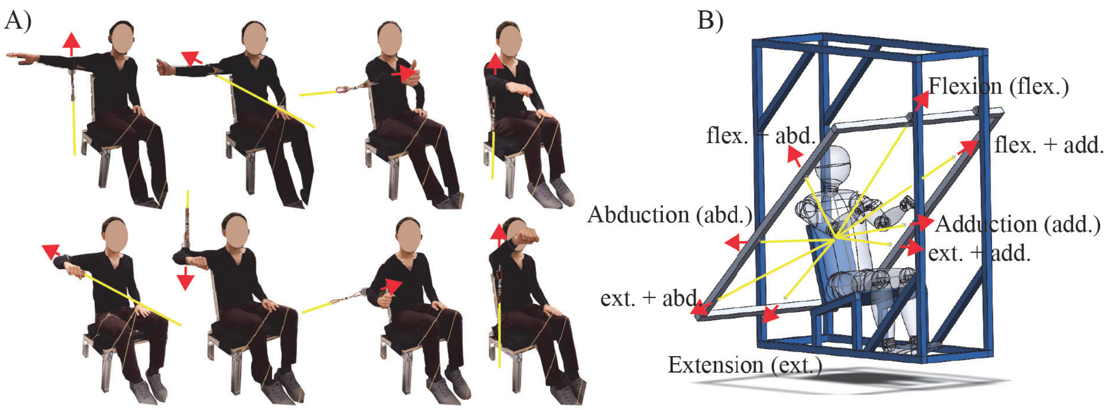
Active human body models for virtual occupant response, step 4

Aktiv humanmodell för prediktering av mänsklig rörelse, steg 4

Publik rapport



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Datum: 2022-01-31

Projekt inom Trafiksäkerhet och automatiserade fordon

FFI Fordonsstrategisk Forskning och Innovation

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1 Summary

Human body models (HBMs) are essential for simulation of pre-crash and in-crash occupant response for development of advanced restraint systems that reduce risk of injuries in crashes. In pre-crash, when vehicle accelerations are relatively low, muscle activation will influence the occupant response. Hence, there is a need to simulate these scenarios in HBMs for humanlike occupant response.

Based on the overall objective, predicting the occupant response through the whole sequence of pre- and in-crash events; the aim of this project was to 1) enhance the muscle controller systems in the SAFER HBM and 2) prepare it for human-like response when subjected to vertical loading. Previous research projects, carried out by the project partners, have implemented muscles and muscle control systems in an HBM and tuned and evaluated the model for sagittal plane while this project aimed at 3) tuning and evaluating the model in oblique and lateral loadings. Finally, the project aimed at 4) an integration of the model into industrial applications for product development.

This project has enhanced the modelling methodology in events with oblique and lateral loading components. Additionally, the project has prepared the model to also reproduce the response of humans in the driver seat. It has also applied the enhanced model to study complex long-duration crash scenarios, like run-off-road crash events. The project combines fundamental research on how to simulate the active muscle response in a biofidelic manner with industrial application.

Significant efforts have been made on developing the muscle activation controllers in the shoulder region of the SAFER HBM. In collaboration with other research projects, updated passive properties were implemented, a crucial foundation for further enhancement of the active response. In order to provide data for model tuning as well as validation, experimental tests were conducted in a controlled laboratory environment. The results generated in these tests were then analyzed and data was directly implemented in the finite element HBM. Late in the project, in-car volunteer tests were performed to further study how car occupants react when subjected to vertical and roll loads similar to those that can be seen in initiation to run-off road crashes.

To take the next step towards reaching the overall objective, further research is suggested related to improvement of the HBM head controller for increased confidence when predicting head rotations. Furthermore, developments on expanded application areas related to sitting postures such as upright, forward-leaning and reclined postures (and including the transfer between them) are also suggested to be explored. An additional field of improvement identified is to expand the model for addressing population variability, by modelling the average female in addition to average male.

2 Sammanfattning på svenska

Humanmodeller är viktiga för att simulera rörelser hos fordonspassagerare vid utveckling av avancerade skyddssystem som syftar till att reducera personskador som kan uppkomma vid olyckor. I situationer med låga accelerationsnivåer såsom bromsning, styrning och avkörningssituationer, finns ett behov att simulera muskelaktivering och muskelkraft för att kunna återskapa ett människolikt rörelsemönster.

