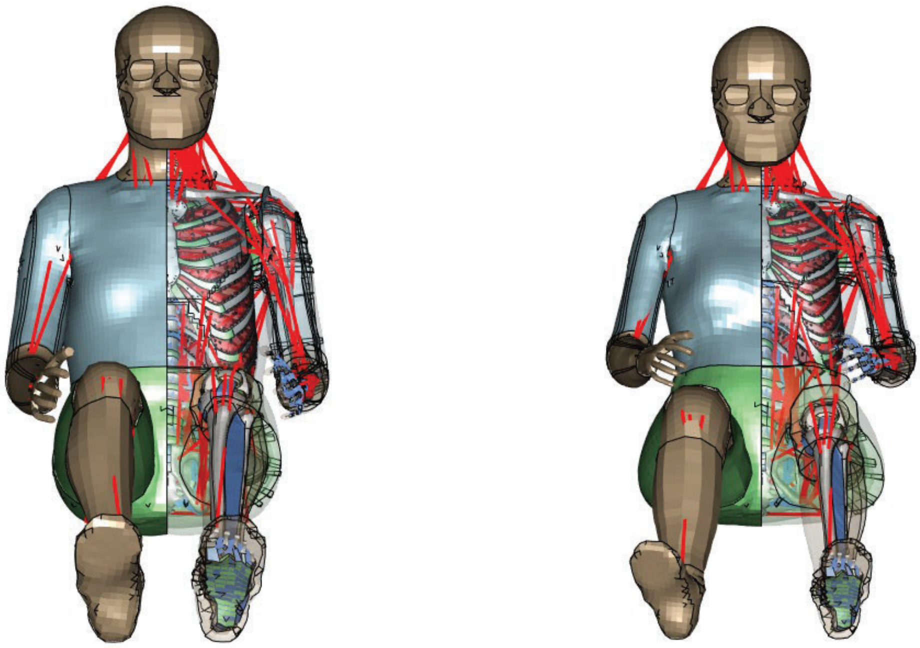
Active human body models for virtual occupant response, step 5 (A-HBM V)

Aktiv humanmodell för prediktering av mänsklig rörelse, steg 5 (A-HBM V)

Public report



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Content

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1 Summary

Human body models (HBM) are virtual tools for simulation of occupant responses in car crashes, capable of recreating injury mechanisms at a detailed level and predicting injury risks. With the addition of muscles and their active control, they have the ability to predict the occupant response in low-g events, such as evasive maneuvers, potentially preceding the crash. An HBM with this ability is called active HBM (A-HBM) and is an essential tool for safety system developments and assessments during whole sequences of events.

Starting in 2009, the project team was a pioneer of A-HBM development and has refined its functionalities in several projects. Since 2018, the A-HBM is an integrated part of the SAFER HBM, for which the active muscles can be turned on or off. As part of the overall objective of an HBM population that can predict occupant kinematics and injury risks, during the whole crash sequence with preceding maneuvers, and combined events, including occupant actions and repositioning; the purpose of this project was to further refine the active muscle control functions. Specifically, the current project has improved the active muscle control capability of the SAFER HBM and usefulness for vehicle and restraint system developments, by incorporating variability of occupant characteristics (sex) and sitting postures.

An advanced head controller was assessed and implemented, enabling a more humanlike prediction of the head kinematics, for which good-to-excellent biofidelity was seen in braking as well as in lane change. Effects of variations in seating were included by simulation studies and conducting volunteer tests, specifically for reclined seating, forward leaning positions and repositioning between such positions and upright sitting. Torso postural control was studied for these situations. The average-sized male SAFER HBM now has a female counterpart. This development showed a first promising step towards including the effects of physiological differences in occupant population into whole-sequence simulations, thereby improving heterogeneity in occupant safety assessment. This is the world-first average-sized HBM with active muscles validated with respect to female volunteer data in pre-crash maneuvers. Together with its whole-sequence simulation capabilities, it makes it unique.

Several simulations series were run providing insights on the usability of the SAFER HBM in whole-sequence simulations with varying conditions, in which pre-crash activated systems may be assessed in line with in-crash restraints. In addition, model usability was addressed through studies on computational efficiency and numerical stability, in addition to development of a user-manual.

The results of this project contribute to the reduction of traffic injuries. When moving closer to “zero injuries”, the situations to address will be more unique and thereby require means to recreate human kinematics and responses for those. With increased degree of automation, the inclusion of muscle activation in a potential pre-crash maneuver is essential for injury prediction in the crash. The active SAFER HBM, capable of whole sequences of low-g and high-g events, has the capacity to do this. This project has taken the muscle control modeling and its application further, contributing to enhance the level of detail and accuracy of prediction for the variety of crash events as well as occupant diversities. The current project has contributed to further improve the model and also helped it to remain the state-of-the-art HBM for advanced research and car safety developments. Ultimately, it contributes to further increase the Swedish vehicle industry’s competitiveness and strengthen the Swedish traffic safety research edge. The SAFER HBM is a globally well-known and respected tool, well associated to Sweden and the project partners. The results of this project will be integrated into the next version of the whole-body SAFER HBM model, which is targeted to become available globally and eventually be a desired tool for standardized assessment of occupant protection.

2 Background

Vehicle safety developments today cover whole sequences of events, including pre-crash and crash situations. Pre-crash safety functions include autonomous vehicle interventions such as evasive braking and steering. In addition, pre-crash activation of restraints including positioning of occupants could be part of the occupant protection strategy.

HBMs are virtual tools for simulation of occupant kinematics in car crashes, capable of recreating injury mechanisms at a detailed level and predicting injury risks. Compared to state-of-the-art crash test dummies, an HBM resembles the human anatomy in more detail and has improved biofidelic responses in different loading directions. Moreover, HBMs can also represent a wider range of male and female occupants of varying anthropometry. With the addition of active muscle control, the HBMs were given the ability to predict the occupant response in low-g events, such as evasive maneuvers, potentially preceding the crash, so called pre-crash event. This functionality brought HBMs to a new level and these so called active HBMs are today essential tools for safety developments and verification of safety systems during whole sequences of events. HBMs may also be implemented in consumer information rating protocols, by agencies such as EuroNCAP and IIHS.

