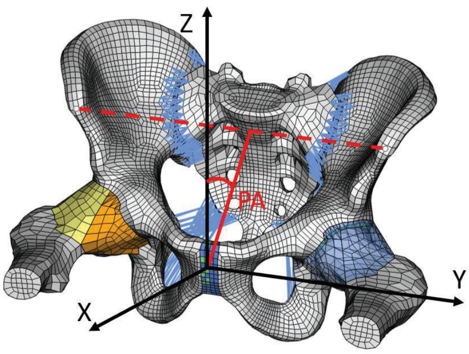
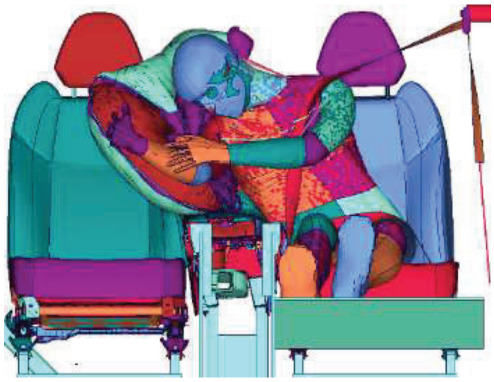
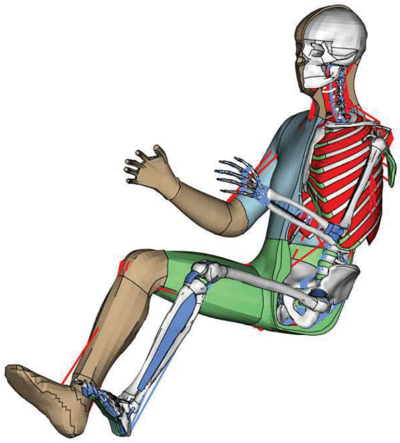
Pelvis and Spine Injury Predicting Models for Women and Men in a Variety of Seating Positions in Future Autonomous Cars (I-HBM step 4)

Public report







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Projekt inom: Trafiksäkerhet och automatiserade fordon

FFI Fordonsstrategisk Forskning och Innovation

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1 Summary

The SAFER human body model (HBM) was further developed and refined to improve the capability of the model to predict kinematics and injury risk for women and men of varying sizes. The main developments were to the pelvis and lumbar spine and the capability to predict injury risk in these.

A statistical shape model of the pelvic bone was developed based on CT scans from 132 adults. The complete model represents 90% of the shape variance in the dataset, while it was shown that using overall anthropometric variables (sex, age, stature, and BMI) the model could predict only about 30% of the variance. Based on the statistical model a new detailed morphable pelvis finite element model was developed using the population average as baseline. The development of the pelvis model included calibration of the pubis symphysis, calibration and validation of the sacro-iliac joint and complete pelvis model validation by reconstructing published quasi-static and dynamic lateral loading experiments. With the new pelvis model, a first step towards developing the capability to predict iliac wing fractures was taken.

Lumbar spine models of an average female and an average male, in addition to a tissue-based injury risk function, were developed and validated. The kinematic and kinetic validation of the lumbar spine model showed that the model compared reasonable to the published experimental data, with axial compression and flexion predictions being closest to experimental results. Using the same method as for the lumbar spine, a model of the cervical and thoracic spine was also developed for later integration into the SAFER HBM. The tissue-based lumbar spine vertebra fracture risk function was based on trabecular compressive strain in the superior-inferior direction. The criterion was based on a fracture onset mechanism, which means that the risk prediction most likely is conservative. In comparison to other recently proposed criteria, the developed injury risk function seemed to have higher precision in predicting the risk for vertebral fracture. The lumbar spine model with the tissue-based injury risk function will be integrated in the next version of SAFER HBM that is planned to be released in December 2023.

A new version of SAFER HBM, the SAFER HBM v10.0, was compiled in the project. The new pelvis model, corresponding to a 50%-ile male, was integrated into the model. Other modifications were to the head model (KTH head model), torso, arms, legs, shoulder and muscle control system. The pre-and post-processing tools were all updated to accommodate the new model. The model was validated by reconstructing published far-side side-impact crash tests (Far-Side), with post mortem human subjects (PMHS), in addition to real world vehicle crashes extracted from Volvo Cars' accident database.