Baserat på det övergripande målet att utvärdera åkandeskydd genom en hel sekvens, är målsättningen med detta forskningsprojekt att utveckla metoder för att förbättra de aktiva egenskaperna hos humanmodellen SAFER HBM och förbereda den för vertikala rörelser. I tidigare forskningsprojekt har projektpartnerna implementerat muskelaktivering i humanmodellen för rörelser i sagittalplanet (bromsning) samt sneda och laterala rörelser. Under hela projektet har validering av modellen och en kontinuerlig tillämpning i industriella problemställningar varit i fokus för projektgruppen.

Detta projekt tar utvecklingen av modellen ett steg vidare genom att applicera metoden för muskelkontroll även för situationer med vertikala rörelser. Modellen kommer även att användas för att studera komplexa krocksituationer med lång duration, tex avkörning och multipla event. Projektet kombinerar grundforskning om hur man simulerar muskelrespons på ett människolikt sätt med industritillämpning för framtida produktutveckling.

De matematiska reglerfunktionerna för muskelaktivering i axelområdet på SAFER HBM har utvecklats i projektet. I samarbete med andra forskningsprojekt har uppdaterade krockegenskaper utan muskelaktivering implementerats och dessa utgör grundläggande parametrar för att ytterligare förbättra den aktiva responsen i modellen i linje med vad som kan förväntas hos verkliga åkande. För att tillhandahålla data för modell-justering såväl som -validering genomfördes volontärprover i en kontrollerad laboratoriemiljö. Resultaten från dessa prover implementerades i SAFER HBM och i ett senare skede genomfördes volontärprov i bil på provbana för att ytterligare studera hur bilpassagerare reagerar när de utsätts för vertikala fordonsrörelser liknande dem som kan ses i början av avåkningsolyckor.

För att ta nästa steg mot att nå det övergripande målet föreslås ytterligare forskning relaterad till förbättring av reglerfunktionen för huvudets rörelse för ökad konfidens vad gäller att förutsäga huvudrotationer. Utökade applikationsområden relaterade till sittställningar som upprätt, framåt- och bakåtlutande ställningar (inklusive förflyttning mellan dem) föreslås utforskas. Ett ytterligare förbättringsområde är att möjliggöra utvärdering av populationen av åkande i bil. Ett första steg är att modellera en genomsnittlig kvinnlig åkande utöver den befintliga modellen av en genomsnittlig man.

3 Background

Striving for zero injuries in crashes with passenger vehicles today involves not only studies of the crash itself but includes an integrated study of the pre-crash and in-crash phases. Examples of technologies developed with the target to reduce the risk or severity of a crash in this field are autonomous braking systems and steering systems that assist the driver in an increasing variety of pre-crash situations. Human Body Models (HBMs) have become valuable virtual tools to simulate occupant responses in these situations. The models have the potential to predict the injury risk on a detailed level and for several body regions/organs, compared to crash test dummies. Crash test dummies are typically developed for single loading directions and representative of some few sizes only, such as average male. While HBMs can have biofidelic sensitivity to different loading directions and a range in g-levels, and can more easily represent different occupant sizes, sex, and anthropometry. In addition, HBMs have the potential to simulate the occupant response in pre-crash and emergency events with muscle controller implemented in the models. These HBMs are often referred to as active HBMs (A-HBMs). Therefore, the ultimate goal for the “Active-HBM projects” is to develop a biofidelic HBM that can predict occupant responses during sequences of events such as combined emergency and impact events, road departure events, and other long duration crash events, and that can predict driver actions such as steering and braking.

In three previous projects (Active human body models for virtual occupant response, Step 1, Step 2 and Step 3), the partners in the project have executed state-of-the-art research on and development of active HBMs. The research performed in Steps 1-3 is world leading and the SAFER HBM is unique, providing a seamless implementation of A-HBM. This fourth step in the series of research collaborations for development of active HBMs build on the foundation that was laid by the previous projects.

4 Purpose, research questions and method

The purpose of the project was to further develop the SAFER HBM for loads in the horizontal plane and expand the usage area into vertical accelerations as seen in initiations to run-off-road crashes.