Starting with implementation of PID controller for the elbow joint in 2009 (Östh et al. 2012; 2015), the project team has further refined the A-HBM functionalities in several following projects, summarized, and presented at the international Enhanced Safety of Vehicles conference during the current project (Pipkorn et al., 2023). Since 2018, the A-HBM is an integral part of the SAFER HBM, for which the active muscles can be turned on or off. With the overall goal of an HBM population that can predict occupant kinematics during whole crash sequences (including combinations of low-g and high-g events) as well as occupant actions and repositioning, the active capabilities are essential for the low-g kinematics performance. At the start of the project, the average sized male SAFER HBM could predict the kinematic response in braking for passengers and drivers, and in steering maneuvers for passengers, as well as prepared for use in vertical loading and for reclined passengers.

3 Purpose, Research Questions and Methods

In line with the overall objective to create a HBM population that can predict occupant kinematics and injury risks, during the whole crash sequence with preceding maneuvers, and combined events, including occupant actions and repositioning; the purpose of this project was to further refine the active muscle control functions. In addition, the project took a step in the development of the active muscles' capability and usefulness for vehicle and restraint system development, by incorporating variability of occupant characteristics (sex) and sitting postures.

The objectives / research questions were:

- to introduce a more advanced head controller, enabling a more humanlike prediction of head rotations and interaction with restraints in the crash phase.
- to take the first step in addressing population variability, by modelling the average female in addition to the average male.
- to further refine the upper body muscle control in upright, forward leaning and reclined seating, and when actively transferring the occupant between these positions.

The project was a collaborative project involving one PhD student and more than nine senior researchers from the academy and industry. Several methods were used, including model development, conducting simulation and optimization series, in addition to analyzing and collecting new volunteer test data for model validation. The areas included model developments, exploring population variability, addressing torso postural control in variations of seating, and industrialization activities and studies on protection principles.

3.1 Model developments

Targeting appropriate boundary conditions and initial posture when the crash phase starts, an advanced head controller and improved torso and shoulder postural control were developed and optimized. A new neck muscle controller was developed, and both the existing and new controllers were tuned to minimize differences between HBM and volunteer displacements in braking and lane change, through multi-objective optimization (Larsson et al., 2023c). In a study from the previous A-HBM project, it was seen that for some load cases the active muscles improved the predictions compared to using the model in a passive configuration, while for other load cases, only minor improvements were seen (Larsson et al., 2019). To improve the predictive capabilities of the SAFER HBM, further refinements were addressed in Larsson et al. (2023c). Larsson et al. (2019) noted that the model did not predict head rotations as well as translations, whereby it was hypothesized that it was because the model responded to translations but not rotations, whereby Larsson et al. (2023c) developed a controller that responded to rotations. The new controller was compared to the previously developed angular position feedback controller (Ólafsdóttir et al., 2019). Both controllers were tuned to match volunteer displacements in braking and lane change.

3.2 Population variability

An average-sized female model was developed based on the average-sized male SAFER HBM as part of this project (Iraeus et al., 2023). Using parametric mesh morphing, complemented with scaling of the muscle cross-sectional area, the morphed model resembles the size and characteristics of a 45 years-old female, with a stature of 162 cm, weight of 62 kg, as a complement to the male SAFER HBM of 175 cm and 77 kg (Figure 1). Its active model responses were validated in braking and evasive turning maneuvers, for two different seatbelt systems (standard/pre-tensioned) using volunteer kinematics from data acquired in previous projects (Ólafsdóttir et al., 2013; Ghaffari et al., 2018).

Six different whole-sequence simulations were run for both models, including three different crash pulses preceded by braking or turning, also varying activation of pre-pretensioner. In addition, some simulations were run including the crash phase only.

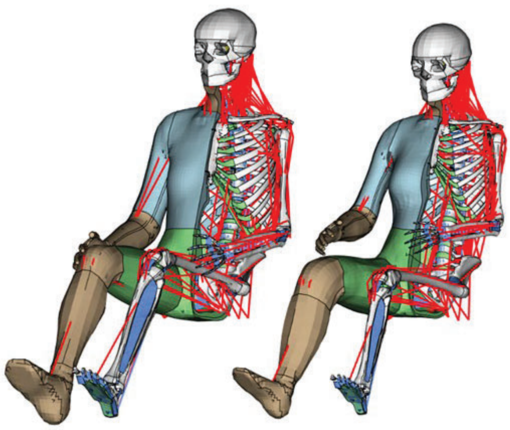

Figure 1. The baseline average-sized male SAFER HBM (left) and the morphed average-sized female SAFER HBM (right).

In another study, volunteer responses collected in a prior A-HBM project (Ghaffari et al., (2018), were analyzed to further study occupant variability (Larsson et al., 2022). Principal component analysis and linear mixed models were used to create predictive models for kinematics and seatbelt time histories, using seatbelt configuration, sex, age, stature, and BMI as co-variates. Monte Carlo simulations of remaining variability were used to generate upper and lower response corridor limits around the predicted responses. In subsequent simulation studies, combinations of human characteristics and boundary conditions were investigated to identify the most influential parameters on forward and vertical displacements in a braking event (Larsson et al., 2023a and 2023d). Larsson et al. (2023a) investigated the sensitivity of the HBM in braking to human characteristics (spinal alignment (PC1 and PC2), muscle physical cross-sectional area (PCSA), neural delay, fat stiffness, muscle stiffness, and skin stiffness) using sensitivity analysis. Also using sensitivity analysis, Larsson et al. (2023d) identified the most important characteristics of the boundary conditions, varying seatbelt position at belt locking, seatbelt stiffness, acceleration shape (PC 1), velocity change, seat position, arm to thigh constraint force, seat to HBM friction and D-ring vertical position. In addition, a synthetic experiment was conducted, where the three most influential characteristics of the boundary conditions and the three most influential HBM characteristics from Larsson et al. (2023d) were randomly varied using Latin Hypercube sampling.

