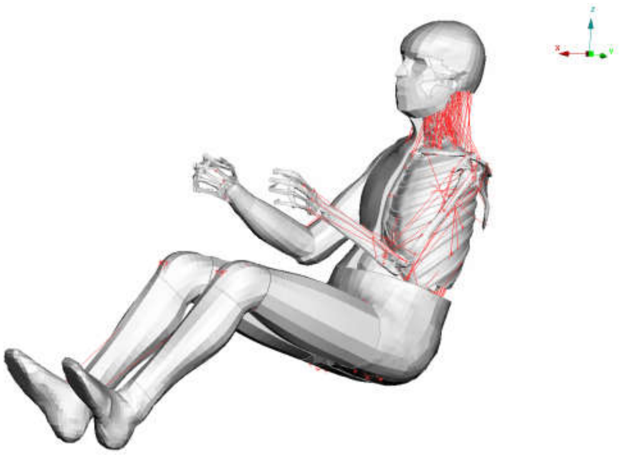
Active human body models for virtual occupant response, step 3
Aktiv humanmodell för prediktering av mänsklig rörelse, steg 3

Public report



Project within 'Trafiksäkerhet och Automatiserade Fordon'

Author Lotta Jakobsson, Volvo Cars

Date 2018-01-31

FFI Fordonsstrategisk Forskning och Innovation
VINNOVA Energimyndigheten TRAFIKVERKET FKG VOLVO SCANIA VOLVO

Content

1. Summary

Real world crashes are usually preceded by events that can include automated or driver initiated braking and steering manoeuvres prior to crash, as well as road departures. During such events, there is a need to take the muscle response of the occupants into account. In previous projects, the project team has developed an active human body model (HBM) capable of predicting human kinematics for autonomous vehicle braking (for driver and front seat passenger). In addition, the lower extremity muscle activity was implemented to enable prediction of human kinematics for anticipatory voluntary driver braking. In parallel projects, the project team is working with the injury prediction capabilities of the HBM during the crash sequence. To enable real world occupant protection evaluation, it is essential to combine these capabilities into one single tool that can predict human responses during sequences of events, such as combined emergency and crash events, road departure events, and other long duration crash events, and that can predict driver actions, such as steering and braking.

With the overall goal of evaluating occupant protection through whole sequences of events; the aim of this project was to develop a methodology to enhance the Active HBM (A-HBM) with oblique and lateral muscle control, validate the model and use it in application areas for safety improvements.

The project has further developed the A-HBM's capability of predicting humanlike kinematics in avoidance manoeuvres. Specifically, a methodology for oblique and lateral muscle control was developed for horizontal plane events, and implemented into the SAFER HBM, developing a seamless tool to simulate pre-crash manoeuvres in addition to crash evaluation. Extensive validation data for lane change manoeuvres, with and without braking, has been gathered and initial validation of the enhanced model was made including braking as well as lane change manoeuvres. In addition, industrial integration of the model was carried out during the project, and applied in areas for safety improvements by the industrial partners.

The SAFER HBM is unique and provides the industrial partners with a highly competitive tool for integrated safety product developments. The project has resulted in several peer-reviewed publications, conference presentations, and a PhD thesis. The work has reached high scientific interest, creating important international cooperation.

In order to reach the overall goal, future development should include methodology enhancements for omnidirectional muscle control, adding vertical loading components and further tuning and validation also addressing specific needs for driver interaction with the steering wheel.

2. Sammanfattning på svenska

Olyckor föregås ofta av förarinitierade eller autonoma manövers såsom inbromsning, styrning eller avkörning. Vid sådana händelser har den muskulära responsen betydelse. Projektgruppen har i ett tidigare projekt utvecklat en aktiv humanmodell som kan prediktera mänsklig rörelse vid autonom inbromsning (förare- respektive passagerarmodell), samt förarinitierad bromsning, där även benens muskelaktivitet är inkluderad. I parallella projekt arbetar projektgruppen med humanmodellens förmåga att prediktera skador vid en krock. För att effektivt kunna utvärdera verkliga olyckor är kombinationen av muskel- och skadeprediktering i samma verktyg av betydelse. Det möjliggör att mänsklig respons kan återskapas och studeras i hela sekvenser av händelser, såsom kombinerad panikmanöver och krock, avkörningssituationer och andra krockar med långa krocksekvenser.

Med det övergripande syftet att kunna utvärdera åkandeskydd genom hela sekvenser av händelser, var målet i detta projekt att utveckla metodik för att möjliggöra vinklad och lateral muskelkontroll i den aktiva humanmodellen, validera modellen och använda den för utveckling av säkerhetssystem i bil.

Projektet har vidareutvecklat den aktiva humanmodellens förmåga i manövers. Specifikt har en metodik för vinklad och lateral muskelkontroll tagits fram och implementerats i senaste versionen av SAFER HBM, vilket har gett projektpartnerna ett effektivt verktyg som kan återskapa mänskligt rörelsemönster vid manöver och krock utan avbrott. En omfattande provserie med frivilliga försökspersoner har genomförts för att samla in data på rörelsemönster och muskelaktivering vid filbytessituationer, med och utan bromsning. Validering av modellen baserat på denna data har påbörjats. Industrialisering av modellen har genomförts och använts av industripartnerna inom säkerhetsutveckling.