During the project, the following research questions were addressed:

- How do shoulder muscles of volunteers respond to local loading of the elbow?
- What is the elbow excursion in these volunteer tests?
- Is there a specific muscle recruitment pattern associated with the loading of the elbow?
- How do volunteers respond to in-vehicle motions including vertical and roll components?
- How can the SAFER HBM shoulder region be improved in order to expand its field of use?

Methods include finite element modelling of the human body, development of muscle controllers, collecting kinematics, electromyography (EMG) and instrument data in volunteer testing and implementation of collected experimental data into the developed computer simulation model.

5 Objectives

An important aim of the finalized project was to further strengthen the cooperation between the Swedish automotive industry and universities within the field of integrated safety, thereby contributing to a common mission of eliminating fatal injuries on Swedish roads – towards Vision Zero. Specifically, this meant addressing the need for new methods and tools to develop safety systems that interact both before and during a car collision. Research activities was focused on virtual test tools and methods that can be used early in the development process of vehicle restraint systems to ensure robust concepts for production vehicles.

At start of the project, the SAFER HBM at that time was capable beyond what was anticipated at its start of development a decade earlier. Nevertheless, the need of improvements is constant and is driven by the safety system development calling for widening of its capabilities. Therefore, the aim of this project (A-HBM step 4) was to **validate the SAFER A-HBM for autonomous braking and steering events, collect additional volunteer data**, and to **further enhance the model development to incorporate biofidelic responses in emergency events with vertical components,** such as in road departure manoeuvres. Such a tool will be essential for the industry to develop future safety systems with an integrated safety approach. This project is a natural step to ensure that our national research on human body models for traffic safety remains internationally competitive and state-of-the-art.

The overall objective has not changed during the project. However, during the project it became apparent that the passive properties (i.e. without muscle activation) of the SAFER HBM needed to be adjusted before the muscle activation properties could be tuned and the modelling technique be further refined. Furthermore, it was identified that the reference coordinate system used for muscle activations control strategy needed to be updated to allow for large vehicle global rotations.

6 Results and deliverables

Emma Larsson completed a licentiate degree at Chalmers University of Technology in March 2021. One master thesis was carried out that contributing to the project results. In total, seven published scientific papers (+1 in preparation/submission), whereof two in peer-review journals (+1) and four peer-review conference contribution, in addition to another conference presentation, resulted from this project.

During the project the SAFER HBM v10 was launched, including the most recent developments in the parallel project on injury prediction capabilities (FFI Dnr 2018-04998) and the active muscle improvements resulting from this project. The A-HBM improvements in the model include:

- Updates to the reference HBM position that is used in order to be able to handle large vehicle rotations, such as during turning manoeuvres where the heading angle changes considerably during the simulation
- PID controller has been adjusted in order to avoid sign error (i.e. switching from positive to negative) in simulations where the HBM returns to the initial position

Project results are further described in the following sub-chapters.

6.1 Volunteer testing

Two volunteer test series were performed in the project. The first series included a custom-built indoor rig for studying shoulder muscle activation. The second aimed at as naturalistic driving conditions as possible and was performed with in instrumented car on a closed-off test track with special arrangements for simulating vehicle accelerations with vertical components. Both these test series were carried out later than originally planned due to COVID-19. The pandemic influenced the recruitment of volunteers and the work environment for test engineers and drivers.

Indoor rig test

In this study, we measured the shoulder muscle activity of volunteers while dynamically perturbing their upper arm at the elbow in eight directions perpendicular to the humerus, while volunteers were in a driving posture (Figure 1). The goal of the study was to build shoulder muscle dynamic spatial tuning patterns (STPs). Further, the kinematics of the arm were also measured during the perturbations. The spatial tuning data are valuable for the development of active shoulder muscle controllers and the kinematic data will be useful for the validation of the shoulder complex in HBMs. The improvements in shoulder muscle controllers enabled by the data collected will ultimately be used to design safer vehicles.

