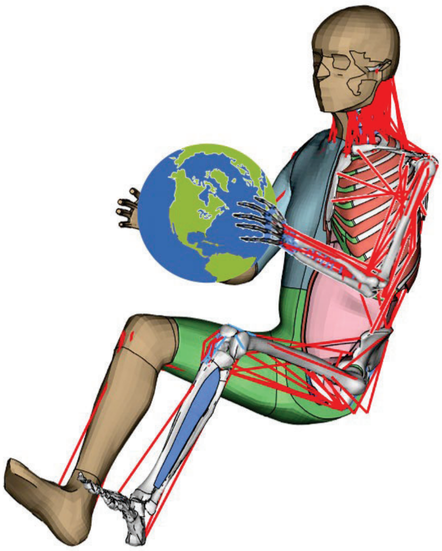
Taking SAFER HBM to the Global Arena: Focusing the Cervical and Thoracic Spine

SAFER HBM för alla: fokus på utveckling av hals- och bröstrygg

Public report



Project within *Trafiksäker automatisering - FFI - Projekt 2022-01654*

Authors Jonas Östh, Lotta Jakobsson, *Volvo Cars*
Bengt Pipkorn, *Autoliv*
Johan Iraeus, Jobin John, Johan Davidsson, *Chalmers*
Olle Bunketorp, *Sahlgrenska*

Date 2025-01-30

Fordonsstrategisk
Forskning och
Innovation

Content

FFI in short

FFI, Strategic Vehicle Research and Innovation, is a joint program between the state and the automotive industry running since 2009. FFI promotes and finances research and innovation to sustainable road transport.

For more information: www.ffisweden.se

1. Summary

With increasing vehicle automation, the variation in occupant positions at the start of crash is expected to increase due to automated interventions, but also because of the growing range of seating positions and activities possible in automated vehicles. Development of protection systems adapted for this, as well as whole sequence pre-crash and crash events arising from automated interventions, increase the requirement on models that approximate human anatomy and kinematics in crash simulations. Current crash test dummies provide a poor representation of these scenarios, while State-of-the art Human Body Models (HBMs) are capable of more accurately predicting human kinematics and injury risk by simulation. Simulation with HBMs has also been adopted by several consumer information programmes, which aim to evaluate whole sequence events as well as a more representative part of the population by simulation. To achieve this, Virtual Testing (VT) using HBM simulations is proposed to assess robustness of occupant protection system performance as a complement to today's physical crash tests. Through several FFI-projects over more than a decade, the project partners have jointly developed an advanced HBM, called SAFER HBM, a unique tool with the aim to evaluate crash protection for all road users.

The overall purpose of this project was to make SAFER HBM a biofidelic, robust, competent, and attractive tool for the project partners' needs, and also contribute to prepare it for being able to share with the community. The specific goals included to further improve the model, with special attention on the spine, enhancing spinal kinematics and injury risk prediction, and to make it technically ready to enable global availability, by replacing third party Intellectual Property (IP).

The project was a collaboration between industry and academia, involving one industrial PhD student, several academic research assistants and more than ten senior researchers. The main method applied was computational impact biomechanics through Finite Element (FE) modelling. In addition to this, advanced design of experiments, statistical shape modelling for updated HBM geometry and objective evaluation methods for model validation was used. Moreover, volunteer experiments were conducted using a combination of film analysis, physical measurements with a digitizer complemented by ultrasound to measure subcutaneous structures.

This two-year project has technically prepared the SAFER HBM for global availability by creating a new version that is free from third party IP. The volunteer tests were carried out to identify the spinal curvature of seated occupants in upright and reclined seating positions. In total, 61 volunteers (31 male, 30 female) were tested, providing a sufficient dataset to create regression models of spinal shape for a population of occupants that can be represented by the morphed SAFER HBM. The SAFER HBM was improved by the integration of new subsystem models of the spine, costovertebral joints, claviculae, scapulae, humeri, femora and patellae. These updates together with a restructuring and renumbering of the model led to the creation of the SAFER HBM v11. In addition to this,

to assess the updated model's performance, a validation catalogue with load cases assessing each body part at subsystem level as well as in whole-body simulations was created using an interactive web-based system to present results (Jupyter Notebooks). A rear-facing high-severity frontal impact test setup was simulated for reclined HBM validation and published for the first time. The cervical and thoracic spine updates are central for modelling the seated occupant response in regular upright seating as today, as well as for future seating variations which can be expected in automated cars. These developments enable the industrial project partners to develop future sustainable and safe vehicles. The project activities towards the Euro NCAP HBM certification for VT allows to make SAFER HBM a tool for VT consumer information protocols around the world, and the projects work has also supported the development of the Euro NCAP protocol for HBM certification.

2. Sammanfattning på Svenska

Med ökande grad av fordonsautomatisering förväntas en större frihet för åkande att sitta i positioner eller utföra aktiviteter som inte är möjliga eller tillåtna i dagens fordon. Utveckling av skyddssystem anpassade för detta, samt simulering av hela olycksförloppet, inklusive den del som föregår en krock (och kan innehålla automatiserade ingrepp), ökar kraven på modeller som efterliknar mänsklig anatomi och kinematik i krocksimulering. Att representera dessa scenarier är inte möjligt med nuvarande krockdockor, men kan göras med hjälp av simulering med humanmodeller (HBMer) som är state-of-the-artverktyg för att prediktera åkandekinematik och skaderisk vid krocksimulering. Denna utveckling har också anammats av flera konsumentinformationsprogram, som avser att kunna utvärdera hela krockförlopp inklusive en mer representativ del av befolkningen. För att uppnå detta föreslås användning av Virtuell Testning (VT) med hjälp av HBM-simuleringar för att bedöma prestanda för passagerarskyddssystem som ett komplement till provning med dagens krockdockor. Genom flera FFI-projekt under mer än ett decennium har projektpartnerna tillsammans utvecklat en avancerad HBM, kallad SAFER HBM som är ett unikt verktyg med ambition att kunna utvärdera och utveckla skydd för alla trafikanter.

Det övergripande målet med projektet var att göra SAFER HBM till ett biofideliskt, robust, kompetent och attraktivt verktyg för projektparternas behov, inklusive att göra verktyget tekniskt tillåtet att användas av fler. De specifika målen inkluderade att ytterligare förbättra modellen, med särskild fokus på ryggradens kinematik och prediktion av skaderisk, samt att ersätta tredjeparts IP.

Specifika forskningsämnen och metoder för projektet var att:

- Definiera ryggradens krökning för kvinnor och män i moderna personbilssäten, upprätt och i ett mer tillbakalutat prototypsäte genom volontärstudier med filmanalys och digitalisering av anatomiska landmärken.
- Utveckla SAFER HBM för att möjliggöra prediktering av kinematiken vid omnidirektionell belastning, genom utveckling och validering av hals- och bröstryggraden. Uppdatera modellen genom att integrera av en ny ryggrad, skuldra, lårben, och modeller av buken.

- Implementera och utforska möjligheten för prediktering av risk för frakturskador i bröstryggen, genom simuleringar som utvärderar modellens töjningsrespons vid frontalkrock.
- Ta de första stegen för att prediktera skador på kotor och mjukvävnad i halsryggen med SAFER HBM, genom att existerande metoder för andra HBMer utvärderas, samt att implementera ett frakturkriterium för ländryggen och utforska dess potential för att förutsäga fraktur också i bröstryggen.
- Tekniskt förbereda SAFER HBM för global tillgänglighet och utveckla demonstratorer och en databas med valideringsdata för att stödja introduktionen samt framtida utveckling av SAFER HBM. Valideringen av modellen jämfört med valideringsexperiment presenteras på ett strukturerat sätt (med hjälp av Jupyter Notebooks).
- Göra SAFER HBM attraktiv genom att certifiera modellen för användning i Euro NCAP VT, genom att delta i arbetsgrupper som utvecklar validering och certifieringsmetoder för HBM.

Projektets utgångspunkt var SAFER HBM V10.0 som är ett state-of-the artverktyg för prediktering av revbensfraktur och hjärnskakningsrisk. Under projektet uppdaterades SAFER HBM till att också prediktera risk för ländryggsfrakturer, samt förbereddes för ytterligare förutsägelse av skada på vävnadsnivå i hals- och bröst-rygg, samt axeln och lårbenet genom uppdatering av dessa kroppsdelar. En valideringsuppsättning för en bakåtvänd höghastighetsfrontalkollision skapades och användes för att utvärdera SAFER HBM i ett möjligt nytt åkandescenario för framtida automatiserade fordon. Projektet har också levererat en doktorsavhandling, ett examensarbete och sex andra vetenskapliga publikationer/presentationer.

Detta tvååriga projekt har tekniskt förberett SAFER HBM för global användning och skapat en uppdaterad version, fri från tredjeparts IP. Uppdateringarna av hals- och bröstryggen är centrala för att biofideliskt modellera den sittandes respons i vanliga sittställningar idag, såväl som för framtida variationer i sittställning som kan förväntas i automatiserade fordon. Denna utveckling gör det möjligt för industriprojektpartnerna att utveckla framtida hållbara och säkra fordon. Projektaktiviteterna mot Euro NCAP HBM-certifieringen för VT gör det möjligt att göra SAFER HBM till ett verktyg för VT-konsumentinformationsprotokoll runt om i världen, och projektarbetet har också bidragit till utvecklingen av Euro NCAP-protokollet för HBM-certifiering.