SAFER HBM är unik och ger industripartnerna ett konkurrenskraftigt verktyg för integrerad säkerhetsutveckling. Projektet har resulterat i flertalet vetenskapliga publikationer, konferenspresentationer samt en doktorsavhandling. Arbetet har väckt stor vetenskapligt intresse och bidragit till viktiga internationella samarbeten.

För att nå det övergripande målet behövs ytterligare utveckling av metodik för tredimensionell muskelkontroll (speciellt addera den vertikala komponenten), ytterligare validering, samt modellutveckling avseende förarens interaktion med ratten.

3. Background

Vehicle safety developments today comprise whole sequences of events, including pre-crash and crash situations. The pre-crash events can be of long duration, more than one second. During such long events, the kinematics of the vehicle occupants can be influenced by the occupants tensing their muscles. Therefore, there is a need to take the muscle response of the occupants into account. Pre-crash technologies are for example autonomous braking and steering in an increasing variety of situations, as well as occupant restraints such as electrical reversible seatbelt pretensioners. Human Body Models (HBMs) have become valuable virtual tools to predict the occupant crash response and offer the capability to understand injury mechanisms on a detailed level and to evaluate injury risks. In parallel projects, the project team is refining the injury prediction capabilities of the HBM during the crash sequence. As compared to crash test dummies, HBMs have biofidelic sensitivity to different loading directions and differences in acceleration levels and can represent different occupant sizes, gender, and anthropometry. In addition, if muscle tonus is implemented in the models, so called Active HBMs (A-HBMs), they have the potential to predict the occupant response in pre-crash and emergency events. Hence, HBMs including the muscle tonus implementation, have the prerequisites needed for occupant protection evaluation for future vehicles, also including an increasing degree of automation. To enable real world occupant protection evaluation, it is essential to combine these capabilities into one single tool that can predict occupant responses during sequences of events; such as combined emergency and crash events, road departure events, and other long duration crash events, but also predict driver actions such as steering and braking. This project focuses on the Active HBM, i.e. the muscle activity implementation.

Starting in 2009, the partners of this project initiated pioneering research on Active HBMs that can predict muscle tonus. In two prior projects (Active human body models for virtual occupant response, Step 1 and Step 2), state-of-the-art research on and development of Active HBMs was executed. Results from Step 1 (FFI Dnr. 2009-2010) confirmed that closed loop control was a feasible approach to predict the human muscle activity for vehicle occupants in autonomous braking events. A first generation A-HBM, the Beta version of the SAFER A-HBM, was developed and compared to 0.7 g volunteer autonomous braking. In Step 2 (FFI Dnr. 2011-2014) experimental data suitable for validation of Active HBMs was produced and analysed. The data comprised kinematics, interaction forces and normalized EMG (electromyography) data of 20 volunteer car occupants, both driver and passengers, in autonomous and driver braking using two different seat belt systems. The enhanced SAFER A-HBM was validated for predicting human kinematics in autonomous braking (driver and passenger) as well as to driver voluntary braking, for which the lower extremity muscle activity was implemented as well. In addition, experimental data from volunteer sled perturbations was analysed to provide knowledge on muscle activity in load cases beyond pure autonomous braking, such as lane change manoeuvres and multiple events, but was not implemented into the model at that stage.

4. Purpose, research questions and method

The ultimate goal for the Active HBM projects is to develop a muscular system model in a biofidelic HBM that can predict occupant responses during sequences of events, such as combined emergency and crash events, road departure events, and other long duration crash events, and that can simulate driver actions such as steering and braking. Such a tool is essential for the industry for developments of integrated safety systems for occupant protection. At the end of the Step 2 project, the developed SAFER A-HBM was capable of predicting an autonomous emergency braking event with biofidelic kinematics and muscle activity. The model was ready to be applied in combined pre- and in-crash simulations, which was required to be useful for vehicle development.

Therefore, the research questions for this project (Step 3) addressed the next steps to enhance the SAFER A-HBM. Towards the ultimate goal, these steps included defining muscle recruitment strategies for movement in the horizontal plane, implementing bracing, and developing a novel methodology to predict the occupants' muscle responses to emergency events with lateral components. Such events are autonomous steering and lane change manoeuvres. In addition, validation data sets to assess model biofidelity were generated. Model integration into the industrial process and ensuring whole sequence (braking and crash) functionality were also important parts of the project.

The two PhD students involved in the project focused on fundamental research on active muscle response of car occupants in autonomous maneuvers. One student concentrated on how to model active muscle responses, implementing closed loop control to predict the active muscle response in lateral and oblique pre-crash situations, based on experimental data analyzed and published in the previous project. The other student focused on performing and analyzing an experimental study with volunteers, measuring muscle activity, kinematics and forces for oblique emergency events, that can be used for biofidelity assessments.