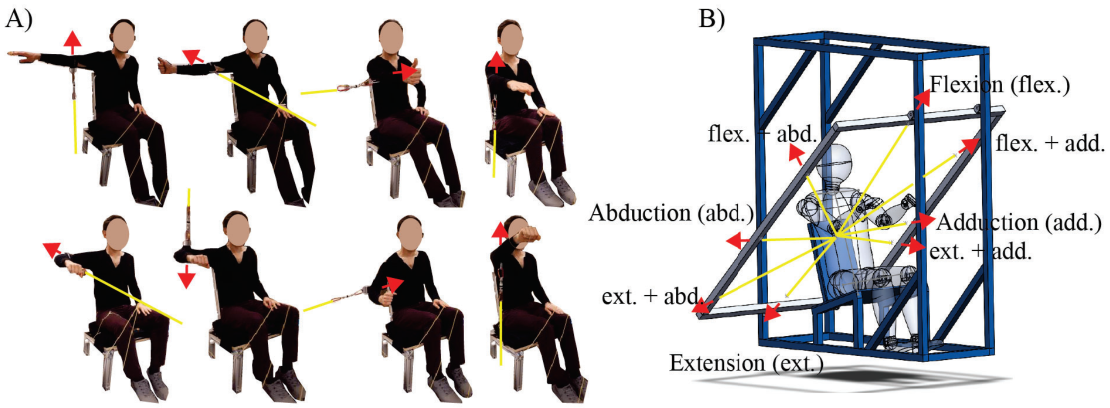

Figure 1. Overview of volunteer rig test setup

Eight male and nine female volunteers were included in the study. Subjects provided written informed consent prior to participating in the study, which was approved by the Swedish Ethical Review Authority. Before the experimental tasks, anthropometric measurements of the subjects were taken and then they were instrumented with surface electrodes, plus a ground electrode on the clavicle. Electrodes were placed with manual palpation and muscle activity was amplified and recorded using an EMG system with a bandpass filter and an additional notch filter for powerline noise.

The first task was to perform shoulder maximum voluntary isometric contractions (MVIC) which were later used to normalize the EMG recordings during the spatial tuning task. Subjects sat on a custom-built seat where their torso was restrained to the seat back with a seatbelt that ran under their arms across their chest. The maximum contractions were performed by pulling on a fixed rope which was attached via a cuff just above the elbow with two repeats; the order was randomized within each repetition. In addition to verbal encouragement, subjects also viewed real-time feedback of the loadcell force readings for motivation.

The second task was the dynamic spatial tunning task. Subjects were first fit to the rig by adjusting the amount of stiff foam on the seat to ensure that the subject's elbow was at a specific spot while their upper arm in a specific angle. The subject's right elbow was tightly strapped into a fixture that maintained their elbow angle and transferred the load from the ropes onto their upper arm. The load cell was now placed in series between the weight and the loading direction rope. In addition to the load cell and EMG, subjects were also fitted with markers that were tracked with cameras.
With instrumentation complete subjects were ready to be exposed to upper arm perturbations in eight directions in a plane perpendicular to their upper arm Subjects were exposed to three

repetitions of each direction, with the order randomized within each set of repetitions. The load was induced by dropping a weight and subjects were blind to the direction. Subjects were instructed that as soon as they felt the weight pull on their arm, they were to pull back in the opposite direction to return to the starting position as fast as they could and try to hold their arm at the starting position. Subjects were reminded of these instructions at least three times during the task.

Results showed that the spatial tunning curves recorded for both sexes were visually confirmed to be unimodal and directionally dependent activity was generally seen for each of the muscles. Due to differences in injury rates between males and females, the data is analysed separately for each sex. All of the muscles studied exhibited some activity in the direction opposite from the preferred activation directions, and this activity is likely co-contraction or antagonist activity. The relatively small standard deviation area for the STPs suggests a consistent recruitment strategy of the muscles across subjects. The STPs for males and females were roughly aligned for most muscles, although differences in the preferred activation directions between males and females were found. For both males and females, the mean trajectory of the elbow point generally followed the loading vector initially, but the path returning to the start point generally deviated from this vector. Females generally exhibited more variability in their peak displacements.

In conclusion, this study showed shoulder muscle activity that varied with loading directions and the spatial tuning patterns developed can be used to determine intermuscular load sharing in feedback controller active human body models. This data is available for males and females, while it remains to be seen if the generally small differences noted in this work justify sex-specific modelling approaches in the shoulder. This study has been summarised and published in an international peer-review journal (Fice et al., 2021, Chapter 7.2).