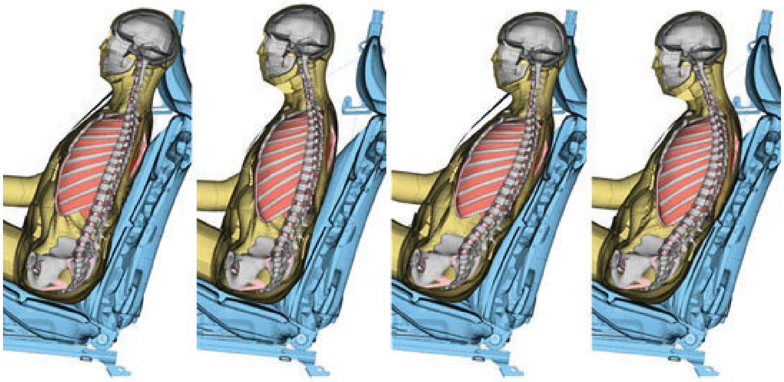

Figure 2. Examples of spinal alignment variations, the most extreme (Larsson et al., 2023a).

3.3 Postural control in variation of seating

Novel seat positions of reclined seating and the rather common, but challenging, posture when the occupant is leaning forward, were addressed through simulations, volunteer tests and modelling developments for torso postural control.

Simulation series

Two simulation series were conducted with the purpose to provide input to the design of the volunteer tests; one included the SAFER HBM in reclined seat position subjected to braking interventions (0.9 g or 0.45 g) or repositioning of the seat backrest, while the other investigated seatbelt pre-pretensioner force and timing needed to reposition an initially forward-leaning SAFER HBM to an upright position during braking of 1.1 g.

The reclined simulation study included ten simulations with the SAFER HBM positioned in a vehicle seat with a seatback angle of approximately 46° (Figure 3a), exposed to a brake pulse (two different levels) or an ‘active seatback’ repositioning intervention. Two different restraint configurations (Belt-in-Seat vs B-pillar) and pre-pretensioner activation were varied. All simulations, except two with the ‘active seatback’, were run with the active muscle setting of the SAFER HBM. The simulation series provided insight into the required braking level needed to get sufficient lumbar and pelvis movements.

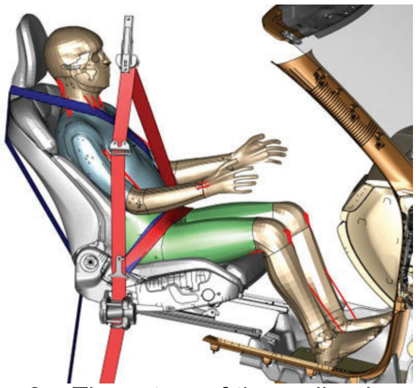

Figure 3a. The set-up of the reclined simulation study for input to the volunteer study, including illustrations of the two seatbelt configurations; Belt-in-Seat (blue) and B-pillar (red).

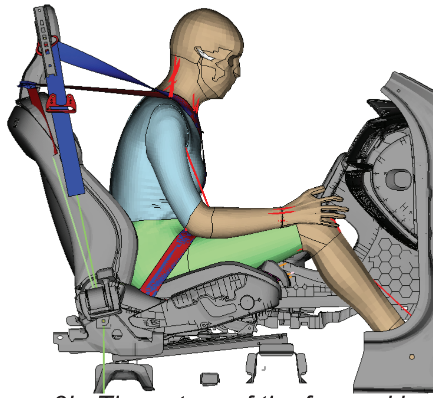

Figure 3b. The set-up of the forward leaning simulation study for input to the volunteer study, including illustrations of the two seatbelt configurations; Belt-in-Seat (red) and B-pillar (blue).

In the forward leaning simulation series (Figure 3b), two sub-studies were included. The SAFER HBM was initially positioned 29° forward from upright, while the seat backrest was upright. In one of the sub-studies simulations were conducted with varied pre-pretensioner forces and activation time in relation to the brake intervention of 1.1 g, varying B-pillar or Belt-In-Seat seatbelt configuration. Some simulations were also run with pre-pretensioning only, i.e., without braking (Mishra et al., 2023). The majority of the simulations were run with the active setting of the muscles. Studying the first thoracic vertebra (T1) horizontal movement it was determined to what degree the SAFER HBM was repositioned. In addition, muscle activation information was studied as input to the volunteer study set-up. For the other sub-study, the simulations were run for 1.1 g braking with Belt-In-Seat seatbelt, with varied pre-pretensioner force. Providing insights to population variability and seating variation, the objective was to find out the magnitude of pre-pretensioner force and the time needed to reposition forward leaning occupants of different sizes. Specifically, the study included three morphed models; a large male (189 cm and 127 kg), the average female (same model as in chapter 3.2.), and a small female (151 cm and 52 kg), in addition to the average male SAFER HBM v10, which was the baseline of the morphing. The muscle PCSA was only varied based on sex, that is, for the large male it was the same as the average male and for the small female it was the same as the average female.

Volunteer tests

With the purpose of collecting data for validation of A-HBMs, a test series was run with instrumented volunteers as front seat passengers riding in an SUV on a closed-off test track at Volvo Cars in Torslanda. In total 9 males and 7 females participated, recruited using advertisements posted at Autoliv, Volvo Cars, Chalmers and SAFER. The study was approved by the Ethical Review Authority in Sweden, application 2022-03970-01.

Each volunteer participated in 29 tests where the following was combined: three torso angles (leaning forward, nominal or reclined), braking or traveling at constant speed, diagonal belt with upper belt anchorage in two positions, non-activated or pre-pre-tensed seatbelt, flexion of the seatback, pull back torso or none. These tests were carried out in semi randomized order. The volunteers were either seated reclined (Figure 4a) or leaning forward (Figure 4b) when the car was harshly braked when driven in 70 km/h. In some tests the volunteers were repositioned; from reclined to upright using an active backrest, or from forward leaning using an active seatbelt. The repositioning tests were also carried out when the car was traveling at a constant speed.

The original seatbelt in the car was removed and the two 'active seatbelts' for the test series were placed with the upper belt anchorage in the original position (B-pillar) and on top of the seatback (Belt-in-Seat), respectively. The two seatbelt configurations allowed for reversible pre-tension via a separate control system and power source. The seatbelts were used both in active and passive modes. In the active mode a nominal tension of up to 450 N was applied. The passenger seatback was also modified, including making the recliner to rotate freely, and adding a telescopic arm to support and control the seatback rotation ('Active Seatback'). The telescopic arm included a cylinder for pressurized air and varied in length enabling the seatback angle to rapidly change from 20° reclined to nominal. Braking events and repositioning the occupant was always carried out when the volunteers were aligned in the mid sagittal plane and when the cars was traveling on a flat stretch of the test track.