SAFER HBM har nu kapacitet för avancerad frakturprediktion i ländryggen och är redo för att implementera denna förmåga också för bröst- och halsryggraden, vilket är viktigt för att möjliggöra utveckling av skydd för åkande i tillbakalutade sittställningar, medan förutsägelser om mjukdelsskador är särskilt viktiga för jämlikhet vid påkörning bakifrån. Framtida forskning kommer att fokusera på att utveckla avancerad skadeprediktion för halsryggraden, vilket möjliggör förutsägelse av skada i en större del av befolkningen genom morphing av HBMer.

3. Background

Real-world occupant protection includes a large variety of crashes and occupant sizes, in addition to combinations of pre-crash and crash scenarios. Pre-crash scenarios may include evasive braking and steering manoeuvres, by the driver as well as from automated vehicle interventions. With increased level of vehicle automation, such interventions are expected to become more common. The crashes occur with varied directions and severities. Crash test dummies have several limitations which make them unsuitable to cover some of these situations. The limitations include, for instance directional dependence, lack of muscle responses and that they only exist in a limited number of occupant sizes. An alternative to crash test dummies is virtual development through simulations with HBMs. HBMs model the human anatomy and tissue properties, are capable of detailed injury risk predictions at tissue level and can represent a wider range of the population through morphing of the model shape to account for *e.g.* age, sex, stature, and weight. Furthermore, automated vehicles may allow for novel seat positions and sitting postures. To evaluate the safety for occupants in such positions requires tools with the versatility of an HBM.

Spinal injuries include injuries to the skeletal structure, the nervous system, and to its stabilizing components, often referred to as soft tissue injuries in the cervical spine. These injuries are the most frequent car occupant injuries and have a relatively high risk of long-term consequences.

4. Purpose, research questions and method

Over the years, the project team has developed the SAFER HBM with the overall goal to be capable of predicting occupant response in any combinations of low-g and high-g loading, in a variety of sitting postures. At the start of the project, the model was state-of-the-art in several areas, such as rib fracture prediction and simulation of the occupant response in combined pre-crash and crash scenarios. An update of the cervical and thoracic spine of SAFER HBM in this project was necessary to enable state-of-the-art performance also for cervical spine injuries with the model. Morphing of the model allow for assessment of both female and male occupants in automated vehicle impact scenarios and the updated spine will also improve the morphed models. Moreover, organisations such as Euro NCAP in Europe (van Ratingen et al. 2020), and the Insurance Institute for Highway Safety (IIHS) in the US, are developing VT protocols and extending them to include HBMs. To make the model eligible for use in these external protocols is of high importance for the project partners' needs. Furthermore, making the model possible to share with a wider community is also important with respect to the VT testing, and before this is possible, several things need to be in place, such as removing and replacing third party IP.

Research topics for the project were:

- Defining the human spinal curvature for female and male seated occupants in modern passenger car seats, upright as well as reclined.
- Developing the SAFER HBM for improved prediction of humanlike kinematic response in omnidirectional loading, by development and whole-body response validation of the cervical and thoracic spine.
- Take the first steps for bony and soft tissue cervical spine injury prediction with the SAFER HBM by reviewing previous HBM studies.
- Implement a preliminary fracture criterion for the lumbar spine and explore its fracture injury risk prediction when applied to the thoracic spine also.
- Technically prepare for making SAFER HBM globally available and produce demonstrators and a database of validation data for supporting the introduction and future developments of the SAFER HBM.
- Make SAFER HBM attractive as a certified tool for the Euro NCAP VT protocol.

The project was a collaboration between industry and academia, involving one industrial PhD student, several academic research assistants and more than ten senior researchers. The main method applied was computational impact biomechanics through FE modelling, and for this the use of advanced design of experiments, statistical shape modelling for updated HBM geometry and objective evaluation methods for model validation. In addition to this, volunteer experiments were conducted using a combination of film analysis, physical measurements with a digitizer complemented by ultrasound to measure subcutaneous structures.

4.1 Data for Spinal Curvature

With the purpose of determining the curvature of the spine and the position of the head, shoulder, and hip, volunteers were positioned in two car seats in the laboratory. One seat was a standard vehicle seat (upright) and the other was a reclined prototype seat (reclined). The study aimed to cover a large part of the population to enable the prediction of postures based on overall anthropometric measurements such as stature and weight and was approved by the Ethical Review Authority in Sweden (application No. 2023-07901-02). In total, 30 female and 31 male volunteers were tested, recruited using internal advertisements at Volvo Cars and Chalmers, and external advertisement through channels such as e-mails to SAFER partners, consultancy companies working in the safety arena, bike club members and Chalmers employees.

For the testing, the volunteers were informed about the procedure, provided consent and data such as year of birth, sex, car driving and traveling habits and anthropometric measures were taken (stature, seated height, weight, spine length, biacromial width, etc.). The volunteers were then dressed in tight fitting cotton undergarments. Anatomical landmarks were identified by palpation and black and yellow film-markers, or spherical markers, were attached to selected landmarks. The volunteers were then seated in the two seats, equipped with pins through the seat back to measure the volunteer external back shape through the seat back. Measurements of the landmarks using a FARO-arm as well as photographs of the volunteer and the probes for subsequent digitalization of positions was taken. The volunteers were asked to position their arms in the lap or on the thigh, as they preferred, and relax. In addition, for the reclined seat they were asked to rest their head on the head restraint. The probes/pins through the seat back, for indicating the external shape of the spine, was lightly pushed towards the volunteer by a tensioned rubber band. To convert these positions to internal spinal shape, the depth of the laminae of the vertebra subcutaneous of the pins was measured using ultrasound. To facilitate the conversion for a population of occupants with varying spine lengths, regression functions were fitted the individual ultrasound data that were used in the conversion.

The tested seating postures were an upright position with 25° seat back angle, with the seat at mid fore-aft travel and the lowest height position, Figure 1. For the reclined position, the prototype seat was set with a 45° seat back angle, hence reclined 20° more than the upright seat. Further modifications included an additional articulation of 17° 380 mm along the seat back frame from the seat back recliner joint, Figure 2. In addition, the head restraint was bent forward 11° at its base to provide a more vertical surface to support the head.

Figure 1. Volunteer seated in the upright seating posture with film marker instrumentation.

Figure 2. Volunteer seated in the reclined seating posture with film marker instrumentation.

4.2 Model Development and Integration

As a first step, the SAFER HBM was restructured into one main model file and fourteen subsystem files, of which one contained all nodes to simplify parametric morphing of the model, and the others regional subsystems (the head, abdomen and pelvis, lower extremities etc.) or functionalities (materials and muscle control algorithms for the Active HBM functionality). A Github repository was initiated for the SAFER HBM files, allowing for improved version control utilizing professional methods used for software development.

A second step was renumbering of the model to a new numbering system, to fit it into a smaller number range and simplify the use of several HBMs in one simulation. Then, new body parts in the form of the spine, costovertebral joints, claviculae, scapulae, humeri, femora and patellae were integrated and replaced the previously existing model parts, Figure 3. Substantial updates were made to the soft tissues of the abdomen, which were updated with a newly created high quality hexahedral mesh with tied, sliding only and surface to surface contacts for interacting structures in the abdominal cavity. For the leg and the lower arm completely new hexahedral meshes were created using a hexa-block method in the pre-processor ANSA (BETA CAE Systems, Luzern, Switzerland).

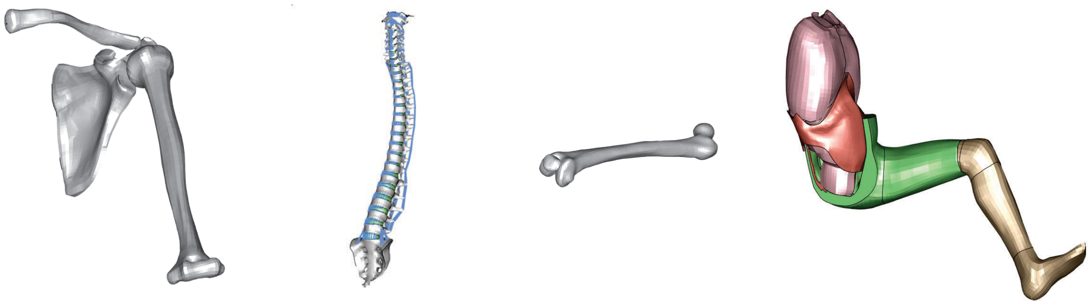


Figure 3. Updated body parts. From left to right: Claviculae, scapulae and humeri; spine; femur and patella; lower extremity and abdomen soft tissues.

After updating and integrating the new body parts, model robustness was assessed using five different high severity load cases to ensure model stability, Figure 4.