In-car tests

The main goal of this study was to provide data to enable evaluations of active HBMs in scenarios where a vehicle runs off the road. To reach this goal, volunteers were seated as front seat passengers in a car that was driven over ramps designed so that the resulting vehicle kinematics resembled those in typical run off road accidents. Data was collected for two scenarios: ‘initiation of a roll accident’ at 75 km/h and vehicle ‘driving across a ditch’ at 50 km/h. All tests were carried out at Asta Zero proving ground on closed-off test tracks. Subjects provided written informed consent prior to participating in the study which was approved by the Ethical Review Board “Etikprövningsmyndigheten” in Sweden, application 2019-06486.

The test vehicle was a 2018 Volvo XC90. Although the car was fitted with seatbelt systems with electrically reversible retractors (ERR), the passenger seatbelt was replaced with an active seatbelt that allows for reversible pre-tension via a separate control system and power source. The belt installed was used both with and without activation of the pre-tensioner. Belt forces and pay-out, in addition to vehicle kinematics were recorded. A ramp designed to simulate ‘initiation of a roll accident’ was produced in concrete, with a maximum height of 260 mm. The ramp was placed on a paved and straight stretch of a typical country road (typical speed limit for the type of road would be 80 km/h). To simulate ‘driving across a ditch’, a wide ditch was dug in a dirt road. The ditch was asymmetric; when descending into the ditch, the car drove on a surface that dropped 260 mm in 1600 mm while when ascending the slope was diminutive.

Volunteer motion capturing was made with three cameras: a front view camera, a side view camera and a rear oblique camera. Data from the cameras were analysed to determine volunteer head and upper torso kinematics. The data analysis was facilitated by performing lens calibrations, establishing joint coordinate systems in all three views and mounting spherical film markers on the volunteers (Figure 2). Anthropometric measurements of the volunteers were recorded to facilitate the above-mentioned analysis.

Figure 2. Photos of a representative female volunteer (stature 172 cm) with film markers affixed to the body prior to testing. Left: Volunteer with typical lap belt and diagonal belt routing. Right: Photo taken from the front of the car and with the camera at the height of the volunteer eyes. Note windscreen masking to reduce the likelyhood that the volunteer noted the ramps prior to driving on these ramps.

Sixteen volunteers, ten males and six females, were tested and each volunteer participated in 12 tests: three ‘initiation of a roll accident’ and three ‘driving over a ditch’ with a belt without activation of pre-tensioning. The same number and distribution of tests where undertaken when the belt was activated just before the event started. These tests were carried out in semi randomised order. The volunteers were interviewed after each test to assess the awareness of the pending test and if the test was by any means uncomfortable.

A preliminary finding was that simulating ‘initiation of a roll accident’ using a car, without jeopardizing the safety of the volunteer, test driver and test engineer, was challenging. The time window available for vehicle roll is rather limited and the resulting vehicle kinematics in these events were complex. Simulating ‘driving over a ditch' was less challenging; the recorded vehicle accelerations were less complex in these events. Head and torso kinematics vary between volunteers. While a few volunteers keep their head relative to torso position and their posture change is mainly due to some rotations of the trunk relative the seat, others were more flexible, with respect to their heads’ movement relative their torsos. Further and detailed occupant kinematics analysis will reveal if there were also differences in how the trunk moved relative to the seat.

Within the project, the tests were successfully executed and the data was collected. Due to the delay caused by the covid-19 restrictions, the data analysis will mainly take part within the ongoing fifth step of the “Active- HBM projects”. The data will result in validation data, as well as scientific papers, and will be used to develop and refine the active SAFER HBM. It will be available for males and females.

6.2 SAFER HBM model development

The development of the SAFER HBM within this project was successfully summarized and presented in a licentiate thesis (Larsson, 2021, Chapter 7.2). Two major areas of improvement were addressed, enhancing neck and lumbar muscle controllers and developing a method for controlling shoulder muscles.