Data on boundary conditions, how people move, and muscle activities were collected. These included diagonal and lap belt forces, seatbelt pay-out, car kinematics, pelvis angle, and muscle activity for selected muscles. Volunteer motion capturing was made with two cameras: a side view camera and a top view camera (to record knee for/aft motions). Photo markers were on the head, upper back, shoulders, chest, arms, and knees. For muscle activity measurements, EMG electrodes were applied on the volunteers and the maximum muscle strength was recorded in a special test rig, prior to tests in the car, for normalization of the muscle activity data. Data from the cameras were analysed to determine volunteer head, upper torso, and pelvis kinematics during testing. Anthropometric measurements of the volunteers were recorded to facilitate the above-mentioned analysis.

Figure 4a. The reclined position. A volunteer in the test car just prior to braking and seatback activation.

Figure 4b. The forward leaning position.

Torso postural control

To study the influence of the muscle routing and torso controller variation for occupants transferring between different degree of reclined and forward leaning postures a simulation series was conducted. The muscle routing for the lumbar extensor muscles was updated to more anatomically correct insertion points than in previous versions of the active SAFER HBM (Östh et al., 2015, Larsson et al., 2023a), Figure 5. In addition, the effect of a local head and torso controller which accounts for the relative angle between head and T1 and T1 and pelvis was studied.

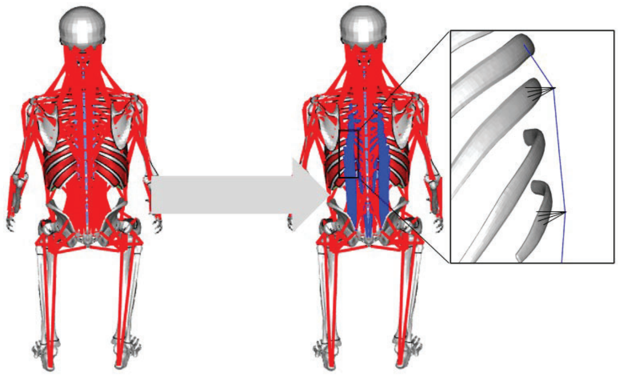

Figure 5. Muscle routing for the active SAFER HBM v10 (left) and the updated muscle routing with anatomically correct insertion points for the lumbar extensor muscles (right, muscles in blue).

3.4 Industrialization and protection principles

To improve computational efficiency while maintaining predictive capability of the SAFER HBM, two master theses were carried out, aimed to investigate the applicability of using Machine Learning to improve the calculation time of combined pre-crash and in-crash simulations. The combined simulations were run using a crash test dummy model. A commercially available software (LUNAR) was used in one of the theses (Wang and Xu, 2022), while graph neural networks were used in the other (Fichera, 2022), to predict the simulation results. Moreover, LS-Opt and OptiSLang, which are tools for optimization and probabilistic and sensitivity analyses, were used, aiming to predict dummy kinematic responses in combined braking and crash events.

The SAFER HBM was used in a numerical stability study investigating the difference in the results when running the same model using different hardware, e.g., different CPUs, and number of cores. The groupable contact parameter in LS-DYNA was varied. The results from the numerical stability study were also analyzed with DiffCrash. An attempt was made to investigate if the source of the variation found in the simulation results could be addressed to a region of the model. It was investigated if the variation could be reduced by a changed modeling technique of the SAFER HBM. A special task on defining a methodology to restart the SAFER HBM at a selected time was carried out with the aim of running one pre-crash simulation and then restarting and simulating different crash simulations. Currently, a full restart of the SAFER HBM is not possible in LS-DYNA with the current methodology to restrict motion of limbs used in various joints.

With the purpose to investigate the influence of muscle activation on the kinematics and injury predictions during crashes, whole-sequence simulations were run varying muscle activation strategies in the pre-crash phase (Östh et al., 2022). A full factorial set-up of two variants of evasive maneuvers (braking and turning) and two crash types (frontal and side impacts) was conducted, including four strategies of muscle activation. The strategies included controllers Off, Active, Hold at a constant control signal and with a startle response (a largely unconscious defensive response to sudden or threatening stimuli). Kinematics, muscle activations, and injury predictions from the different simulations were compared. In the other study, the SAFER HBM was positioned as a supine occupant, i.e., the model was lying down face-up on a bed, while exposed to a frontal impact scenario with or without braking. Different muscle activations (no active muscles, neck and lumbar muscles active, and neck, lumbar, and leg muscles active) were then compared.

To demonstrate the benefits of the SAFER HBM for evaluation of protection principles in crashes preceded by evasive maneuvers, three different studies were carried out. Wass et al. (2022) included ten simulations with two different side-impact configurations combined with two impact speeds. Possible effects of restraint intervention by a reversible seatbelt retractor and a far-side airbag function were studied, analyzing displacements and tissue level injury predictions (Figure 6a). Another study was the first study of SAFER HBM whole sequence simulations applied for rear-end crashes (Figure 6b), including the three standardized rear-end impact crash pulses by EuroNCAP (low, mid, and high-severity), focusing kinematics and overall kinetics responses. The rear-end impact study also included simulating different muscle activation strategies in the pre-crash phase. These were similar, but not identical, to Östh et al. (2022) and included Off, Active, Hold after pre-crash, startle response, or partially braced. The third study was a frontal impact study, including two types of seatbelt configurations (Figure 6c), B-pillar mounted and Belt-In-Seat. They were evaluated for both crash-only and combined braking and crash events for reclined seating. The aim was to study the difference in estimated injury risks and kinematics between the two seatbelt configurations. The Belt-In-Seat was chosen as the baseline case, based on previously published tests. The shoulder belt retractor load limiting was varied with the B-pillar geometry to either a higher or lower level than the Belt-In-Seat to get the same forward excursions or the same shoulder belt force, respectively.

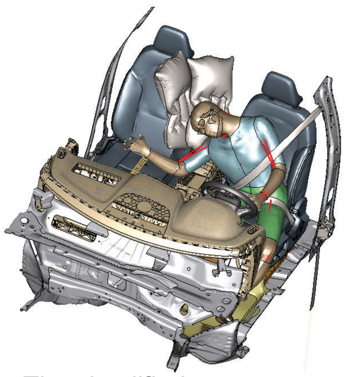

Figure 6a. The simplified car compartment model used for the parameter study in Wass et al. (2022), showing SAFER HBM's maximum lateral excursion during the side impact phase.

