necessity to reach full benefit of the project results.

5.1 Delivery to FFI-goals

The goal to "work to ensure that new knowledge is generated and implemented, and that existing knowledge is implemented in industrial applications" has been addressed by working together throughout the project. Specific activities were made to ensure that the model can be used within the industrial process, as well as concerns were taken to ensure that all participants were well educated in state-of-the art safety system functionalities as well as state-of-the-art academic knowledge was shared. Additionally, new knowledge was generated jointly through planning, execution and analysis of volunteer tests in cars were state-of-the-art systems such as autonomous braking and pre-prepretension seat belts were a part. In these tests, the kinematics of vehicle occupants in emergency braking vehicles was studied.

This new knowledge was used to develop and validate a mathematical model of a human that can predict occupant motion, muscle tension and bracing in a heavy braking vehicle. The model will be used by the industrial partners, Volvo Cars, Volvo Group and Autoliv to develop safety systems that help reduce the number of deaths and serious injuries in car crashes, specifically frontal impacts.

The goal to "contribute to continued competitive automotive industry in Sweden" has been addressed by developing a unique tool that will be used to develop new integrated safety systems. This tool is only available for the industrial partners in the project; Volvo Cars, AB Volvo and Autoliv. By using the tool, the industry can develop, patent and market safety systems that increase their competitiveness in the global automotive market. Additionally, the project results will help strengthen the "safety image" of the involved partners.

The goal to "strengthen collaboration between the automotive industry and government agencies, universities, colleges and research" has been addressed thorough the involvement of vehicle manufacturer, supplier and university in the project. From the university, both senior researchers and graduate students have been active. Beside the continuous interaction within the project group, additional industrial contacts were achieved by the project students when carrying out experiments (volunteer tests) with Volvo cars and Autoliv restraint systems. During this process, the experts in the

integration of protection systems from Volvo Cars and experts in belt components from Autoliv were involved and networked with each other and the graduate students. Additionally, being an associated SAFER project, the results have regularly been shared with other SAFER partners, which encompasses a number of relevant actors within industry, government agencies, society, universities and institutes.

6. Dissemination and publications

6.1 Knowledge and results dissemination

Safety vision initiatives, including the Swedish national "Vision Zero" and the Volvo Cars' "Vision 2020" state challenging goals to eliminate traffic injuries. In line with this, there is a need to address every situation potentially causing injury. Hence, there is a need to simulate a human in crash events beyond regulatory test situations and this development drives the need for projects like this; creating tools addressing these situations. This project takes an important step in developing a model for pre-brake situations. A sub-seeding project "Active human body models for virtual occupant response, step 3" (Dnr 2014-03931) will take this model development further and help boost the progress as well as the feasibility and applicability of the results in the current project. Other relevant projects are projects related to Human body model developments, including injury criteria prediction "Improved injury prediction using HBM, step 2" (Dnr 2013-01287) as well as projects on collision avoidance / mitigation system developments, including Autonomous Drive.

6.2 Publications

The publications from the project encompasses peer-reviewed publications, academic theses and conference presentations as presented below. The Chalmers Publication Library (CPL) reference number is included.

6.1.1. Peer-reviewed publications

Khodaei H, Mostofizadeh S, Brolin K, Johansson H, Östh J. (2013). Simulation of active skeletal muscle tissue with a transversely isotropic viscohyperelastic continuum material model. *Proceedings of the Institution of mechanical engineers. Part H, journal of engineering in medicine*. 227 s. 571-580. [CPL 173982]

Ólafsdóttir J, Östh J, Davidsson J, Brolin K. (2013) Passenger Kinematics and Muscle Responses in Autonomous Braking Events with Standard and Reversible Pre-tensioned Restraints. *International IRCOBI Conference on the Biomechanics of Impact*, p. 602-617, Gothenburg, Sweden, September 11-13. [CPL 188819]

Ólafsdóttir JM, Brolin K, Blouin J-S, Siegmund GP (2014) Dynamic Spatial Tuning of Cervical Muscle Reflexes to Multi-directional Seated Perturbations. Submitted for publicationto *Spine*, in review with minor revision.

Ólafsdóttir JM, Östh JKH, Davidsson J, Brolin K (2013) Passenger Kinematics and Muscle Responses in Autonomous Braking Events with Standard and Reversible Pre-tensioned Restraints. *Proceedings of the IRCOBI Conference*; Gothenburg, Sweden, pp. 602–617. [CPL 188819]

Östh J, Brolin K, Bråse D (2014) A Human Body Model with Active Muscles for Simulation of Pre-Tensioned Restraints in Autonomous Braking Interventions. *Traffic Injury Prevention* (in press), DOI: 10.1080/15389588.2014.931949. [CPL 201718]

Östh J, Brolin K, Carlsson S, Wismans J, Davidsson J. (2012) The Occupant Response to Autonomous Braking: A Modelling Approach That Accounts for Active Musculature. *Traffic Injury Prevention*, 13(3):265–277. [CPL 151227] (results from previous project, published and revised in this project)

Östh J, Brolin K, Happee R. (2012a) Active muscle response using feedback control of a finite element human arm model. *Computer Methods in Biomechanics and Biomedical Engineering*, 15(4):347-361. [CPL 155448] (results from previous project, published and revised in this project)

Östh J, Eliasson E, Happee R, Brolin K (2014) A Method to Model Anticipatory Postural Control in Driver Braking Events. *Gait and Posture* 40:664–669. [CPL 201716]

Östh J, Ólafsdóttir JM, Davidsson J, Brolin K (2013) Driver Kinematic and Muscle Responses in Braking Events with Standard and Reversible Pre-tensioned Restraints: Validation Data for Human Models. *Stapp Car Crash Journal* 57:1–41. [CPL 188685]