The aim of the first paper (Larsson et al. 2019, Chapter 7.2) was to enhance the active neck and lumbar muscle controllers of the SAFER HBM v9 and compare the occupant kinematic predictions to volunteers in braking, lane change and combined manoeuvres. Enhancements were made to the neck and lumbar controllers implemented in the SAFER HBM v9, where one controller was implemented to emulate reflexes from the vestibular system, i.e., angular position feedback (APF), and one to emulate the stretch reflex in muscle spindles, i.e., muscle length feedback (MLF). Enhancements were made to the APF part of the control system, where updates were made to the reference coordinate system in which the reference posture is determined. Three different reference coordinate systems were implemented in the HBM, and model performance was evaluated for the three different reference coordinate systems.

Whereas the original implementation aimed at maintaining the posture in the global reference system, the enhanced models aimed at maintaining a set posture in either 1) a completely local reference system, 2) the vehicle coordinate system, or 3) the gravity field but rotating with the HBM around gravity direction.

The three different APF controllers were evaluated in a combined lane change and braking load case. One of the APF configurations was compared to volunteers in braking, lane change, and combined lane change and braking. All three directions were evaluated using two different seatbelt configurations: a regular seatbelt and a belt with an electrical pre-pretensioner, yielding a total of six load cases. The kinematic predictions and muscle activation signals were objectively evaluated using CORA. The kinematic CORA results ranged from 0.78 to 0.88 for the active models and 0.70 to 0.82 for the passive configuration. It was concluded from the study that the **active muscles improve the predictions** compared to using the model in a passive configuration for some load cases, while for other load cases, only small differences were seen. The largest difference between active and passive models was seen in combined lane change and braking with a standard seatbelt. The best correlation to volunteers for the active model was seen in combined lane change and braking with pre-pretensioned seatbelt.

The objective of the second paper (Larsson et al. 2022, Chapter 7.2) was to develop a method of controlling shoulder muscles in HBMs, based on human physiological data, to be used to model drivers in horizontal-plane evasive manoeuvres. The aim of the study was to predict human-like elbow displacements when exposed to dynamic loading to the elbow. In the study, 179 beam elements were updated or added to the right shoulder of the SAFER HBM v10 and the controller strategy (Larsson et al., 2019, Chapter 7.2) was adapted to the shoulder. The muscles spanning the glenohumeral joint were controlled with angular position feedback (APF), with intermuscular load sharing based on directionally dependent muscle activation data from volunteer experiments. The muscles spanning the scapulothoracic joint were controlled using muscle length feedback (MLF). The model was evaluated by simulating a volunteer experiment in which a dynamic load was applied to the elbow in eight directions using a weight drop. Peak elbow displacement, time to peak elbow displacement, and detailed elbow kinematics of the model were compared to results from the volunteer experiments. A sensitivity study was performed to show the effect of varying the gains of the APF controller.

It was found that the active controller reduced peak elbow displacement for all directions, and for two of the gain combinations, **the model was capable of producing peak displacements within**

one standard deviation of the volunteers, in all eight directions, with a time to peak within one standard deviation in four of the directions. The successful prediction of peak elbow displacement showed that the controller is ready to be implemented and evaluated in full-body driver simulations.

6.3 Industrial applications

During the project, the enhanced developed SAFER HBM has continuously been integrated as a tool for industrial product development. This is important both in a short and a long-term perspective. In the short-term perspective, by making sure that the tools are ready to run ("plug and play") the threshold for using the SAFER HBM is kept low and the acceptance for the tools is ensured already while the project is ongoing. In a long-term perspective, feedback from industrial partners is crucial in order to ensure that any updates made to the SAFER HBM is made in a way that keeps the tool applicable, relevant and attractive for use by the engineering community.

A wide range of industrial applications were studied within the project. A new modelling approach was applied to include the effect of **thick clothing** for the SAFER HBM, replicating common real-world situations, see Figure 3. This approach, inspired by airbag modelling, was used to study the potential effect of seat belts equipped with ERR and their activation during the pre-crash phase. Starting by studying braking manoeuvres, followed by frontal impacts, it was shown that ERR seat belts efficiently can reduce pre-crash crash slack and simulations suggested that ERR can be used for improving the seat belt interaction at impact for car occupants wearing thick clothing. Similar studies were performed both at Autoliv and Volvo Cars to test robustness of the proposed methodology.