Figure 6b. Cross-section of the SAFER HBM during a rear-end impact simulation with the muscle controllers active, subjected to the low severity pulse in the rear-end impact study.

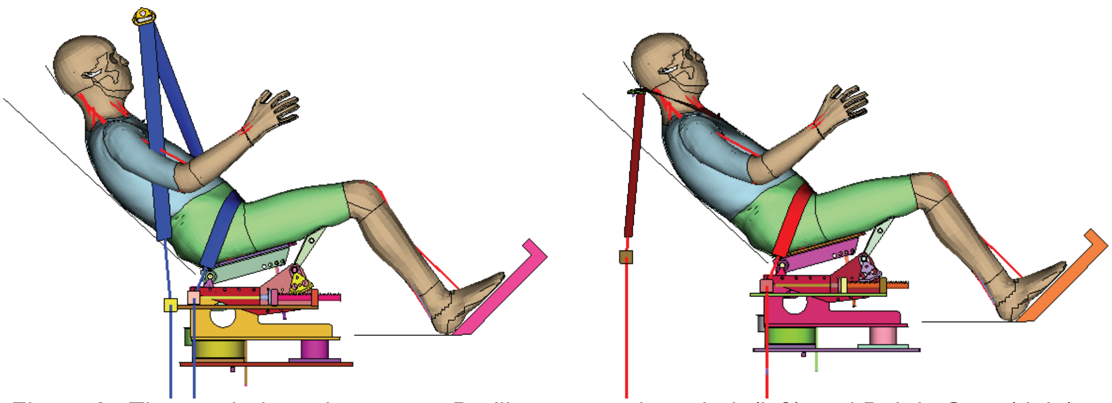

Figure 6c The seatbelt study set-ups; B-pillar mounted seatbelt (left) and Belt-in-Seat (right)

The project went beyond the maneuver followed by crash sequences, expanding the whole sequence simulations with the SAFER HBM to also explore multiple impacts and a run-off road context. A first step in simulating multiple impacts was taken, i.e., one vehicle involved in more than one impact. Two different multiple crash scenarios were simulated with both the passive and the active setting of the SAFER HBM. A 3 g frontal impact followed by another 20 g frontal impact after 1 s, in addition to a 12 g frontal impact followed by a 20 g frontal impact after 1 s. The simulations were run both with and without a generic seatbelt pretensioning functionality in between the crashes. The second multiple impact scenario was also compared with a single 20 g frontal impact in terms of injury risks. The simulations of the run-off road scenario, Figure 7, was modeled as a 1000 ms simulation using recorded accelerations from a physical run-off road crash test. A total of 10 simulations were run with either driver or passenger, with varied pre-pretensioner force levels and activation times.

Figure 7. The HBM during the run-off-road event, exposed to vertical acceleration leading to a forward and downward motion of the head and neck, as well as compressive loads in the lumbar spine (left). The corresponding position of the car in the physical run-off road crash test (right).

4 Objective

In line with the overall objective, this project has improved the active muscle control capability of the SAFER HBM and its usefulness for vehicle and restraint system development, by incorporating variability of occupant characteristics (sex) and sitting postures. The specific objectives were to introduce a more advanced head controller, enabling a more humanlike prediction of head angle and interaction with restraints in the crash phase, to further refine the upper body control in upright, forward leaning and reclined postures and when actively transferring the occupant between these postures, and to take the first step in addressing population variability, by modelling the average female in addition to the average male.

Overall, all the specific objectives were reached, and important steps were taken maintaining leadership for the SAFER HBM in in active muscle control developments. This includes the development of the first mid-sized female HBM tuned with female volunteer data in pre-crash maneuvers, improvements of head controller, torso control studies and overall numerical model quality assessment.

In addition to the planned activities, validation data from 2016 collected in a prior A-HBM project was analyzed, published, and used for study of occupant variability.

Due to the pandemic and other technical issues, the planned volunteer test series was delayed a year. Although the test series was run during the project, the main parts of the analyses could not be made within the time-frame of the project. Consequently, the model improvements with respect to repositioning was made based on prior data, limiting the extent of refinement. The project group plans to catch up with this work in ongoing or coming joint research projects on SAFER HBM improvements.

5 Results and Deliverables

At the start of the project, the average-sized male SAFER HBM was capable of predicting the kinematic response in braking for passengers and drivers, and in steering maneuvers for passengers, as well as prepared for use in vertical loading and for reclined passengers. After the project, a corresponding average-sized female SAFER HBM is available. The active capabilities were enhanced and assessed, specifically in the head and torso area, including torso control for reclined passenger. The SAFER HBMs abilities for whole sequence simulations for a variety of situations were demonstrated.

The project has delivered one PhD thesis, two Master theses and twelve publications.

5.1 Model developments

The active muscle control at start of the project showed more biofidelic model kinematic predictions in simulations of evasive maneuvers, compared to using the same model without active muscles (Larsson et al., 2019). Several improvements were made during the project such as tuning as well as including a rotational controller as presented in Larsson et al. (2023c). The SAFER HBM with tuned controllers could predict passenger head kinematics with good to excellent biofidelity, with overall CORA scores of 0.90-0.94 in braking and 0.81-0.82 in lane change. Head translations were better predicted compared to head rotations. In addition, the angular position feedback controller (first presented in Ólafsdóttir et al., 2019) provided better predictions compared to the rotational controller developed in Larsson et al. (2023c). When varying model parameters in braking, the forward displacements were more similar to volunteers early in the maneuver compared to later in the maneuver (Larsson et al., 2023d)

5.2 Population variability

The average-sized female version of the SAFER HBM developed within the project was able to reproduce the postural response of average female volunteers during pre-crash maneuvers (Iraeus et al., 2023). It showed good biofidelity for occupant kinematics prediction in braking event, and fair biofidelity in the evasive turning maneuvers. The whole-sequence simulations revealed some differences between the female and male models, with the female model showing lower upper body forward displacements, and higher pelvis displacements, regardless of crash configuration and seatbelt configuration. This can be attributed to the difference in stature, mass, and adipose tissue. This development shows a first promising step towards including the effects of physiological differences in occupant population in whole-sequence simulations to improve occupant safety.