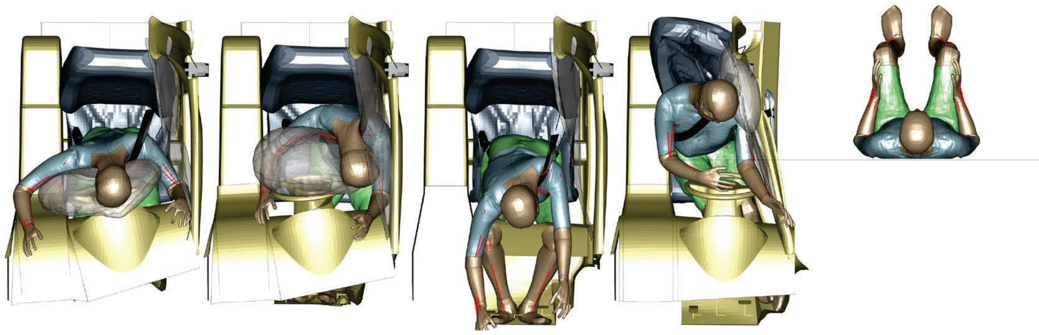


Figure 4. SAFER HBM high severity robustness verification load cases. From left to right: driver frontal impact, driver oblique impact, rear seat frontal impact, driver side impact and free fall on the back to rigid surface.

4.3 Model Validation

For validation of the updated SAFER HBM v11, possible objective validation acceptance metrics were reviewed and tested in the project, such as CORA (Gehre et al., 2009), ISO/TS 18571 (ISO, 2014) and the Biofidelity Ranking System (Hagedorn et al., 2022). It was decided to utilize the ISO/TS method, to conform with the proposed method in the ongoing Euro NCAP VT certification.

For a structured model validation that can be reproduced for later versions of the SAFER HBM, a catalogue of validation load cases aiming to address each body part at subsystem level and each impact direction on whole body level was developed.

4.4 Spine Injury Prediction

A number of cross-disciplinary workshops including the senior project members with expert knowledge in the field of injury biomechanics were held to discuss and identify potentially relevant cervical spine injury mechanisms, considering future automated vehicle and novel seating positions, resulting in a mapping of possible cervical spine injury mechanism to consider in future work. Moreover, the scholarly literature on previous cervical spine models and implemented injury prediction methods was reviewed. In addition, a simulation study with the updated SAFER HBM was done to reconstruct an accident to evaluate thoracic spine injury predictions using the fracture prediction previously developed for the lumbar spine by Iraeus et al. (2023), see Figure 5 and Figure 6. This accident was previously presented in Jakobsson et al. (2016), as Case 3.

Figure 5. The car from the accident included in the accident reconstruction study on thoracic spine injury prediction.

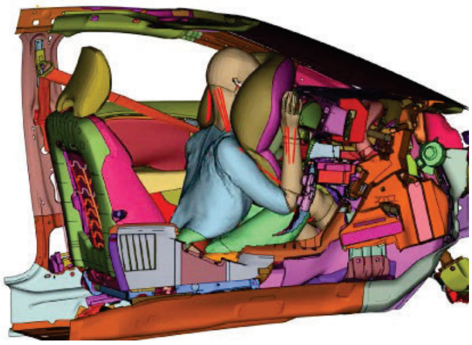


Figure 6. The interior model and the SAFER HBM v11.0.1 in the accident reconstruction.

4.5 Utilization

Performance specification and quality routines for the SAFER HBM were created by the project team, to ensure that coming updates have an equally high level of reliability before potential release to a broadened user base. For the validation results from the model validation part of the project, a framework for a validation catalogue using Jupyter Notebooks, web-based interactive computation platforms that allows for calculation and visualization of simulation results compared with test data, were implemented. Demonstrators of use cases with the SAFER HBM was developed, showing the detailed model structure and application in frontal impact sand motorcyclist impacts. Visualizations of some of these demonstrators was done using Virtual Reality (VR) equipment that allows for a 3D visualization of the HBM and simulation results. Lastly, a CAE setup of a high-severity rear-facing frontal impact, Figure 7, was created (Östh et al. 2024) and used for comparing the SAFER HBM v10 and v11 with the THOR, Hybrid III, BioRID and Post Mortem Human Subject (PMHS) data from an experimental test setup (Kang et al. 2020).

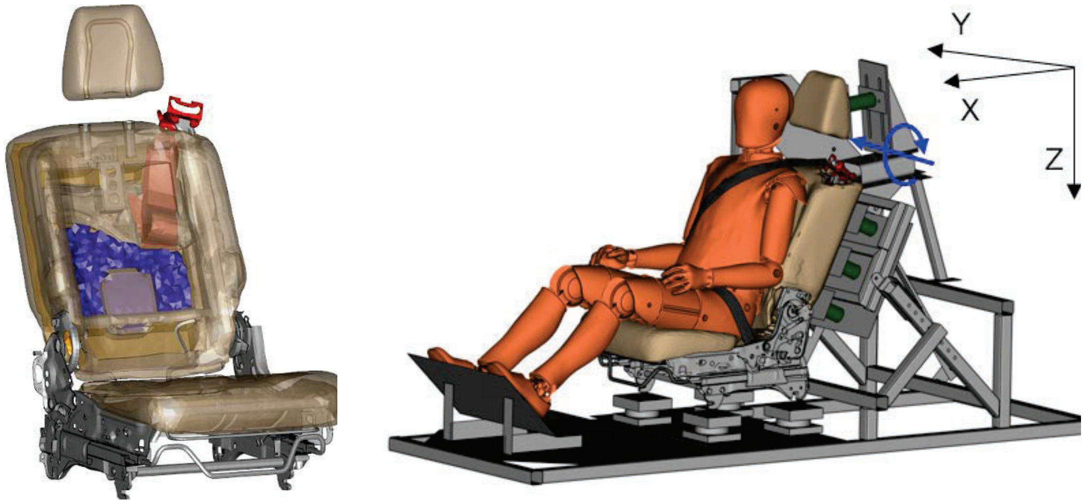


Figure 7. Seat model (left) and sled model with the THOR crash test dummy (right) developed for high-speed rear facing frontal impact validation of the SAFER HBM and comparison to the crash test dummies THOR, Hybrid III and BioRID. Figure adapted from Östh et al. (2024).

5. Objective

The overall purpose of this project was to make SAFER HBM a biofidelic, robust, competent, and attractive tool for the project partners' needs, and also contribute to prepare it for being able to share with the community. The specific goals included to further improve the model, with special attention on the spine, enhancing spinal kinematics and injury risk prediction, and to make it technically ready to enable global availability, by removing third party IP.

As part of the model development and integration work, it was also planned to update the spinal curvature to that recorded from the volunteer tests in the project. However, a milestone decision (M1) was taken to not include this update as this is a major model update that might change its response and the SAFER HBM was undergoing certification for upcoming Euro NCAP VT protocols during the project.

The project also aimed to expand the current state-of-the-art capabilities of SAFER HBM also to the cervical and thoracic spine, and this was reached by the update to these parts done. Another specific aim was to safeguard the unique capabilities to model the combined pre-crash and in-crash occupant in-crash response including muscle activation which is crucial for instance for prediction of cervical spine injuries.

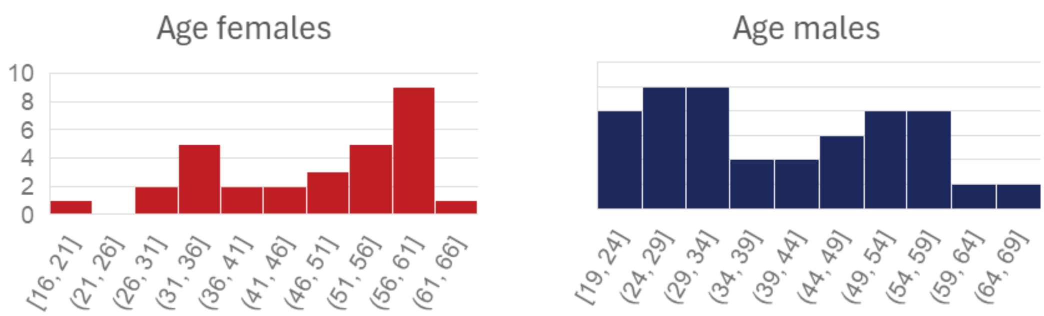
6. Results and Deliverables

At the start of the project, the SAFER HBM v10, was a state-of-the-art HBM with respect to tissue level rib fracture and brain injury prediction, and at the end of the project the updated SAFER HBM v11 was complemented by additional tissue level injury prediction for lumbar spine fracture prediction, and prepared for further tissue level injury prediction in the cervical and thoracic spine, the shoulder and the femora by the update of these body parts. The cervical spine will be further developed in a follow-up project that was granted (2023-02612, Advancing Neck Injury Prediction in Car Crashes using the SAFER HBM). In addition, the model was technically made ready for sharing to external parties as all third party IP was removed. A validation setup for high-speed rear-facing frontal impact was created and used to assess the SAFER HBM in a possible novel seating scenario for future automated vehicles.