Beside the fundamental research by Chalmers, industrial application activities were performed as an important part of the project. The industrial partners were responsible for defining the requirements for the active human body model regarding performance, validity range and boundaries. In addition, the industrial partners worked in cooperation with Chalmers in setting up the test vehicle and method for carrying out the volunteer tests. Furthermore, the industrial partners adapted it to the industrial environment, including integration of the A-HBM into a SAFER HBM capable of a braking event followed by a crash, and applied it in studies on integrated safety evaluations.

5. Objective

In line with the overall goal of enhancing the SAFER HBM for increased capabilities for vehicle developments, with the purpose to predict human motion in the full crash sequence for scenarios with pre-crash lateral components, the specific objectives for the project were:

- Develop a methodology that predicts human muscle response for omnidirectional motions in the horizontal plane.
- Implement the methodology to enhance the SAFER A-HBM to achieve biofidelic responses in emergency events with lateral components.
- Generate validation data for autonomous steering and lane change manoeuvres, tracking kinematics, muscle response, vehicle motions, and interaction forces between occupant and vehicle interior.
- Implement the SAFER HBM (at different versions) into industrial environment and use it in application areas for safety improvements.
- Academic theses and publications, in addition to project dissemination contributing to international knowledge and collaboration.

The overall objectives have not changed during the project.

However, the content in WP5 to understand how muscle activity changes when the occupants are aware of an impending emergency event compared to unaware subjects was changed. Instead work was refocused to assess the relevance of using dynamic spatial tuning patterns of neck muscles (resulting from the previous project Step 2), that were determined in volunteer subjected to perturbations, as model input in simulations with pre-crash like accelerations. Therefore, a novel set of experiments were conducted in collaboration with MEA Forensic, Vancouver, Canada.

The complexity of the volunteer experiments in WP2 were higher than initially foreseen, therefore some changes were made to the project. The analysis of the volunteer tests were limited to a subset of the passengers, for which the model was validated. As a complement to our own generated data, additional validation data was obtained through international cooperation. As a consequence, the licentiate thesis for one of the PhD students was not finished as part of this project.

Additional support was gratefully received during the project to ensure the deliverables.

6. Results and deliverables

Project results

Jóna Marin Ólafsdóttir completed a doctoral degree at Chalmers University of Technology in June 2017. Three master theses involving five students were performed contributing to the project results. In total, six published peer-reviewed articles (+5 in preparation/submission), three conference publications, and an additional eight presentations (without publications) at international technical conferences, seminars or workshops resulted from this project.

At the end of the project the SAFER HBM v9.0 was launched, including the most recent developments in the parallel project on injury prediction capabilities (FFI Dnr 2015-04864) and the A-HBM improvements resulting from this project (see Figure 2 and front page). The A-HBM improvements in the model include:

- a new set of active muscles in the cervical spine, lumbar spine, abdomen, legs, and arms,
- horizontal-plane omnidirectional implementation of muscle control in the cervical and lumbar spine, enabling these muscles to react to longitudinal as well as lateral stimuli; including two different muscle control schemes representing vestibular and muscle spindle feedback, which can be used separately or combined,
- enhancement of the implementations in the simulation software to decrease computational time and improve clarity and simplicity of the model, as an essential step in model industrialization.

The A-HBM implementation was enhanced to simulate muscle response to any load direction in the horizontal plane (Ólafsdóttir et al. 2017). A method to simulate muscle response in horizontal-plane omnidirectional loading was developed, including representation of vestibular and muscle spindle feedback. Input from the vestibular system was represented by anatomical joint angular feedback and input from muscle spindles were represented with muscle length feedback. This method required definition of muscle load sharing and recruitment patterns for omnidirectional horizontal plane motions. The dynamic spatial tuning patterns from Step 2 (FFI project report A-HBM2) were used to define muscle load sharing in the model. The method was verified regarding neck muscle strength and multi-directional responses (Figure 1) using gravity loading for different directions. The results were promising, although experimental volunteer data was lacking for comparisons (Ólafsdóttir et al 2017, Ivančić and Pradhan 2017). Subsequently, this horizontal-plane omnidirectional method was implemented in the SAFER A-HBM for the lumbar and cervical spine, and combined with previous implementation for muscle control of the extremities.

Industrialization of the developed SAFER A-HBM was an important part of this project. The A-HBM version from Step 2 was adapted to be used in industrial environments at Volvo Cars and Autoliv (Eliasson and Wass, 2015). The coding of the closed loop control within the finite element solver LS-DYNA was so computationally costly that it was not feasible to run the SAFER HBM, with the integrated A-HBM, in a full vehicle environment. Therefore, collaboration with the LS-DYNA distributor, Dynamore Nordic (Linköping, Sweden), has been ongoing since Step 1. Alternative implementations have been evaluated (Andersson 2013), but it was not until 2017 that a breakthrough was accomplished, simplifying the implementation of the closed loop control so that it only marginally increased the computational cost. Hence, this project has provided several new features to LS-DYNA that have been implemented, and will be available for all users in the next official release. Therefore, it was now feasible to merge the efforts of several ongoing research projects into one single HBM that can be used with either active or passive muscles. This work resulted in the creation and launch of the SAFER HBM v9.0, which comprised the A-HBM model results of this project and the most recent developments in the parallel project on injury prediction capabilities in crash (FFI Dnr. 2015- 04864), Figure 2.