Analyzing the volunteer data from Ghaffari et al., (2018), it was concluded that although some of the variations in displacements could be explained by occupant characteristics such as sex, stature, age and BMI, the largest effect was seen when changing seatbelt system between a standard inertia-reel seatbelt and a seatbelt with pre-pretensioning

(Larsson et al. 2022). The seatbelt was a predictor of kinematics in 33% of possible prediction models, where using a pre-pretensioned seatbelt often reduced displacements compared to using an inertia reel seatbelt. The other predictors could only predict kinematics or seatbelt forces in 6% or fewer possible prediction models. This provided insights into occupant variability. In the subsequent simulation studies, occupant spinal alignment and seat longitudinal position was identified as influential parameters of forward displacements in braking (Larsson et al. 2023d). When varying the three most influential occupant characteristics (spinal alignment PC1, spinal alignment PC2 and muscle physiological cross-sectional area) (from Larsson et al. 2023a) and the three most influential boundary conditions (seat longitudinal position, velocity change and seatbelt stiffness), the vertical displacements varied similarly compared to how volunteers varied (Larsson et al. 2023d). Forward displacement corridors were around 25% of width from volunteer corridors when varying these parameters. The most influential parameter was seat position, moving the seat forward with 66% of the travel range reduced the head displacements by 45 mm, followed by spinal alignment PC2, a more curved spine reduced the displacements, altering the curvature by 2 SD (from -1 SD to +1 SD) reduced head displacements with 28 mm. Together, these two parameters explained 70%-79% of the forward head and torso displacements seen in the simulations.

5.3 Postural control in variation of seating

The simulation series gave input to planning and setting the parameters of the volunteer test study. The repositioning from the reclined simulation study provided insight into the required braking level needed to get sufficient lumbar and pelvis movements when reclined. The forward leaning simulation study provided data on muscle activation and to what degree a volunteer was expected to be repositioned.

Although delayed in time, the volunteer tests were successfully conducted in the project and data were successfully collected and available for analysis from 454 tests, including 23 different set-ups. Only in a few tests, one or more components of the test equipment failed. A preliminary analysis could be done in the current project, providing some novel insights. Almost all volunteers´ torsos were pulled into nominal position when the volunteers were leaning forward, and the ‘active seatbelt’ was in active mode while the car was traveling at constant speed. It could also be seen that the volunteers tensed several muscles and by doing so somewhat resisted the intended function of activated seatbelt. Differences between the two seatbelt configurations (Belt-in-Seat and B-pillar) were seen for this behavior. In the comparable set-up, but while the car was braking, it could be seen that all volunteers´ torsos were pulled back, but to a less extent than when travelling at a constant speed. When reclined and the car was travelling at constant speed, all volunteers were successfully repositioned when the seat backrest was rapidly raised from reclined to nominal. For a few volunteers, the head continued a bit forward of a typical nominal position. However, when the car was braking at the same time as the seatback was raised, the average volunteer exhibited a torso flexion of about 17 deg relative nominal position and neck was in flexion.

The muscle routing and controller variation simulation study for occupants transferring between different degree of reclined and forward leaning showed that the routing of the lumbar extensors had some, but not large, effect on the occupant pre-crash and crash kinematics in whole-sequence repositioning and frontal impact simulations. The local controller changed the amount of muscle activation compared with the baseline active SAFER HBM, which affected the amount of pelvis rotation during repositioning considerably.

5.4 Industrialization and protection principles

The SAFER HBM showed good performance with respect to numerical stability. In the numerical stability study using different hardware, the SAFER HBM showed that when the “groupable” functionality of contacts was used for the tied contacts, more variation in the simulation results could be expected. The studies on the computational efficiency while maintaining predictive capability provided good insights on the performance of different models. Principal Component Analysis showed better performance than Graph Neural Networks in terms of lower errors and less computational time.

To support standardized use of the model and quality-assured analysis independent of the user, a user-guideline for the SAFER HBM v10 was developed. It included a protocol for setting up the model and running it in different scenarios along with guidance on post-processing. Such a user-guideline is important when targeting making the model available for more users.

In the study by Östh et al. (2022), exploring different muscle activation strategies and their impact on crash response, it was showed that injury predictions could be affected by the inclusion of active musculature in high acceleration impacts. In the supine study too, injury predictions for the lumbar spine and femur were affected due to leg muscles activation.

The studies including pre-crash to crash simulations demonstrated the capability of the SAFER HBM to do whole-sequence simulations of varied types, as well as the benefits of the model for evaluation of protection principles in crashes preceded by evasive maneuvers. The studies included frontal impacts, side impact and rear-end impacts as well as different seating like upright and reclined. The results provided insights on the usability of the SAFER HBM in different kinds of whole-sequence simulations, in which pre-crash activated systems may be assessed in line with in-crash restraints. Various protection principles were evaluated such as Belt-In-Seat, seatbelt pre-pretensioner, and far-side airbag. The results showed the importance of including pre-crash kinematics and muscle activations, enabling the assessment of occupant protection countermeasures activated during the pre-crash phase. Moreover, the large span of occupant responses that can be found in complex events and need to be handled by an A-HBM was demonstrated. For instance, the peak lumbar spine forces were almost always concentrated to the lower lumbar vertebra (L5) for the whole-sequence frontal impacts, while for the run-off road simulations peak compressive forces were found at the upper end of the lumbar spine (L1).

The project expanded the content of whole sequence simulations, also exploring multiple impacts and run-off road scenarios. This clearly demonstrated the capabilities of the active SAFER HBM and is a result of the continuous improvements made for the active muscle control.

5.5 Contribution to the objectives of the FFI program

The results of this project contribute to the reduction of traffic injuries, supporting the work towards the Vision Zero ambition of reducing fatalities and injuries in traffic. The results are set to contribute to long-term injury reduction. The inclusions of the heterogeneous population and the implementation into advanced tools such as HBMs are essential, acknowledging that when moving closer to “zero injuries”, the situations to address will be more unique and thereby require means to address those. Although the studies in this project was applied for car occupants, the focus on a model resembling a human during dynamic events will also help benefitting other traffic categories, such as occupants in heavy goods vehicles and two-wheelers.