The project delivered one PhD thesis, one MSc Thesis and six other scholarly publications/presentations.

6.1 Data for Spinal Curvature

For the 61 volunteers who participated in the tests aimed at determining spinal curvature and position of bony landmarks for seated occupants the age was rather evenly distributed for the males, while there were fewer young female volunteers in the sample, Figure 8. The volunteer stature and weight were close to those of the average Swedish population, Figure 8. However, this population average is taller and heavier than the SAFER HBM and these differences call for the development of a statistical model of the spinal curvature data.



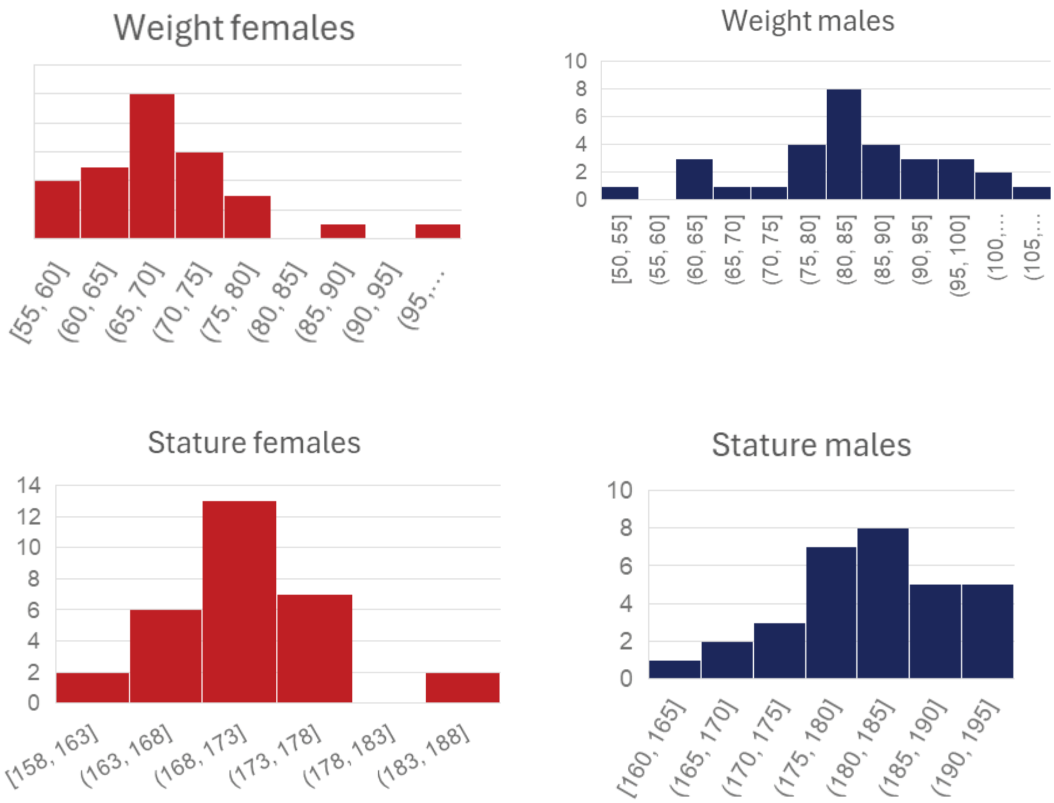


Figure 8. Volunteer characteristics distributions for age (years), weight (kg), and stature (cm).

Digitalization of the photos provided raw data, Figure 9. The figure shows a volunteer in the reclined seat with digitized data overlayed (in the form of coloured dots). The data match the original photo but with minor deviations which are due to compensation of the film-plane to marker distances. The raw body marker data were converted to bony landmark position, Figure 10. The raw seat data were also converted, to positions that indicated the curvature of the vertebrae laminae. For this conversion the distance between the cutaneous and the laminae of some selected locations along the spine were measured using ultrasound. A 3-deg polynomial curve was fitted each for each volunteer data set, Figure 11 and these regressions subsequently used in the estimation of the laminae curvature, Figure 12. To facilitate a proper estimation of the laminae curvature of the population of occupants with varying spine lengths, the regression functions must be used on an individual bases and with different data for the two seats tested (see example of occupant height at one probe position in the two seats tested, Figure 13).

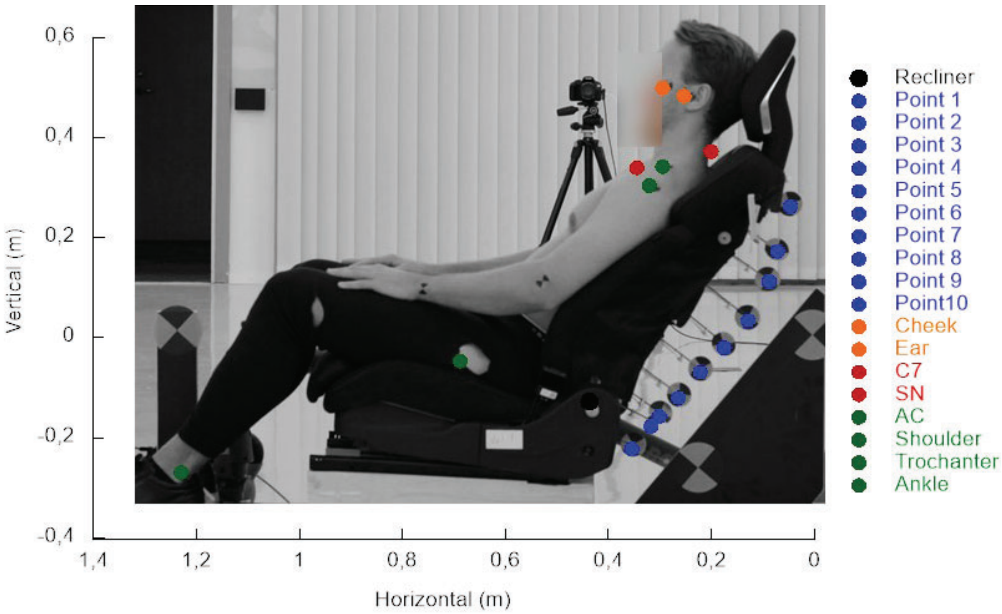


Figure 9. Example of a volunteer in the reclined seat with raw data from digitalization of the photos overlayed.

Figure 10. Photo of a volunteer in the reclined seat with overlay of digitized photo data converted to bony landmarks.

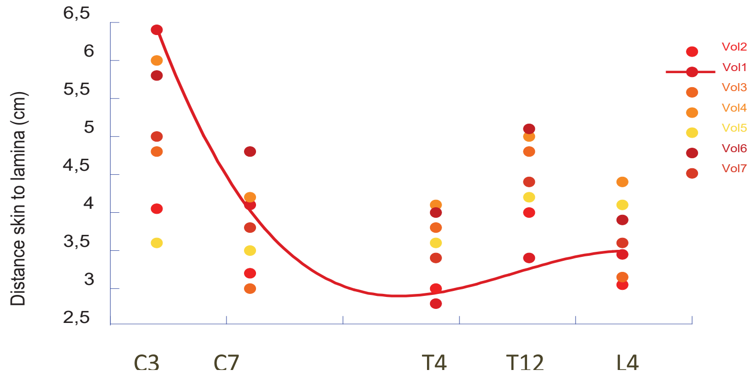


Figure 11. Example of raw volunteer skin-to-vertebrae lamina distances measured with ultrasound and a 3-deg polynomial fit function fitted the data.

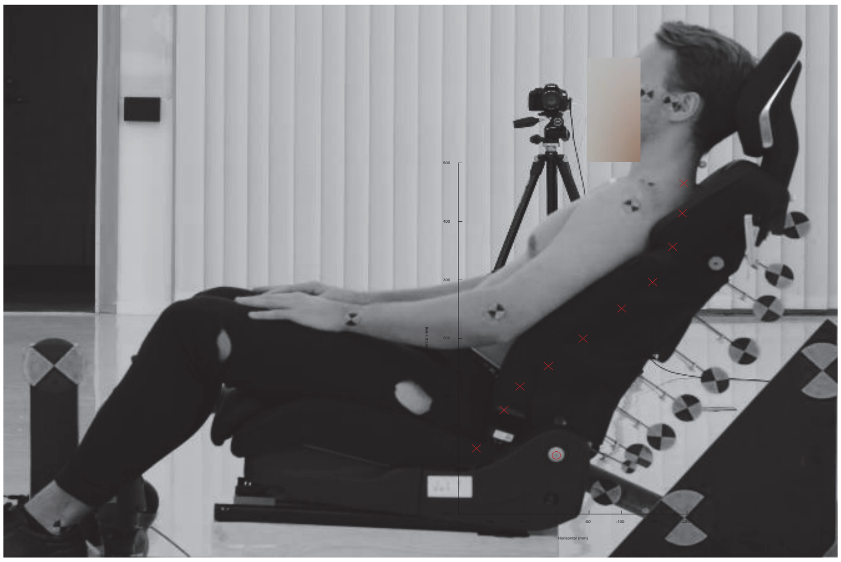


Figure 12. Photo of a volunteer in the more reclined seat with overlay of the vertebrae laminae data.