Versions of the enhanced SAFER A-HBM, with omnidirectional muscle control for the horizontal plane, were compared to several volunteer data sets; far side and lateral sled test (Arbogast et al., 2012), passengers subjected to autonomous manoeuvres in frontal and lateral directions (Huber et al., 2015), passengers subjected to autonomous braking (Ólafsdóttir et al., 2013) and passengers subjected to autonomous lane change and lane-change with braking (data from this project, Figure 2). The new model with active control produced results for autonomous braking comparable to the previous sagittal plane muscle control method from the previous project (Step 2). Further, the initial validation results showed that the model predicted volunteer motion in lane-change and lane-change with braking manoeuvres with promising results (examples in Figures 3 and 4). In conclusion, the validation of the SAFER A-HBM passenger (with omnidirectional muscle response) provided reasonable correlation to volunteer data and identified potential to improve the biofidelity by tuning the muscle control parameters and to improve the shoulder model in the base-line model.

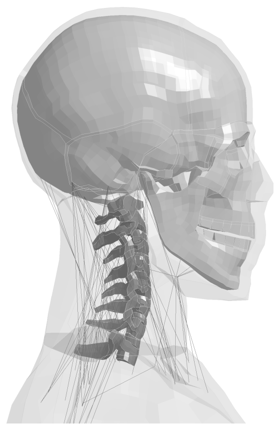


Figure 1. Head/neck model used to verify the novel methodology for omnidirectional muscle responses in the horizontal plane.

Figure 2. The SAFER HBM v9.0 positioned in the vehicle seat and restraint system for simulation of the autonomous lane-change volunteer experiments performed within the project.

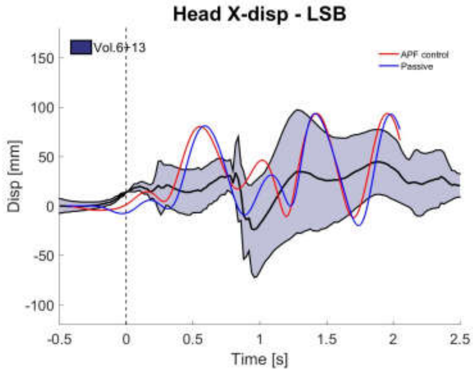


Figure 3. Head frontal displacement during lane change event with standard belt compared to two volunteers.

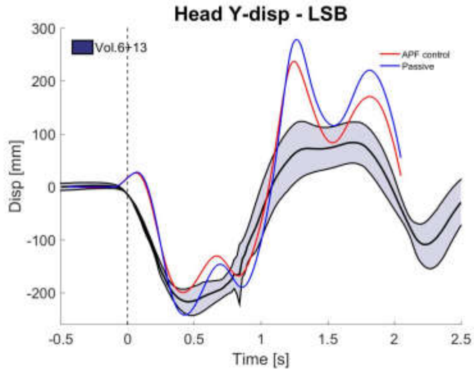


Figure 4. Head lateral displacement during lane change event with standard belt compared to two volunteers.

Experimentally derived dynamic spatial tuning patterns for neck muscles (from Step 2) was used in this project as direct input into the SAFER A-HBM to define load sharing between individual muscles, as described above. However, it remained unclear if load sharing defined from experimental perturbations were representative for other load cases. Therefore, four volunteers were tested in the same experimental conditions (the UBC Clinical Research Ethics Board approved the study); seated on a sled-mounted car seat that was accelerated in eight directions (0°, ± 45°, ± 90°, ± 135°, 180°). An acceleration level of 0.55 g (net $\Delta v = 4.0$ m/s, $\Delta t = 0.7$ s) was chosen to simulate possible pre-crash vehicle manoeuvres. The pre-crash like pulse evoked higher reflex activity compared to the perturbation pulse for most muscles. The activation levels were, however, often within the interquartile range of the levels from perturbations. Similar median spatial tuning was induced by both acceleration pulses. Hence, it was concluded that the dynamic spatial tuning patterns used for model input were appropriate.

In parallel to the model development and validation, an extensive experimental volunteer study was conducted in 2016 to provide data for tuning and validation of the A-HBM (approved by Ethical Review Board at the University of Göteborg). A Volvo V60 was extensively instrumented, see Figures 5 and 6. A steering and braking robot was used to ensure automated and repeatable avoidance manoeuvres. For the recording of muscle activations and motions the volunteers were instrumented with 19 pairs of electromyography (EMG) and exterior video markers. In total, 25 volunteers were subjected to braking, lane changes, combined braking and lane change, and U-turns; in driver and front passenger position, respectively, using two different types of seat belt designs. Altogether, 18 different combinations were repeated three times for each volunteer. An example of passenger kinematics during lane change without braking event is illustrated in Figure 7. Data was generated on muscle activity, vehicle data (including occupant interacting loads) and 3-D kinematics. The extensive data is still being processed and analysed with the purpose of creating corridors for kinematics, muscle data and interacting loads to be used for model tuning and validation. Two draft papers, presenting a complete set of the male passenger data for lane change and lane change with braking, will be submitted in April 2018.