Figure 3. SAFER HBM wearing thick clothing highlighted in orange (seat belt and head restraint hidden for visualization)

A novel application to **side impacts** was made where the influence of active muscles and ERR pre-tension force level was studied for both two pre-crash scenarios: with pure braking (longitudinal acceleration) as well as scenarios with combined braking (longitudinal) and steering (lateral acceleration) accelerations. In this study, it was found that ERR was influential in pure longitudinal braking scenarios. When lateral pre-crash accelerations were present, the combination of seat belt forces and active muscles determined the occupant pre-crash crash excursion. By utilizing the seamless pre-crash/in-crash capability of the SAFER HBM, not only pre-crash excursion can be studied but also the effects of a following crash.

The usage domain for the current SAFER HBM was stretched by studies in **reclined seated positions**, see Figure 4**.** This served two purposes, studying preliminary interaction between occupants, seats and restraint systems as well as early identification of any numerical issues that may arise when expanding the model to occupant use cases beyond the situations where it has been validated for. Also, these simulations serve as to guide decisions for future studies aimed at collecting further tuning and validation data. In the current study, it was identified that the situations of more belt slack and no arm support increased activation of muscles in the lumbar region and suggested that this would be important when the application domain of the SAFER HBM is to be extended.

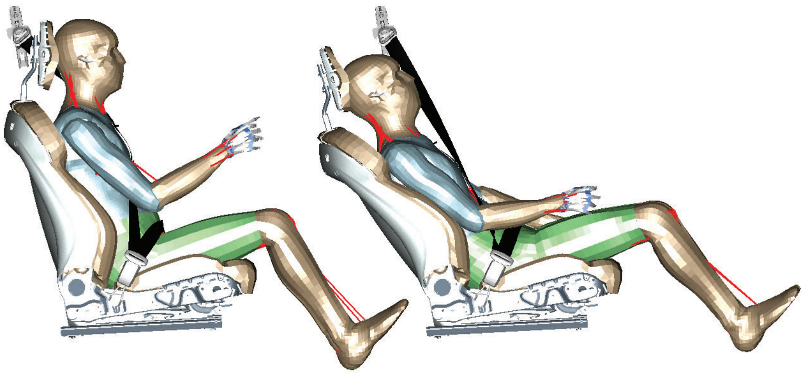

Figure 4. SAFER HBM in upright position and reclined position.

Additionally, the close collaboration between the industrial partners within the project enabled that significant steps could be taken to improve the **numerical performance**. Normally, a positive scaling effect when running finite element simulations on parallel processor is expected (i.e. when increasing the number of processors, the total time for running the simulation is expected to reduce). This was observed not to be the case with SAFER HBM v.9, but thanks to detailed analysis it was identified that the simulation time could be considerably reduced by modifying how internal contacts are defined and executed. For simulations without active muscle control, the muscle control algorithm was deactivated for the SAFER HBM v10, improving numerical scaling considerably. With these countermeasures, a positive scaling with the number of processors was restored.

6.4 Contribution to the objectives of the FFI program

On the overall level, the project contributes to the FFI objective of reducing the number of injured and fatalities in road crashes, enabling safe vehicle automation while strengthening the competitive position of Swedish automotive industry.

Reducing the number of injured and fatalities in road crashes requires a systemic approach, not only by joining forces between authorities, academia and vehicle manufacturers. In this mission, approaching road crashes in a sequential manner for which pre-crash factors are studied as factors influencing in-crash parameters, provides an important perspective on road safety. By combining these approaches, the project therefore **contributes to vision zero,** specifically by enabling to address run-off road crashes. The overall objective of the series of SAFER HBM research projects is to develop a biofidelic HBM that can predict occupant responses during any sequence of events. The successful implementation of improved muscle implementation and recruitment patterns in the shoulder area as well as volunteer data collection for vertical vehicle accelerations provide significant contributions to this vision. Predicting occupant kinematics in vehicle manoeuvres with vertical components is an important asset for the industrial partners when developing safety systems that help reduce the number of deaths and serious injuries in car crashes.