6.1.2. Academic theses

Andersson S (2013) Active Muscle Control in Human Body Model Simulations: Implementation of a feedback control algorithm with standard keywords in LS-DYNA. *Master thesis*, Chalmers University of Technology, Gothenburg, Sweden. [CPL 182123]

Blomgren N, Eliasson E, Ericson J, Lundahl O (2013) Modellering och Simulering av Benmuskulatur Inför Fordonskrock. *Bachelor thesis*, Chalmers University of Technology, Gothenburg, Sweden. [CPL 179557]

Ólafsdóttir JM (2014) Volunteer Muscle Activity in Dynamic Events. Input Data for Human Body Models. *Licentiate Thesis*, Chalmers University of Technology, Gothenburg, Sweden. [CPL 202600]

Östh J. (2014) Muscle Responses of Car Occupants: Numerical Modeling and Volunteer Experiments under Pre-Crash Braking Conditions, *Doctoral thesis*, Department of Applied Mechanics, Chalmers University of Technology, Gothenburg, Sweden, ISBN/ISSN: 978-91-7385-987-5. [CPL 194443]

6.1.3. Conference presentations and other

Brolin K. (2012) 'Kan vi utveckla säkerhetssystem med hjälp av virtuella människor?' Presentation at the seminar "*Den ömtåliga människan*" arranged by SAFER and NTF Väst, Gothenburg, Sweden, May 10.

Brolin K, Gras LL, Östh J, Mendoza-Vazquez M, Ólafsdóttir J, Davidsson J. (2013) Human Body Modeling for Integrated Safety Analyses, Adult and Child Models, Presentation at the *4th International Symposium on Human Modelling and Simulation in Automotive Engineering*, Aschaffenburg, Germany, May 13-14. [CPL 192673]

Brolin K, Mendoza-Vazquez M, Östh J, Ólafsdóttir J, Paas R, Davidsson J. (2013) Human body modeling for integrated safety analyses using THUMS, Presentation at the *THUMS European Users' Meeting*, Manchester, England, June 6. [CPL 192670]

Brolin K, Östh J, Nydahl M. (2014) Evaluation at low g-level loading. Presentation at the *5th International Symposium on Human Modelling and Simulation in Automotive Engineering*, Munich, Germany, October 16-17. [CPL 205756]

Brolin K, Östh J, Ólafsdóttir J, Davidsson J. (2014) Finite element musculoskeletal model with feedback control to simulate spinal postural responses. *7th World Congress of Biomechanics*, Boston, July 6-11. [CPL 202494]

Ólafsdóttir J, Brolin K, Blouin J, Siegmund G (2014) Cervical Muscle Responses to Multidirectional Perturbations. *7th World Congress of Biomechanics*, Boston, July 6-11 [CPL 202733]

Östh J, Ólafsdóttir , J, Brolin K. (2014). Modelling of Car Occupant Muscle Responses in a Finite Element Human Body Model, *11th World Congress and 5th European Conference on Computational Mechanics*, July 20-25, 2014, Barcelona. [CPL 200876]

Östh J, Ólafsdóttir J, Brolin K. (2014). Modeling Active Human Muscle Responses during Driver and Autonomous Avoidance Maneuvers, *3rd International Workshop on Computational Engineering*, October 7–10, Stuttgart, Germany. [CPL 204563]

Östh J. (2014) Feedback Control in LS-DYNA and Application for Modeling Muscle Responses of Car Occupants . *Nordic LS-DYNA Forum*, October 9, Gothenburg, Sweden. [CPL 205248]

7. Conclusions and future research

The active human body model developed in this project is capable of replicating human motion in autonomous braking situations as well as in voluntary braking. The model was validated for both passenger vehicle drivers and passengers. In the volunteer tests carried out the velocity of the vehicle when braking was initiated was not varied. In all tests braking was initiated at a velocity of 70km/h. Therefore future validation of the active model human should include human motion in various types of braking and braking at both higher and lower velocity than 70km/h.

The current version of the active human body model is validated for pre-crash longitudinal motion of a vehicle occupant. Future validations of the model will also include the crash phase. Therefore there is a need to validate the model for the whole sequence from pre-crash braking to crash. A method to do the validation is to reconstruct a number of accidents from the field in which the pre-crash motion of the vehicle and the occupant injuries are known.

Next step in the development of the active human body model is to make the model capable of replicating human motion in vehicle avoidance maneuvers as well. The model should predict human motion in both voluntary avoidance maneuvers as well as autonomous avoidance maneuvers.

In the current model, one-dimensional Hill type muscles are used in conjunction with a closed look control system to model human response. A drawback with the one-dimensional Hill type muscles is that they are not capable of include wrapping of the muscles around skeleton parts of the human body. In addition the muscles cannot take contact between the muscle and bony parts of the body into account. Therefore, in future developments of the model three-dimensional muscle modelling can be evaluated.

The goal with the active human model is that the model can predict human motions in complex events such as run-off-road crashes and multiple accidents. Therefore future validation will also include complex volunteer motion such as representative run-off-road human kinematics.

The current version of the human body model is very time consuming to run on a state-of-the-art computer system. A state-of-the-art computer system distributes the model on numerous processors. The more processors that are used the shorter run time it will require. However, when running the current version of the active human body model the run time is not reduced when more processors are added. Therefore future work will also include reducing the run time of the model.

Ultimately, in a futuristic view, the active human body model can be coupled to a behavior model to model anticipatory human motion.

8. Participating parties and contact persons

The participants in the project were Autoliv Development, Volvo Cars, Chalmers University of Technology, Umeå University, Volvo Group Truck Corporation.

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