Figure 5. The test vehicle used for the volunteer study, and a volunteer prepared for test.

Figure 6. Interior view of the front passenger seat position in the test vehicle.

Figure 7. Video data from one male volunteer in a lane change without braking manoeuvre, front view (top row) and lateral view (bottom row) for time= 0, 0.5s, 1s, 1.5s and 2s (left to right).

The model was adapted for industrial applications and is used at Autoliv and Volvo Cars, where studies on braking followed by frontal impacts have been in focus so far. Studies include, among other, evaluation of braking pulse and vehicle speed (Östmann and Jakobsson, 2016), variation of force levels for electrical reversible seatbelt pretensioners (pre-pretensioner) while braking prior to crash (Saito et al, 2016) and the differences when including seat belt slack (Pipkorn and Wass, 2017).

The SAFER HBM is sensitive to the speed reduction due to pre-braking as shown in Figure 8, comparing with and without pre-braking prior to a frontal impact. In addition to the differences in the kinematic responses, some differences were observed for the occupant responses for injury risk evaluations.

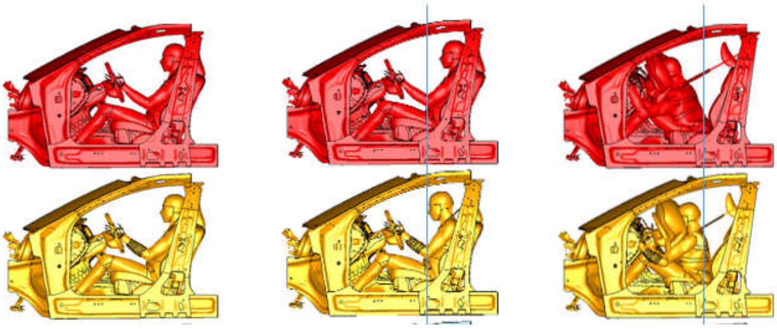


Figure 8. Influence of pre-braking on kinematical response; no pre-braking (top) and pre-braking 2s prior to crash (bottom), reducing impact speed from 64km/h to 56.5km/h. (Östmann and Jakobsson, 2016)

Figures 9 and 10 provide some additional examples of published results using the SAFER HBM in an emergency braking followed by a frontal impact. The effect of pre-pretensioning on occupant kinematics and chest deflection is shown. It is also shown that the pre-pretensioner is more efficient when there is an initial slack in the seatbelt. Initial seatbelt slack is very likely in real world situations, due to clothing such as thick coats, although never included in standardized crash test methods.

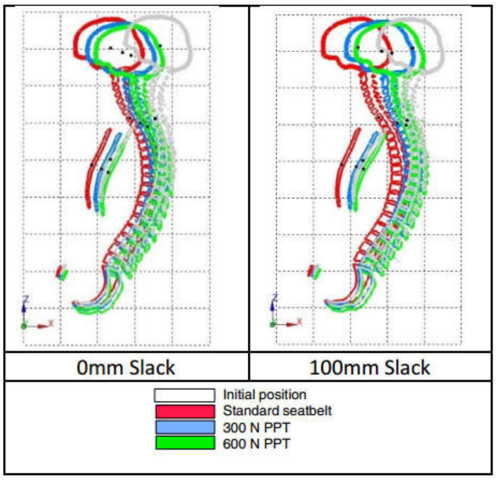


Figure 9. Initial position and position at crash after 1sec pre-brake, comparing standard seatbelt to two levels of pre-pretensioning, and the effect of initial seat belt slack (Pipkorn and Wass, 2017).

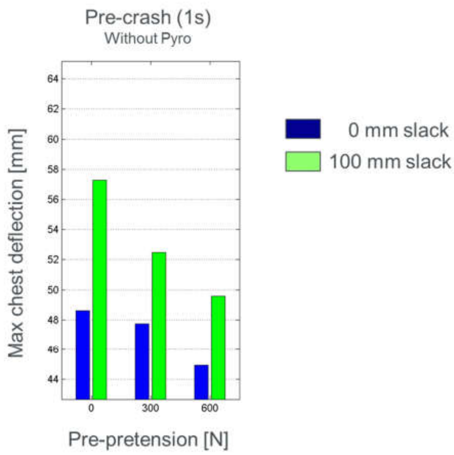


Figure 10. Chest deflection for different pre-pretensioning during braking, comparing with and without seat belt slack (Pipkorn and Wass, 2017).

Future studies will include presence of lateral manoeuvres and a combination of steering and braking in advance to a crash, thanks to the enhancements of the A-HBM during the project. In addition, the SAFER HBM v9.0 will be used in an extended set of crash directions preceded by a variety of pre-crash manoeuvres. The model provides the industry partners with a unique tool for integrated safety system developments.

Contribution to the objectives of the FFI program

The results of this project has provided knowledge and outreach, in addition to increasing international awareness and helped to strengthen Sweden as a hub in vehicle safety. By this, the results of this project have contributed to the goal of the Vision Zero of reducing fatalities and injuries in traffic as well as increasing Swedish vehicle industrial competitiveness.