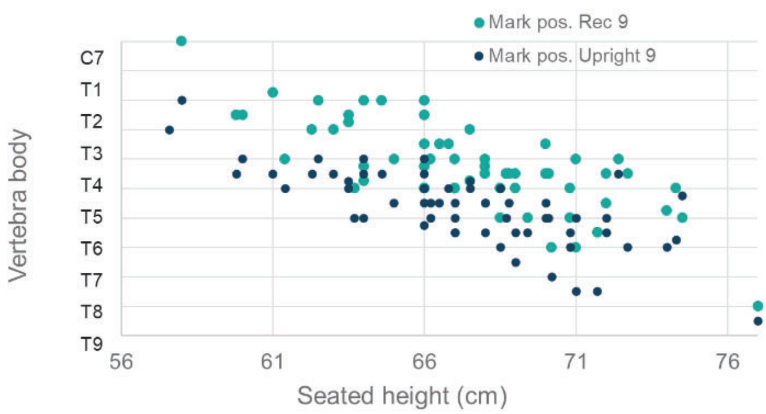


Figure 13. The volunteer vertebrae that were closest to point 9 in the reclined seat (green) and upright seat (blue).

6.2 Model Development and Integration

The model development and integration resulting in SAFER HBM v11 is described in detail in the report "Development of the SAFER HBM v11" from the project (Iraeus et al. 2024). The parts which were replaced or updated are shown in Figure 14, including the spine, costovertebral joints, claviculae, scapulae, humeri, femora and patellae. The updated v11 was simulated successfully for all the defined robustness load cases, Figure 4.

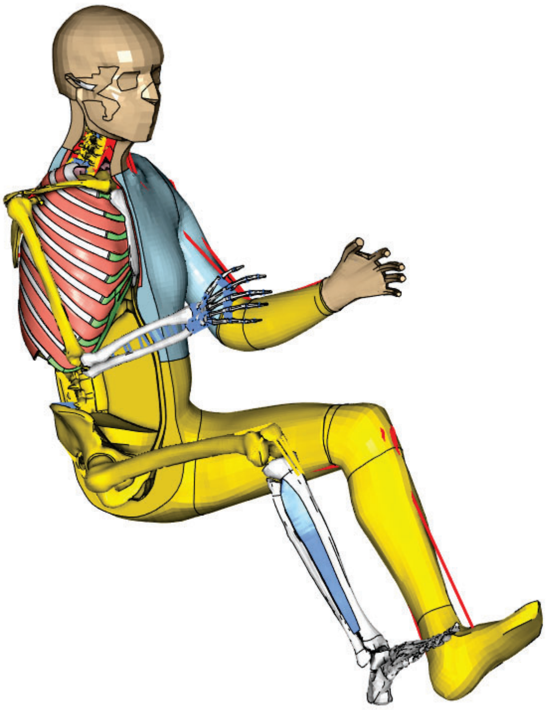


Figure 14. The resulting SAFER HBM v11 after updating. The gold/yellow body parts are parts which have been updated or replaced since the previous model version within this project.

6.3 Model Validation

More than 30 validation setups were developed, Table 1 in the Appendix, and implemented as Jupyter Notebooks in a Validation Catalogue for interactive evaluation of simulation results. As far as possible, time history data from the HBM simulations was compared with the experimental data using the ISO/TS 18571 method. For example, for the Forman et al. (2015) back hub impact, Figure 15, the HBM and impactor kinetics had an average an average ISO score of 0.74, with a range of 0.52–0.91. An ISO score of 1.0 means a perfect match between model prediction and test results.

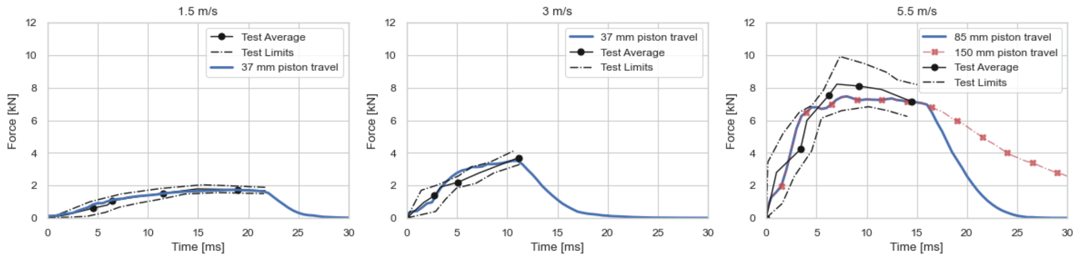


Figure 15. SAFER HBM v11 responses to Forman et al. (2015) back hub impacts with the HBM response in blue and red, compared with the experimental data in black. Figure extracted from the Jupyter Notebook Validation Catalogue developed in the project.

6.4 Spine Injury Prediction

The review of previous studies on HBM cervical spine injury prediction included 80 publications between 1987 and 2022. The most modelled injury was ligament failure, and the most common injury criterion was a force or stress Injury Assessment Reference Value (IARV). More advanced studies also included sequential ligament failures. Several studies reported on the importance of muscle tension for neck injury tolerance, which must be accounted for. Only one study included a probabilistic approach, using injury risk functions. Most often, for the rest of the reviewed studies, a threshold value (IARV) was used to indicate risk of injury.

For the thoracic spine injury prediction evaluation in the accident reconstruction study, feasible results, Figure 17, were achieved. In the real-life accident (Jakobsson et al. 2016) the occupant had a L5 compression fracture, but no thoracic spine injury which is reflected by the highest risk prediction for L5 in the simulation. These results warrant further validation and verification of the vertebral body strain-based injury criteria (Iraeus et al. 2023) also for the thoracic spine of the SAFER HBM.

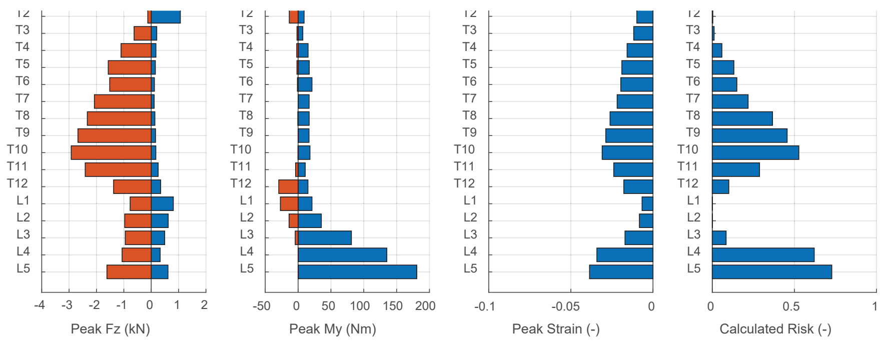


Figure 16. Peak vertebral cross-sectional Fz force and My moment, and peak superior-inferior strain and associated lumbar vertebra body fracture risk for the accident reconstruction simulation.

6.5 Utilization

The Jupyter notebook framework for the validation catalogue, Figure 17, was iteratively improved and used to assess the updated SAFER HBM v11. Moreover, the as part of the developed quality routines for model development, feedback from the industrial partners using the updated SAFER HBM was continuously reported back to the project via the Github issue handling system. In total several model version updates was done during the project with the milestone v11.0.0 followed by v11.0.1, v11.0.2, v11.0.3 and lastly v11.1.0.

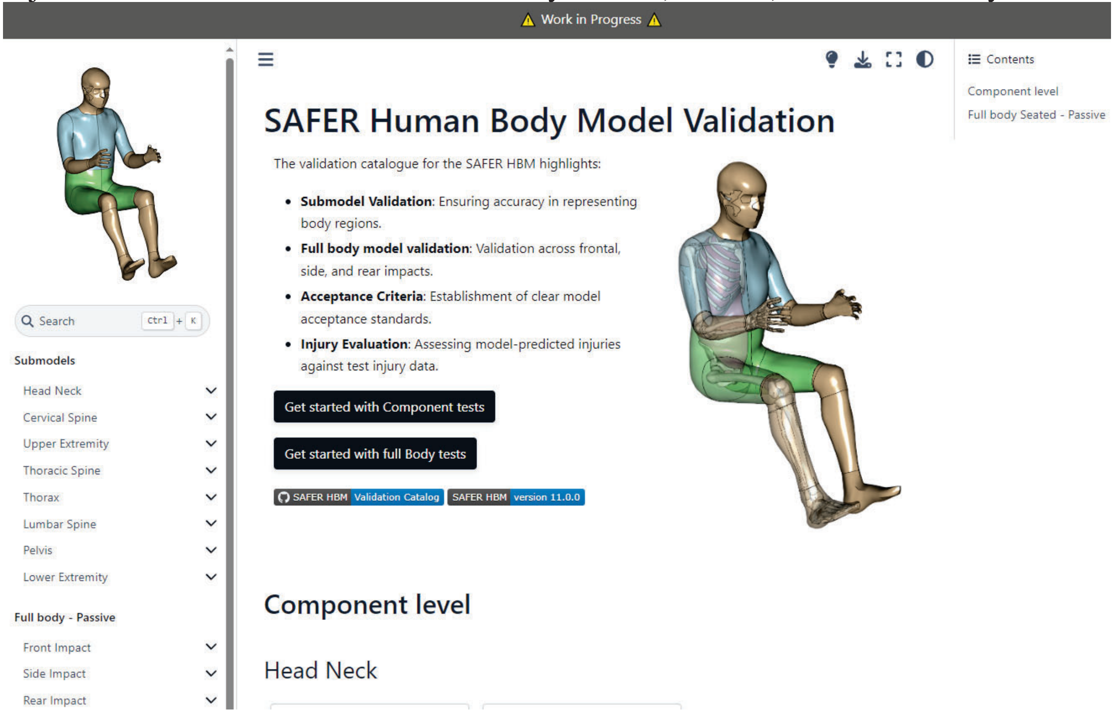


Figure 17. Jupyter notebook interface for the validation catalogue load cases (Table 1).