The project contributed to further increase the Swedish vehicle industry’s competitiveness and to strengthen the Swedish traffic safety research edge. The SAFER HBM, developed through several FFI projects, is a world-leading tool for assessing occupant protection. Its capabilities to include the pre-crash event is one of the model's unique features. This project has taken the muscle control modeling and its application further, contributing to enhance the level of detail and accuracy of prediction the variety of crash events as well as occupant diversities. The SAFER HBM is a globally well-known and respected tool, well associated to Sweden and the project partners. The results of this project will be integrated into the next version of the whole-body model, which is also targeted to become available globally and eventually be a desired tool for standardized assessment.

Important steps were taken on reclined and forward leaning seating positions, including repositioning from such positions. It was shown that the muscle control's influence on pelvis rotation was important in such scenarios. This has implications on how well the prediction of the seatbelt interaction with the pelvis can be simulated during crash, when preceded by a repositioning event. The SAFER HBMs capabilities of whole-sequence simulations now may include a larger range of initial sitting postures, as well as repositioning measures by seatback movement, seatbelt pre-pretensioner or car braking. Hence, assessing the ADAS or pre-crash triggered restraints as part of the occupant protection can now be made, which is essential with the focus on increased automation. In addition, the learnings from this project will help to develop safer restraints for a larger variety of seat positions and sitting postures, such as reclined seat, thereby enabling safer transportation for the customers asking for more relaxed as well as more activity-based travelling.

Another step included the development and tuning of the female model with respect to muscle activation, based on female volunteer data. Although other female sized HBMs exist, no one has so far implemented it into a model capable of whole-sequence simulations, nor have an average-sized female model with validated pre-crash kinematics using corresponding female data. Further steps, including a larger variety of individual differences can be included based on the methods used in this study.

6 Dissemination and Publications

The project results are utilized in product development and advanced engineering projects within the industrial partners of the project. The SAFER HBMs are used as complements to the standardized crash test dummies available, providing further insights into occupant protection needs. Furthermore, the knowledge and assessment tools created in the project are used in educational activities within Chalmers Master Programs, Theses at Master and Bachelor levels, as well as assignments in different university courses.

The project was a part of the HBM competence cluster at SAFER Vehicle and Traffic Safety Centre at Chalmers. The HBM competence cluster is based on a continuous path of research projects working in sequence or parallel towards creation of the SAFER HBM. This cluster collaborates with international researchers, whereby the project has benefitted from being part of the cluster, as well as contributed to the cluster. Hence, the impact of the results and publications from the current project have been boosted and clearly contributed to demonstrate the high international level of Swedish research within this area.

The model developments will be integrated into the next update of SAFER HBM model, version 11. This model is planned to be made available beyond the ownership of the three project partners, as of today. Making the SAFER HBM available for the rest of the world will benefit global safety as well as further strengthen the acknowledgements of Swedish traffic safety research.

6.1 Knowledge and Result Dissemination

How are the project results planned to be used and disseminated?		Comment
Increase knowledge in the field	X	The model developments are state-of-the-art enabling improved whole-sequence simulation, which also has been show-cased and shared through publications and presentations.
Forwarded to other advanced technological development projects	X	Project results are used as input to vehicle and restraint developments by the industrial partners.
Forwarded to product development projects	X	The results are used in development of restraints and vehicles for production, by the industrial partners.
Introduced on the market	X	The project results are used when developing vehicle and restraint system for the market. In addition, the ambition is to make the SAFER HBM model as such globally available during 2024.
Used in investigations / regulatory / licensing / political decisions	X	The project results, integrated into the SAFER HBM, are used for research and publications influencing global standards, regulatory framework and consumer information programs such as EuroNCAP, USNCAP and IIHS.

6.2 Publications and Conference Presentations

Theses

Emma Larsson. **Passenger kinematics in evasive maneuvers - Advancing Active Human Body Modeling and Understanding Variability in Passenger Kinematics During Evasive Maneuvers.** PhD Thesis. Dept of Mechanics and Maritime Sciences, Division of Vehicle Safety, Chalmers University of Technology, Sweden, August 2023. ISBN 978-91-7905-889-0 https://research.chalmers.se/publication/536882

Peifeng Wang, Qiang Xu. **Applicability of using machine learning to improve computational efficiency of combined pre-crash and crash simulations**. *Master Thesis in Automotive engineering* 22:67, Dept of Mechanics and Maritime Sciences, Chalmers Univ. of Techn, October 2022 https://hdl.handle.net/20.500.12380/305724

Chiara R Fichera. **Predicting Finite Element Simulation output using Machine Learning.** *Master Thesis in Biomedical Engineering*, Department of Mechanics and Maritime Sciences, Chalmers Univ of Techn, 2022. https://odr.chalmers.se/server/api/core/bitstreams/41315085-60ab-4e39-8ccc-6e1bc9040914/content

Peer-review articles

Fice JB, Larsson E, Davidsson J (2021) **Dynamic spatial tuning patterns of shoulder muscles with volunteers in a driving posture**, Front. Bioeng. Biotechnol., 24 November 2021 https://www.frontiersin.org/articles/10.3389/fbioe.2021.761799/

Wass J, Östh J, Jakobsson L (2022). **Active human body model simulations of whole-sequence braking and far-side side impact configurations whole-sequence far-side impact simulations**, IRCOBI Conference www.ircobi.org/wordpress/downloads/irc22/pdf-files/22112.pdf

Östh J, Larsson E, Jakobsson L (2022) **Human body model muscle activation influence on crash response**, IRCOBI Conf. www.ircobi.org/wordpress/downloads/irc22/pdf-files/22101.pdf

Larsson E, Ghaffari G, Iraeus J, Davidsson J (2022). **Passenger kinematics variance in different vehicle manoeuvres – biomechanical response corridors based on principal component analysis**, IRCOBI Conference www.ircobi.org/wordpress/downloads/irc22/pdf-files/22100.pdf

Iraeus J, Mishra E, Östh J (2023) **Comparison of average female and male active HBM responses in whole-sequence frontal crash simulations**. IRCOBI Conference http://www.ircobi.org/wordpress/downloads/irc23/pdf-files/2398.pdf

Mishra E, Mroz K, Lubbe N (2023) **Repositioning forward-leaning passengers by seatbelt pre-pretensioning.** Traffic Injury Prevention 24:8, 716-721, DOI: 10.1080/15389588.2023.2239408 https://www.tandfonline.com/doi/full/10.1080/15389588.2023.2239408?src=

Larsson E., Iraeus J., Davidsson J. (2023a) **Investigating sources for variability in volunteer kinematics in a braking maneuver, a sensitivity analysis with an active Human Body Model**, *Frontiers in Bioengineering and Biotechnology*. In review.