The overall goal is to develop a biofidelic HBM that can predict occupant responses during any sequence of events. The successful integration of omnidirectional muscle recruitment capability within this project has contributed significantly to this goal. The significant enhancement of the unique tool during this project is an enabler to further add steering functionality, which is an important step towards full implementation. Predicting occupant kinematics in evasive steering manoeuvres as well as braking is essential for the industrial partners to develop safety systems that help reduce the number of deaths and serious injuries in car crashes. A human model that can predict occupant kinematics in dynamic events preceding a crash is of highest importance when moving towards higher degree of automation, and integrated safety technologies are as important as restraint systems for occupant protection.

The SAFER HBM v9.0 is unique in its capability of seamlessly predicting human motion in a pre-crash manoeuvre prior to a crash. The project has significantly contributed to the continued competitiveness of the automotive industry in Sweden. This tool is only available for the Swedish partners in the project. 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 research developed through the project has created high academic acknowledgement and attracted international collaborations, hence also contributed to increased Swedish academic competitiveness. Directly following the finalization of the project two Horizon 2020 projects were granted, in which Chalmers is one of the largest contributors. The state-of-the-art research on active HBMs and volunteer tests served as an important base, and the partners' collaboration will be further boosted working together in these international context.

The combination of partners, including a vehicle manufacturer, a safety system supplier, and the academia comprise a strong combination. The project combined the activities of two PhD students. The project design facilitated prompt feedback into the vehicle industry, involving the main actors of vehicle safety design in Sweden. Although small in size in an international perspective, the project has been very successful both in quick and state-of-the art research findings as well as leading the discussions making an impact on the global agenda.

The project has contributed to strengthening the collaboration between the automotive industry and government agencies, universities, colleges and research institutes. 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. HBM is one of the core areas within SAFER and is interacting with several other projects, nationally as well as internationally.

Internationally, Sweden is respected as a nation with great knowledge, experience and development in vehicle safety. This project has helped to maintain and develop the competence for the partners in the project leading the way for occupant protection aspect in the growing vehicle automatization developments. The project is a role model in terms of contributing to and benefiting from the SAFER research environment. The project's context and network are essential aspects, both when addressing reduction of fatalities and injuries in traffic as well as increasing Swedish vehicle industrial competitiveness.

7. Dissemination and publications

7.1 Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	x	Substantial publication, presentation and sharing with peer-researchers internationally
Be passed on to other advanced technological development projects	x	Project results are used in in house projects at Volvo Cars and Autoliv
Be passed on to product development projects	x	Project results are used in in house projects at Volvo Cars and Autoliv
Introduced on the market		N/A
Used in investigations / regulatory / licensing / political decisions		Maybe in a future step

In addition to the publications and conference presentations listed in Chapter 7.2, some important international exchanges and disseminations have been part of the project, exemplified by:

- International exchange within project:
    - Cooperation agreement between Chalmers and Kompetenzzentrum – Das virtuelle Fahrzeug, Forschungsgesellschaft mbH (Austria) on data exchange.
    - Cooperation on volunteer test series with MEA Forensic Engineers & Scientists and University of British Columbia, Vancouver, Canada, during spring 2016.
    - Continuous interaction with TUC (THUMS User Consortium), through Autoliv
    - Interaction with the GHBMC (Global Human Body Model Consortium), through Autoliv and Chalmers.

- Project results have been presented at:
  - Master courses at Chalmers (TME201 Vehicle and traffic safety, TME196 Impact biomechanics)
  - International Course on Transportation Planning and Safety, TRIPP, IIT Delhi, India on yearly basis, early December.
  - FFI-konference: ”Hur kan forskningsresultat från fordonsindustrin bidra till Agenda 2030”, 23 November, 2017, Stockholm

Additionally, the project results are to be used as parts in several projects:

- A-HBM step IV (FFI application)
- ViVA II (ongoing Vinnova project Dnr. 2016-03353)
- OSCCAR (EU project within Horizon 2020 MG.3.2)
- VIRTUAL (EU project within Horizon 2020 MG.3.2)

7.2 Publications and conference presentations

The project has resulted in a total of one Doctoral Thesis, three Master Theses, six published peer-reviewed articles (+5 in preparation/submission), three conference publications, and additionally eight presentations (without publications) at international technical conferences, seminars or workshops; as listed below:

Academic theses and student work

Ólafsdóttir JM (2017). **Muscle Responses in Dynamic Events. Volunteer experiments and numerical modelling for the advancement of human body models for vehicle safety assessment**. *Doctoral thesis*, Serie 3668, Department of Mechanics and Maritime Sciences, Chalmers University of Technology. ISBN/ISSN: 978-91-7597-594-8 [Nr. 249498]

Eliasson E, Wass J (2015). **Industrialisation of a Finite Element active Human Body Model for vehicle crash simulations**. *Master thesis* 2015:52, Department of Applied Mechanics, Chalmers University of Technology, Göteborg, Sweden 2015:52. [CPL. 218339]

Ivančić A, Pradhan V (2017). **The influence of isometrically derived neck muscle spatial tuning patterns on head response in dynamic conditions**. *Master thesis* 2017:72, Department of Applied Mechanics, Chalmers University of Technology. [Nr. 250523]

Xiao Yang (2017). **Biofidelity assessment of the active human body model compared to volunteer braking and steering maneuvers**. *Master thesis* 2017:86, Department of Applied Mechanics, Chalmers University of Technology. [Nr. 253962]

Pradhan V (2017). **Optimization of recruitment patterns of individual neck muscles in an isometric setup and their influence on the head and neck kinematics for a dynamic load case.** *Internal technical report from summer project.* Department of Mechanics and Maritime Sciences, Chalmers University of Technology.