The performance of the SAFER HBM v11 was assessed in the high-severity rear-facing frontal impact setup that was created for the project. The average ISO Scores were above 0.74 for X accelerations and displacements. A detailed description of the complete validation is available in Östh et al. (2024) and an example is shown in Figure 18.

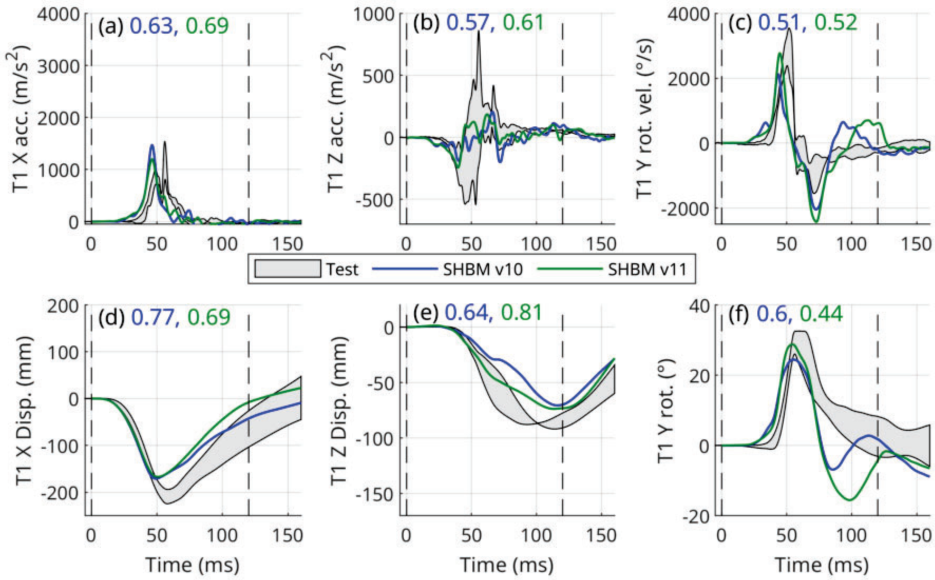


Figure 18. HBM T1 kinematics in the upright (25°) position in comparison with PMHS data from Kang et al. (2020). The number after the letter notation for each panel is the ISO score, and the time interval used for its calculation is indicated by the dashed lines. Acc. = Acceleration; Disp. = Displacement; Rot. = Rotation; Rot. Vel. = Rotational Velocity. Figure adapted from Östh et al. (2024).

6.6 Contributions to the Objectives of the FFI Program

The substantial update of the SAFER HBM in this project, including the cervical and thoracic spine, is central for modelling the seated occupant response in regular upright seating as today, but even more for future seating variations which can be expected in automated vehicles. The model now has the capability for advanced spinal fracture prediction for the lumbar spine and is ready for increased capabilities in the thoracic and cervical spine, which is essential to enable equal occupant protection for reclined seating. These developments enable the industrial project partners to develop future sustainable and safe vehicles, in line with the subprogramme "Safe Automated Driving" and the focus area of "Safety for road users inside and outside the vehicle". The project activities towards the Euro NCAP HBM certification for VT serves to make SAFER HBM a preferred tool for VT consumer information protocols around the world, adding visibility as well as safety benefits for the Swedish safety research community.

Thanks to the model advancements in the project, the SAFER HBM is now technically ready for enabling global availability, by the removal of third party IP. The other aspects of setting up the model for global availability in a robust, long-term and quality-assured context is ongoing. When achieved, the results of this and several prior FFI-research projects will reach a wider community and safety contributions. The development of demonstrators and the validation database developed in this project will also be essential contributor to the global availability context, for the introduction as well as to help maintain high quality of future versions of SAFER HBM.

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	The model developments are state-of-the-art, which also has been show-cased and shared through publications and presentations.
Be passed on to other advanced technological development projects	X	Project results are used as input to vehicle and restraint developments by the industrial partners, as well as three additional research projects involving the partners.
Be passed on to product development projects	X	The results are used in development of vehicles and restraints 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.
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 Euro NCAP, USNCAP and IIHS. The updated SAFER HBM v11 is part of the ongoing certification of HBMs for Euro NCAP VT.

The work done in the project to identify spine injury prediction challenges a provided the basis for a new project application for continued work with the cervical spine. It will further enable state-of-the-art injury prediction for novel seating postures in future automated vehicles was submitted and granted (2023-02612, Advancing Neck Injury Prediction in Car Crashes using the SAFER HBM). Additional projects building on this project's results are one on shoulder injury prediction for cyclists (TRV 2021/127378) and Safe and Comfortable Seat Belts for All (FFI 2024-03637).

7.2 Publication

The project delivered one PhD thesis, one MSc Thesis and six other scholarly publications/presentations.

Theses

Leledakis A (2024) *Heterogeneity in Car Occupant Safety – Using Numerical Simulations to Address Real-world Safety*. PhD Thesis, Chalmers University of Technology, Gothenburg, Sweden.

Svensson-Qvistberg S, Zetterlund G (2024) *Developing Lumbar Spine Fracture Injury Risk Functions for Frontal Impact Anthropomorphic Test Devices using Paired Human Body Model Simulations*. MSc Thesis, Chalmers University of Technology, Gothenburg, Sweden.

Peer-review Papers

Leledakis A, Östh J, Iraeus J, Davidsson J, Jakobsson L (2023) Influence of an Individualised Shoulder Belt Position for Diverse Occupant Anthropometries on Seatbelt Interaction in Frontal and Side Impacts. *Proc. IRCOBI Conference*, Cambridge, UK.

Östh J, Gröndahl E, Kang Y-S, Jakobsson L (2024) Validation of the SAFER HBM in Rear-Facing Upright and Reclined Position in High-Speed Frontal Impacts. *Proc. IRCOBI Conference*, Stockholm, Sweden.

Non-peer Review Papers/Presentations

Iraeus J, Brynskog E, John J, Östh J, Pipkorn B, Davidsson J (2024) Development of the SAFER HBM v11. Report 2024:06, Chalmers University of Technology, Gothenburg, Sweden. https://doi.org/10.5281/zenodo.10886711

Pipkorn B, Jakobsson L, Iraeus J, Östh J (2023) The SAFER HBM–A Human Body Model for Seamless Integrated Occupant Analysis for all Road Users. *Proc. 27th ESV Conference*, Yokohama, Japan.

Other Presentations

Pipkorn B (2024) Human Body Model for Tissue Based Injury Prediction. *Airbag* 2024.

Pipkorn B, Östh J, John J, Niranjan Poojary Y, Riazi A, Iraeus J (2024) SAFER HBM for all Road Users. *CARHS Human Modelling Symposium*.

8. Conclusions and Future Research

This two-year project has technically prepared the SAFER HBM for global use, creating a version free from third party IP, the SAFER HBM v11. The cervical and thoracic spine updates are central for modelling the seated occupant response in regular upright seating as today, as well as for future seating variations which can be expected in automated vehicles. These developments enable the industrial project partners to develop future sustainable and safe vehicles and restraint systems. The project activities towards the Euro NCAP HBM certification for VT allow to make SAFER HBM a preferred tool for VT consumer information protocols around the world. The project's work has also supported the development of the Euro NCAP protocol for HBM certification.

The SAFER HBM, in addition to advanced rib fracture and concussion risk prediction, now has the capability for advanced spinal fracture prediction for the lumbar spine and is ready for increased capabilities in the thoracic and cervical spine. The modelling of the spine is essential for overall occupant protection assessment in upright seating, and even more in reclined seating, for which the use of the fracture prediction is critical. The advancements of the cervical spine are important for equality, providing a fundament to adapt to different sizes and sex.

Future research, in addition to further developing advanced injury prediction for the cervical spine, should further develop injury prediction methods for HBMs. A challenge will be to verify the injury prediction for morphed HBMs, to allow for fully assessing the injury risk in the population. State-of-the-Art HBMs such as the SAFER HBM utilizes local, tissue level, injury criteria for example strain and as long as the geometric variation is captured when morphing HBMs to a new occupant size validity of the injury prediction should follow. However, this is challenged by the necessity to use non-converged FE meshes for current HBMs, which could mean that strain responses are affected by morphing and how to handle this influence requires further research.