Larsson E et al. (2023b) **Development of a shoulder muscle feedback controller for human body models**, Annals of Biomedical Eng, submission pending

Larsson E, Iraeus J, Pipkorn B, Östh J, Forbes PA, Davidsson J (2023c) **Predicting occupant head displacements in evasive maneuvers; tuning and comparison of a rotational based and a translational based neck muscle controller,** planned for submission for Frontiers in Bioengineering and Biotechnology, included in PhD thesis, paper C

Larsson E, Iraeus J, Davidsson J (2023d) **Synthetic experiments to investigate occupant variability in braking maneuvers, a simulation study using Active Human Body Models.**, Draft manuscript included in PhD thesis, paper E

Conference presentations / papers:

Larsson E. **Accounting for shoulder muscle activity in HBMs**. Virtual Testing, Human Modelling in Pedestrian Protection, Carhs Seminarium, June 2021.

Pipkorn B, Jakobsson L, Iraeus J, Östh J (2023) **The SAFER HBM – A Human Body Model for seamless integrated occupant for all road users**. Paper No. 23-0242, ESV Conference, April 2023, Yokohama, Japan. https://www-esv.nhtsa.dot.gov/Proceedings/27/27ESV-000242.pdf

Other presentations:

DYNAmore: project results part of presentation at Virtual Testing, Human Modelling in Pedestrian Protection, Carhs Seminarium, June 2021

SAFER Project day, 10th March, 2023. Presentation by Emma Larsson

7 Conclusions and Future Research

This two-year project has advanced the active muscle controllers of the SAFER HBM and the model's usefulness for vehicle and restraint system development, by incorporating variability of occupant characteristics and sitting postures. It also show-cased several applications of whole-sequence simulations, including the muscle's influence on kinematics during a pre-crash event and injury prediction during crash. In addition, model usability was addressed through studies on computational efficiency and numerical stability, helping to maintain as the state-of-the art-HBM for real-world occupant protection analyses.

A more advanced head controller was assessed and implemented, for which good-to-excellent biofidelity was seen in braking as well as lane change, especially in head translation. The implemented rotational feedback controller showed promising results in predicting occupant head displacements in lane change and braking, while a tuned version of the previously implemented angular position feedback controller provided superior results. The tuned controllers help towards more humanlike prediction of head displacements and interaction with restraints in the crash phase. Further developments include updated lumbar muscle routing with correct anatomical insertion points and an evaluation of the lumbar and abdomen muscle controller.

The average-sized female version of the active SAFER HBM showed a very promising first step towards inclusion of the effects of physiological differences for the diverse population when improving occupant safety. The average-sized male SAFER HBM now has a female counterpart. Although several challenges remain, such as to investigate the effects of active musculature in occupant models on injury risks, include more types of crash scenarios, in addition to expand to additional sizes of occupants, it serves as an essential proof point of addressing population variability. This is the world-first average-sized HBM with active muscles tuned based on female volunteer data in pre-crash maneuvers. Together with its whole-sequence simulation capabilities, it makes it unique.

Further input to enhanced understanding of population variability was gained in analyzes of a large set of volunteer test data, collected in a prior project, investigating influences of occupant and vehicle factors. In subsequent simulation studies, variation in spinal alignment together with seat positions were further studied providing insight into their influence on forward head and torso displacement in braking. Simulations on occupant muscle responses in the HBM requires controlled and well documented test series with volunteers exposed to a variety of low-g maneuvers, such as steering or braking maneuvers. Over the years, the project partners have produced such volunteer data and plan to continue to do so, also including studies in variation in spinal alignment and other individual variations, looping it with simulation studies using the HBM.

Torso postural control, necessary for reclined, forward leaning position and repositioning between such positions and upright sitting, was studied. Simulations series on reclined and forward leaning postures were conducted, learning from the model and providing input to the set-up of volunteer tests. In addition, an update of the torso muscle routing was investigated using different controller variants, providing insights on its influence of pelvis rotation during repositioning. The test series involving 16 volunteers, conducted in the current study, will provide input to further refining the upper body control in upright, forward leaning, and reclined positions, and when actively transferring the occupant between these postures. This is critical information to enhance the usefulness of the model in such situations. Especially for reclined seating, a prediction of pelvis rotation plays an important role for seatbelt interaction and thereby the fundamental protection of the occupant. This project provided proof points for this. More insights will be made when the data from the volunteer test series in finalized. This work is within the plan for the SAFER HBM further developments and will be prioritized in future projects to finalize.

A large variety of simulations were run, exploring different muscle activation strategies as well as demonstrating its capabilities in whole-sequence simulations of varied types, as well as the benefits of the SAFER HBM for evaluation of protection principles in crashes preceded by evasive maneuvers. The results provided insights on the usability of the active SAFER HBM in different kinds of whole-sequence simulations, in which pre-crash activated systems may be assessed in line with in-crash restraints. The project expanded the content of whole sequence simulations, also exploring multiple impacts and run-off road. This clearly demonstrated the active capabilities of the SAFER HBM and is a result of the continuous improvements made for the active muscle control.

In addition, overall model developments to enhance its run-ability, quality and usability were made, including studies on computational efficiency, numerical stability, and development of a user-manual.

At the start of the project, the average sized male SAFER HBM was capable of predicting the kinematic response in braking for passengers and drivers, and in steering maneuvers for passenger, as well as prepared for use in vertical loading and for reclined passengers. After the project, a corresponding average sized female SAFER HBM is available. The active capabilities are enhanced overall, specifically the head controller has been tuned to match volunteers in braking and lane change, and lumbar muscle routing has been updated. In addition, torso control for reclined passenger has been implemented. The SAFER HBMs abilities for whole sequence simulations for a variety of situations are demonstrated. The model developments will be part of the SAFER HBM planned to be launched for global access during 2024.

8 Project Partners and Contact Persons

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9 References

References in addition to the project's publications listed in Chapter 6.2.

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Ólafsdóttir JM, Östh J, Davidsson J, Brolin K (2013) **Passenger kinematics and muscle responses in autonomous braking events with standard and reversible pre-tensioned restraints**. IRCOBI Conference Sept 2013, Gothenburg, Sweden.

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