Peer-reviewed publications:

Ólafsdóttir JM.,Brolin K, Blouin J-S, Siegmund GP (2015). **Dynamic spatial tuning of cervical muscle reflexes to multidirectional seated perturbations**. *Spine*. 40(4): E211-E219. [Nr. 212915]

Östh J, Brolin K, Bråse D (2015). **A Human Body Model with active muscles for simulation of pre-tensioned restraints in autonomous braking interventions**. *Traffic Injury Prevention*. 16 (3) s. 304-313. [Nr. 201718]

Saito H, Matsushita T, Pipkorn B, Boström O (2016). **Evaluation of frontal impact restraint system in integrated safety scenario using Human Body Model with PID controlled active muscles**, Paper no: IRC-16-35, *Ircobi Conference*, Malaga, Spain.

Östmann M, Jakobsson L (2016). **An examination of pre-crash braking influence on occupant crash response using an active Human Body Model**. Paper no: IRC-16-37, *Ircobi Conference*, Malaga, Spain.

Ólafsdóttir JM, Fice JB, Mang DWH, Brolin K, Davidsson J, Blouin J-S, Siegmund GP (2016). **Neck muscle activation patterns in dynamic conditions**. *Traffic Injury Prevention*, 17(S1):219-221. [Nr. 243720]

Cutcliffe H, Olafsdottir J, Östh J, Davidsson J, Brolin K (2017). **Gender differences in Occupant Posture during Driving and Riding**. Paper no: IRC-17-12, *Ircobi Conference*, Antwerp, Belgium [Nr. 252245]

Conference publications/presentations

Östh J, Brolin K, Davidsson J, Pipkorn B, Jakobsson L, Törnvall F, Lindkvist M (2015) **Muscle activation strategies in Human Body Models for the development of integrated safety**. *The 24th ESV Conference Proceedings*, Paper No. 15-0345, Gothenburg, Sweden.

Cutcliffe H, Brolin K, Östh J, Ólafsdóttir J, Davidsson J (2015). **Gender differences in occupant posture and muscle activity with motorized seat belts**. *The 24th ESV Conference Proceedings*, Paper No. 15-0384, Gothenburg, Sweden. [Nr. 220924]

Pipkorn B, Wass J (2017). **Pre-crash triggered pretensioning of the seat belt for improved safety**. *The 25th ESV Conference Proceedings*, Paper no: 17-0104, Detroit, USA.

Other presentations

Ólafsdóttir, JM (2015). **Modeling muscle recruitment in Human Body Models**. *TRIPP Young Researcher Symposium*. New Delhi, India.

Östh J (2016). **Status of the SAFER Active HBM and AHBM validation wrt experimental data.** TUG AHBM workshop, March

Östmann M, Jakobsson L (2016). **An examination of pre-crash braking influence on occupant crash response using an Active Human Body Model.** *Human Model Symposium. 6th International Symposium on Human Modeling and Simulation in Automotive Engineering*, Heidelberg, Germany, October 20-21.

Brolin K, Ólafsdóttir JM, Iraeus J, Östh J, Davidsson J (2016). **Towards omni-directional active human body models.** *6th International Symposium on Human Modeling and Simulation in Automotive Engineering,* Heidelberg, Germany, October 20-21. [Nr. 247604]

Ólafsdóttir JM, Fice JB, Mang DWH, Brolin K, Davidsson J, Blouin J-S, Siegmund GP (2016). **Neck muscle activation patterns in dynamic conditions**, *Poster presentation at AAAM Conference* Waikoloa, HI, USA. (Published in *TIP* 17(S1), see Peer-reviewed publications)

Ólafsdóttir JM, Brolin K, Siegmund GP (2016). **Neuromuscular control scheme for predicting omnidirectional head motions with a Finite Element Human Body Model**. *AAAM's Student Symposium*. Waikoloa, HI, USA.

Ólafsdóttir JM, Fice JB, Mang DWH, Brolin K, Davidsson J, Blouin J-S, Siegmund GP (2017). **Trunk muscle recruitment patterns in simulated pre-crash events**. *AAAM 61st Annual Scientific Conference*, Las Vegas, USA, Oct 14-18. (in Press for TIP)

Iraeus J, Davidsson J, Brolin K (2017). **Recent HBM activities at Chalmers University**. Presentation at Conference: *Human Body Modelling in Automotive Safety*, Berlin, Germany, November 28-29.