Specific body areas of interest for improved modeling in HBMs and improved injury prediction are the lower extremities, with leg, foot and ankle injuries that can lead to a risk of long-term impairment. Improved injury prediction in this area would help analysis of occupants in vehicles, but also other road users. Strain based injury criteria for HBMs have typically been developed for skeletal structures such as the ribs or vertebral bodies and will also be relevant for the lower extremities. However, central to long term impairment injuries are also synovial joint injuries which require improved modelling in HBMs to capture local loads and provide metrics that can be used as injury criteria (for instance ligament strains). Similar to the cervical spine, lower extremity injuries are also influenced by muscle activation, which should be accounted for depending on occupant actions before and during crash (pre-crash braking drivers or bracing passengers).

Lastly, while the adult population can be covered by morphed HBMs such as the SAFER HBM, HBMs of children remain a more immature research area that gives rise to interesting questions on for instance chest injury prediction, which is mostly done targeting rib fractures for the adult population while injury mechanisms are different for children.

9. Participating Parties and Contact Persons

Autoliv	CHALMERS	SAHLGRENSKA UNIVERSITETSSJUKHUSET VGR	VOLVO
Bengt Pipkorn Karl-Johan Larsson Linda Eriksson	Johan Iraeus Jobin John Johan Davidsson Ali Riazi Yash Niranjan Poojary	Olle Bunketorp	Lotta Jakobsson Katarina Bohman Alexandros Leledakis, Industrial PhD student Emil Gröndahl Catherine Lef Jonas Östh (resp.) jonas.osth@volvocars.com, +46 728 88 91 72

10. References

Crandall J (2011) *ATD Thoracic Response Test Development Gold Standard Buck Condition 2: Force Limited Belt, 30 km/h Frontal Impact. A Report Prepared for NHTSA*, Cooperative Agreement No. DTNH22-09-H-00247, Washington D.C., USA.

Demetropoulos CK, Yang KH, Grimm MJ, Khalil TB, King AI (1998) Mechanical Properties of the Cadaveric and Hybrid III Lumbar Spines. *Stapp Car Crash Journal* 42.

Duma S, Schrieber P, McMaster P, Crandall J, Bass C, Pilkey W (1999) Dynamic Injury Tolerance for Long Bones of the Female Upper Extremity. *Journal of Anatomy* 194(3): 463–471.

Forman J, Lessley D, Kent R, Bostrom O, Pipkorn B (2006) Whole-body Kinematic and Dynamic Response of Restrained PMHS in Frontal Sled Tests. *Stapp Car Crash Journal* 50: 299–336.

Forman J, Perry B, Henderson K, Gjolaj JP, Heltzel S, Lessley D, Riley P, Salzar R, Walilko T (2015) Blunt Impacts to the Back: Biomechanical Response for Model Development. *Journal of Biomechanics* 48(12): 3219–3226.

Forman JL, Lopez-Valdes F, Lessley DJ, Riley P, Sochor M, Heltzel S, Ash J, Perz R, Kent RW, Seacrist T, Arbogast KB, Tanji H, Higuchi K (2013) Occupant Kinematics and

Shoulder Belt Retention in Far-Side Lateral and Oblique Collisions: a Parametric Study. *Stapp Car Crash Journal* 57: 343–385.

Gehre C, Gades H, Wernicke P (2009) Objective Rating of Signals using Test and Simulation Responses. *Proc. ESV Conference*, Stuttgart, Germany.

Guillemot H, Got C, Besnault B, Lavaste F, Robin S, Le Coz JY, Lassau JP (1998) Pelvic Behavior in Side Collisions: Static and Dynamic Tests on Isolated Pelvic Bones. *Proc. ESV Conference*, Windsor, ON, Canada

Hagedorn, H, Stammen J, Ramachandra R, Rhule H, Thomas C, Suntay B, Kang Y-S, Kwon HJ, Moorhouse K, Bolte JH IV (2022) Biofidelity Evaluation of THOR-50M in Rear-Facing Seating Configurations Using and Updated Biofidelity Ranking System. *SAE International Journal of Transportation Safety* 10(2): 291–375.

Harden AL, Kang Y-S, Hunter RL, Bendig A, Bolte JH IV, Eckstein NI, Smith AGF, Agnew AM (2022) Preliminary Sex-specific Relationships between Peak Force and Cortical Bone Morphometrics in Human Tibiae Subjected to Lateral Loading. *Proc. IRCOBI Conference*, Porto, Portugal.

Hardy WN, Schneider LW, Rouhana SW (2001) Abdominal Impact Response to Rigid-Bar, Seatbelt and Abdominal Loading. *Stapp Car Crash Journal* 45.

Iraeus J, Niranjan Poojary Y, Jaber L, John J, Davidsson J (2023) A New Open-Source Finite Element Lumabr Spine Model, its tuning and validation, and Development of a Tissue-based Injury Risk Function for Compression Fractures. *Proc. IRCOBI Conference*, Cambridge, UK.

ISO (2014) *ISO/TS 18571 Road Vehicles – Objective Rating Metric for Non-Ambigous Signals*. International Standard Organization, Geneva, Switzerland.

Ivarsson J, Crandall J, Genovese D, Bose D, Bolton J, Provencher J-A, Erwin M, Manaswi A, Untariou C (2006) *Development of a New Tibia Index. A Report Prepared for NHTSA*, Cooperative Agreement No. DTNH22-01-H-07292.

Ivarsson J, Genovese D, Crandall JR, Bolton JR, Untaroiu CD, Bose D (2009) The Tolerance of the Femoral Shaft in Combined Axial Compression and Bending Loading. *Stapp Car Crash Journal*, 53: 251.

Jakobsson L, Björklund M, Westerlund A (2016) Thoracolumbar Spine Injuries in Car Crashes. *Proc. IRCOBI Conference, Malaga, Spain.*

Kang YS, Kwon HJ, Stammen J, Moorhouse K, Agnew AM (2020) Biomechanical Response Targets of Adult Human Ribs in Frontal Impacts. *Annals of Biomedical Engineering* 49(2): 900–911.

Kang YS, Stammen J, Moorehouse K, Bolte J IV (2018) Head and Neck Response of Post Mortem Human Subjects in Frontal, Oblique, Side and Twist Scenarios. *Proc. IRCOBI Conference*, Athens, Greece.

Kang YS, Stammen J, Ramachandra R, Agnew AM, Hagedorn A, Thomas C, Kwon HY, Moorhouse K, Bolte JH IV (2020) Biomechanical Responses and Injury Assessment of

Post Mortem Human Subjects in Various Rear-facing Seating Configuration. *Stapp Car Crash Journal* 64: 155–212.

Kemper A, Stitzel J, Matsuoka F, Masua M (2005) Biofidelity of the SID-IIs and a Modified SID-IIs Upper Extremity: Biomechanical Properties of the Human Humerus. *Proc. ESV Conference*, Washington, DC, USA.

Kemper AR, McNally C, Duma SM (2008) Dynamic Compressive Response of the Human Pelvis Axial Loading of the Sacroiliac Joint. *Biomedical Sciences Instrumentation*, 44: 171–176.

Kent R, Lessley D, Sherwood C (2004) Thoracic Response to Dynamic, Non-impact Loading from a Hub, Distributed Belt, Diagonal Belt, and Double Diagonal Belts. *Stapp Car Crash Journal* 48: 495.

Kindig MW (2009) *Tolerance to Failure and Geometric Influences on the Stiffness of Human Ribs under Anterior-Posterior Loading*. PhD Thesis, University of Virginia, Charlottesville, VA, USA.

Lebarbé M, Petit P (2012) New Biofidelity Targets for the Thorax of a 50th Percentile Adult Male in Frontal Impact. *Proc. IRCOBI Conference*, Dublin, Ireland.

Miller CS, Madura NH, Schneider LW, Klinich KD, Reed MP, Rupp JD (2013) PMHS Impact Response in 3 m/s and 8 m/s Nearside Impacts with Abdomen Offset. *Stapp Car Crash Journal* 57.

Nightingale RW, Chancey VC, Ottaviano D, Luck JF, Tran L, Pange M, Myers BS (2007) Flexion and Extension Structural Properties and Strengths for Male Cervical Spine Segments. *Journal of Biomechanics* 40: 535–542.

Ortiz-Paparoni M, Op't Eynde J, Kait J, Bigler B, Shridharani J, Schmidt A, Cox C, Morino C, Pintar F, Yoganandan N, Moore J, Zang JY, Bass CR (2021) The Human Lumbar Spine during High-rate under Seat Loading: a Combined Metric Injury Criteria. *Annals of Biomedical Engineering* 49:3018–3030.

Ortiz-Paparoni MA, Pigue M, Cameron R (2020) Building a Whole Spine from Segments: Lumbar Spine Response during Dynamic Compression. *Proc. IRCOBI Conference*, Online.