Furthermore, the project results contribute to the **safe vehicle automation in the Swedish transport system**, by preparing the automotive industry for future products with a higher degree of automated vehicle interventions. With a model like the SAFER HBM, effects of vehicle kinematic manoeuvres in terms of occupant pre-crash kinematics as well as subsequent crash response can be evaluated with the same tool. A prerequisite for further automatization is that the level of traffic safety is maintained or improved, and in many situations computer simulation is the most effective tool for approaching this task. In the strive for creating knowledge and **reinforcing Sweden as a leader within automotive safety**, as well as securing the competitiveness of the automotive industry in Sweden, the results of this project have provided knowledge and was successfully disseminated. In addition to increasing international awareness, this has helped to strengthen Sweden as a centre for vehicle safety.

Remaining a **unique tool**, the updated SAFER HBM has a capability of seamlessly predicting human motion in a pre-crash manoeuvre prior to a crash. The enhanced capability added during this project further reinforces this position when looking into automated driving solutions of the future, where integrated safety technologies are predicted to be as important as restraint systems for occupant in-crash protection.

Building on the preceding series of successful research projects, this project further strengthens collaboration between industry and academia. A strong collaboration team, of a vehicle manufacturer, a safety system supplier, a simulation software supplier and the academia, continues to be the core of all activities in the project. Without this, the challenges from the ongoing pandemic creating consequences in terms of delayed volunteer tests could not have been faced. From the university, both senior researchers and graduate students have been involved in project activities. During this process, experts in the integration of protection systems from Volvo Cars and experts in seat belt components from Autoliv were involved supplying graduate students with valuable feedback throughout the project. Additionally, being an associated SAFER project, the results have regularly been shared with other SAFER partners, which includes a number of relevant actors within industry, government agencies, society, universities and institutes.

In summary, the project has reached its objectives and successfully contributed to the FFI objectives by supplying state-of-the art vehicle safety development tools unique in its capability. With a strong project team, challenges were overcome and underlined the strength of joint forces between academia, industry and government.

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	Publications and sharing presentation 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		Possibly 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:
  - 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)

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

- I-HBM step IV (Vinnova project Dnr. 2018-04998)
- OSCCAR (EU project within Horizon 2020 MG.3.2)
- VIRTUAL (EU project within Horizon 2020 MG.3.2)

7.2 Publications and presentations

Theses

Larsson, Emma (2021). **Towards a Human Body Model Tor Prediction of Vehicle Occupant Kinematics in Omni-Directional Pre-Crash Events**. *Licentiate Thesis*. Department of Mechanics and Maritime Sciences, Chalmers University of Technology, Göteborg, Sweden

Lüke Marc (2019). **Evasive Pre-Crash Maneuver Influence on Occupant Crash Response using an Active Human Body Model**. *Master Thesis*. Hochschule Osnabrück, Germany

Publications

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8 Conclusions and future research

In this project, further steps have been taken to improve the unique tool SAFER HBM for seamlessly predicting human motion in pre-crash manoeuvres prior to a crash as well as studying the effects of subsequent crashes. In conclusion, the expanded usage domain of the model was based on the following model enhancement and validation efforts.

In terms of model enhancement, it was found that an HBM with active neck and lumbar musculature can predict passenger head and torso kinematics in horizontal-plane evasive manoeuvres while allowing for large vehicle rotations. It was also found that an HBM with an active shoulder muscle controller could successfully predict elbow peak displacement when subjected to dynamic loading to the elbow. In two series of experiments, valuable data for the future tuning and validation of the SAFER HBM were collected by using measurements on volunteers. Relating to model validation, the HBM with active muscles using a control strategy with a coordinate system that remained aligned with gravity gave a better correlation to the executed volunteer rig tests than the same model in a passive configuration for lane change with braking and standard seat belt.

During the course of the project, the following **areas for future research** for a further expanded usage domain of SAFER HBM were identified:

- Updating the rotational controller for improved head pre-crash position prediction
- Tuning and further validating the model
- Updating controller to handle repositioning from a reclined to upright postures
- Analysing collected volunteer data from in-car tests and create corridors for further model validation and extending model to handle vertical loading

The team of partners remained a strong entity throughout the project and the next project of the active part of the SAFER HBM is ongoing (step 5).

9 Participating parties and contact persons

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The project was started April 1st 2018 and ended December 31st 2021. The project was granted extension in order to finish the in-car volunteer tests (described in chapter 6.1) which were delayed due to covid-19 restrictions.