Abstracts or manuscripts submitted or in preparation

Ólafsdóttir JM, Fice JB, Mang DWH, Brolin K, Davidsson J, Blouin J-S, Siegmund GP (2017). **Trunk muscle recruitment patterns in simulated pre-crash events**. *In Press for TIP.*

Ólafsdóttir, JM, Östh, J, Brolin, K (2017). **Modelling reflex recruitment of neck muscles in a finite element human body model for predicting omnidirectional head kinematics**. *Submitted for journal publication.*

Brolin K, Eliason E, Ólafsdóttir JM, Iraeus J, Davidsson J (2018). **Comparison of an active human body model to volunteers in emergency steering and braking events.** *In preparation for IRCOBI Conf, Sept.*

TBD et al. **Passenger kinematics in autonomous lane change and lane change with braking manoeuvres using standard and reversible pre-tensioned belts.** *In preparation for IRCOBI Conf, Sept.*

Ghaffari G, Brolin K, Bråse D, Pipkorn B, Svanberg B, Jakobsson L, Davidsson J. **Passenger muscle responses in autonomous lane change and lane change with braking manoeuvres using standard and reversible pre-tensioned belts**. *In preparation for Journal submission*

8. Conclusions and future research

The enhanced Active Human Body Model developed in this project is capable of predicting human kinematics during an evasive manoeuvre followed by a crash. Specifically, it is designed/capable of predicting humans in vehicle avoidance manoeuvres, in addition to autonomous and voluntary braking situations. During this project, the Active HBM was further enhanced with respect to muscle model design enabling horizontal-plane omnidirectional kinematics in addition to becoming a seamless tool simulating pre-crash manoeuvres in addition to crash evaluations.

Muscle model developments include three-dimensional muscle modelling capable of simulating muscle response to any load direction in the horizontal plane. In the prior generation model, one-dimensional Hill type muscles were used in conjunction with a closed loop control system to model human response. With the inclusions of reactions to longitudinal as well as lateral stimuli for the cervical and lumbar spine, the omnidirectional needs could be addressed. Validation at this stage show promising results. Future developments of the model should include driver interaction with the steering wheel where the shoulder model needs to be improved regarding anatomical detail, specifically capturing the complex interaction of ligaments and muscles connecting the bones of the shoulder (clavicle, scapula and humerus). Future challenges encompass novel research on how car occupants use their muscles during driving, focusing on muscles in the arm and shoulder complex.

The project has taken initial steps in evaluating the enhanced model's capability of predicting human motion in vehicle avoidance manoeuvres, in addition to braking capabilities which was a result of the prior project. Initial validation efforts were made for a subset of male passengers in lane change manoeuvres with and without braking. Further validation of the active model should include more types of manoeuvres as well as occupant positions and groups. The extensive volunteer test series performed within the project provide a source of validation detail in several situations, including driver, passengers, male and females in a variety of manoeuvres.

During the project the model was integrated and implemented into industrial context. Several industrial application studies were performed with the model in a braking followed by frontal impact sequence. These studies provided evidence that it can be used for industrial purposes providing input on effect of active safety technologies as well as seat belt design and activation. Future studies should include steering manoeuvres preceding a crash, as well as crashes of more situations than frontal impacts.

The goal with the A-HBM is that the model can predict human kinematics in complex events such as run-off-road crashes and multiple events. Therefore, future developments need to include methodology enhancements for omnidirectional muscle control, adding vertical loading components, in addition to the model development mentioned above.

However challenging, as a natural future step more sizes and occupant characteristics should be included and evaluated, whereby a family of SAFER HBMs being representative for a larger population could be created and used in vehicle developments. Additionally, in a futuristic view, the Active Human Body Model can be coupled to a behaviour model to model anticipatory human motion.

9. Participating parties and contact persons

The project partners are Autoliv Research, Chalmers University of Technology and Volvo Cars, with the main participants throughout the project:

- **Bengt Pipkorn**; Autoliv Research
- **Johan Davidsson**, Chalmers
- **Karin Brolin**, Chalmers
- **Jóna Marin Ólafsdóttir**; Chalmers, PhD student
- **Ghazaleh Ghaffari**; Chalmers, PhD student
- **Merete Östmann,** Volvo Cars
- **Lotta Jakobsson**, Volvo Cars, project leader and contact person (lotta.jakobsson@volvocars.com; +46 766 210314)

In addition, the following researchers have contributed in parts of the project:

Autoliv

- **Dan Bråse**
- **Leila Jaber**
- **Jacob Wass** (external during part of the project)

Chalmers

- **Johan Iraeus**

Volvo Cars:

- **Linus Wågström**
- **Bo Svanberg**
- **Jonas Östh**

10. References

References in addition to the **project publications listed in Chapter 7.2**:

Arbogast K. et al., (2012). **The effect of pretensioning and age on torso rollout in restrained human volunteers in far-side lateral and oblique loading**. *Stapp Car Crash Journal*, Vol. 56, pp. 443-467.

Huber P. et al., (2015). **Passenger kinematics in braking lane change and oblique driving maneuvers.** *Proceedings of the IRCOBI conference*, Lyon, France, pp. 783-802

Ólafsdóttir et al., (2013). **Passenger kinematics and muscle responses in autonomous braking events with standard and reversible pretensioned restraints**. *Proceedings of the IRCOBI Conference*; Gothenburg, Sweden, pp. 602-617