Panjabi MM, Brand RA, White III AA (1976) Mechanical Properties of the Human Thoracic Spine – As Shown by Three- Dimensional Load-Displacement Curves. *Journal of Bone and Joint Surgery* 58-A(5): 642–652.

Panjabi MM, Crisco JJ, Vasavada A, Oda T, Cholewicki J, Nibu K, Shin E (2001) Mechanical Properties of the Human Cervical Spine as Shown by Three-Dimensional Load-Displacement Curves. *Spine* 26(24): 2692–2700.

Shaw G, Parent D, Purtsezov S, Lessley D, Crandall J, Kent R, Guillemot H, Ridella SA, Takhounts E, Martin P (2009) Impact Response of Restrained PMHS in Frontal Sled Tests: Skeletal Deformation Patterns under Seat Belt Loading. *Stapp Car Crash Journal* 53: 1–48

Stemper BD, Yoganandan N, Pintar FA, Response Corridors of the Human Head-Neck Complex in Rear Impact (2004) *Annual Proceedings/Association for the Advancement of Automotive Medicine*, Miami, FL, USA.

van Ratingen M (2020) Update on Virtual Testing in safety assessment of new vehicles from Euro NCAP. IRCOBI pre-conference workshop “VIRTUAL-OSCCAR Workshop: Progress in Virtual Testing for automotive applications”, 8 September 2020, online.

Viano DC (1989) Biomechanical Responses and Injuries in Blunt Lateral Impact. *SAE transactions, Journal of Passenger Cars* 98: 1690–1719.

Viano DC, Hardy WN, King AI (2001) Response of the Head, Neck and Torso to Pendulum Impacts on the Back. *Crash Prevention and Injury Control* 2(4): 289-306.

Wilke H-J, Herkommer A, Werner K, Liebsch C (2017) In Vitro Analysis of the Segmental Flexibility of the Thoracic Spine. *PLoSOne* 12(5): e0177823.

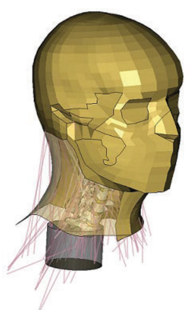
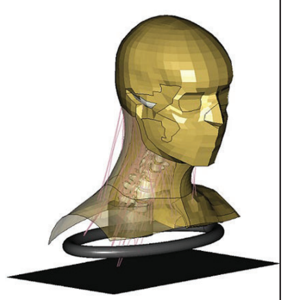
Yamamoto I, Panjabi MM, Crisco T, Oxland T (1990) Three-dimensional Movements of the Whole Lumbar Spine and Lumbosacral Joint. *Spine* 14(11): 1256–1260.

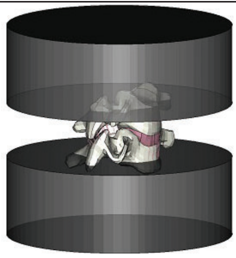
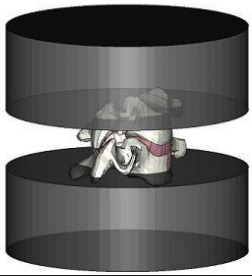
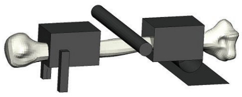
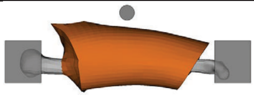
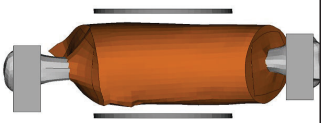
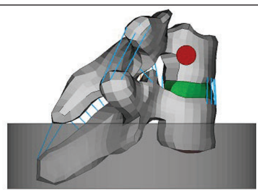
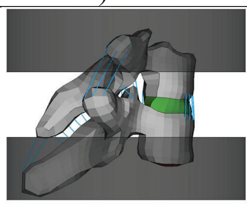
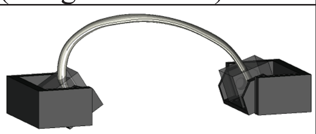
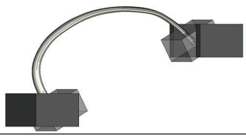
Zhang Q, Kindig M, Li Z, Crandall JR, Kerrigan JR (2014) Development of Structural and Material Clavicle Response Corridors under Axial Compression and Three Point Bending Loading for Clavicle Finite Element Model Validation. *Journal of Biomechanics* 47(11): 2563–2570.

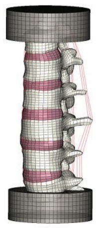
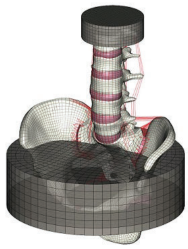
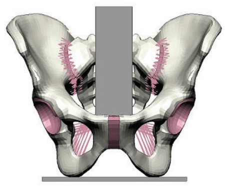
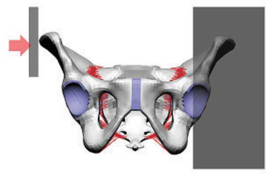
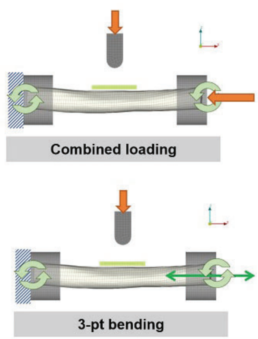
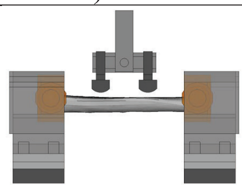
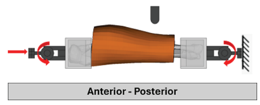
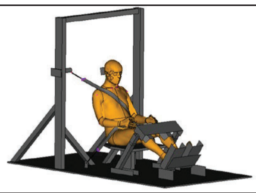
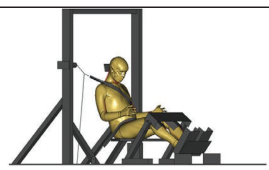
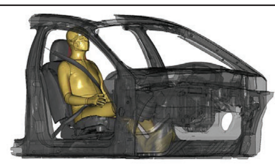
11. Appendix

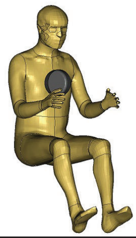
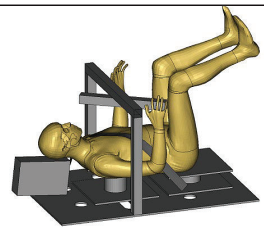
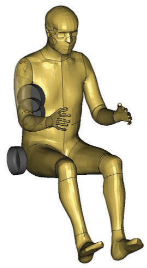
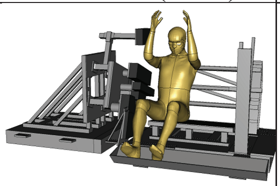
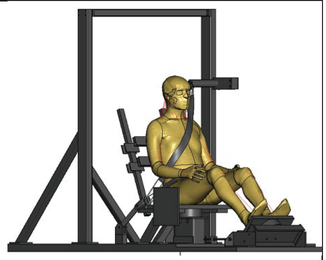
A summary of the validation setups developed in the project is presented in Table 1.

Table 1. Overview of the load case and validation setups developed in the project.

Submodel			
Head Neck	Extension (Stemper et al. 2004).	Front, lateral, oblique and twist (Kang et al. 2018)	
			
Cervical Spine	Flexion-Extension (Nightingale et al. 2007)	Axial rotation and Bending (Panjabi e t al. 2001)	

			
Upper Extremity	Humerus Three-point Bending (Kemper et al. 2005)	Clavicle Axial Compression and Three-point Bending (Zhang et al. 2014)	Upper Arm Three-point bending (Duma et al. 1999)
			
Upper Extremity cont.	Upper Arm Compression (Kemper 2005)		
			
Thoracic Spine	Axial Tension and Compression (Panjabi 1976)	Axial Rotation, Lateral and Flexion-Extension (Wilke et al. 2017)	
			
Thorax	Isolate Rib Anterior-Posterior Bending (Kang et al. 2020)	Isolate Rib Anterior-Posterior Bending (Kindig et al. 2009)	
			
Lumbar Spine	Compression-Tension and Bending (Demetropoulos et al. 1998)	Axial-Rotation and Bending (Yamamoto et al. 1990)	Dynamic Comeprssion (Ortiz-Paparoni et al. 2020; 2021)

			
Pelvis	Sacrum Inferior-Superior Loading (Kemper et al. 2008)	Pelvis Lateral Loading (Guillemot et al. 1998)	
			
Lower Extremities	Femur Bending and Axial Compression (Ivarsson et al. 2009)	Tibia Four-point Bending (Harden et al. 2021)	Leg Bending and Combined Loading (Ivarsson et al. 2006)
			
Whole Body			
Frontal Impact	Shaw et al. (2009)	Crandall et al. (2011)	Forman et al. (2009)
			
	Lebarbé et al. (2012)	Kent et al. (2004)	Hardy et al. (2001)

			
Side Impact			
	Viano et al. (1989)	Miller et al. (2013)	Forman et al. (2013)
			
Rear Impact			
	Viano et al. (2001)	Forman et al. (2015)	Kang et al. (2020)/ Östh et al. (2024)