To enable development of the SAFER HBM capability to predict submarining (lap belt slides over iliac wings of the pelvis), further updates to the model were done. For this purpose, a development version of the model, the SAFER HBM v10.1.x, was compiled with updates to the geometry of the pelvis and soft tissue properties, as well as the new lumbar spine model. Whole-body validation of the model was carried out including seven different submarining-related scenarios, focusing on the thigh/hip/abdomen updates.

To enable further studies of submarining risk in future seating positions a seat and seatbelt model with and without an anti-submarining system (pelvis restraint cushion) was developed and validated. The model was validated by means of sled tests with the THOR dummy. The tests comprised either a production or a semi-rigid laboratory seat in which the seat back and seat pan angles were varied. The seatbelt system consisted of a state-of-the-art retractor with pretensioning and load limiting. Generally, there was good agreement between the model predictions and mechanical test results for all seating positions. The validated seat and seat belt system will, when the new version of SAFER HBM becomes available, be used for further evaluations of the capability of SAFER HBM to predict submarining and injury risk. In addition, the models will be

used in parametric studies investigating the influence of various countermeasures on submarining and lumbar spine vertebra fracture risk.

The development of SAFER HBM started in 2008 and has been carried out by a series of successful FFI financed projects, with collaborative efforts by industrial and academic partners. The current project partners included Chalmers, Autoliv, Volvo Cars and Sahlgrenska University Hospital. In total, the project has generated one licentiate degree, seven publication (whereof six peer-reviewed), one licentiate thesis and four master’s theses. The project has provided the partners with a state-of-the art human body model that is capable of predicting submarining risk for average males and lumbar spine vertebra fracture risk for varying ages of vehicle occupants. The tool will be used by the industrial partners to develop and evaluate possible countermeasures that will help protect women and men of varying ages, height, and weights in both upright and reclined seating positions, in future vehicles with or without high degree of automation.

2 Background

Future passenger cars are likely to facilitate a larger variety of seating positions compared to today’s cars. In particular, reclined seating positions are predicted to become more frequent with the introduction of highly automated or “self-driving” vehicles (Östling et al., 2019; Jorlöv et al., 2017). The reclined seating position can result in unfavorable occupant kinematics in a crash and injury prediction assessment needs are beyond capabilities of current crash test dummies and finite element human body models (HBMs). In addition, occupant characteristics, such as sex, age and weight, have influence on risk of injuries and fatalities in vehicle crashes (Bose et al., 2011; Kahane, 2013; Forman et al., 2019; Abrams and Bass, 2020). Obesity, an increasing anthropometric trend, is identified as a risk factor for adverse outcomes, including death, in vehicle crashes (Zhou et al. 2006; Chooi et al. 2019). Hence, in order to maintain and improve occupant protection in passenger cars, today’s challenges include addressing a wide range of the vehicle population, alternative seating positions as well as capabilities of assessing injuries at a more detailed level.

Current standardized tests use crash test dummies, also known as Anthropomorphic Test Devices (ATDs), to assess injury risks. However, current ATDs (both mechanical and virtual) have limitations in assessing injury risk with various seating positions and occupant characteristics due to their design constraints. Therefore, to maintain current level of safety for new seating positions and to enable further reductions of people killed and injured in traffic there is a need to include advanced HBMs in the development of restraints.

These HBMs and injury prediction tools have to be developed and validated for assessment of various occupant sizes and variations in seating positions, such as reclined. The challenges when occupants are seated reclined, include unfavorable occupant crash kinematics, potential submarining (lap belt slides over iliac wings of the pelvis) and lumbar spine loading, in addition to altered seat-belt loading paths. Submarining may result in injuries to internal organs and high lumbar spine loads increased risk for vertebral fractures. In addition, in future vehicles the pelvis may be exposed to high loads beyond current types of vehicles.

The development of the SAFER HBM started in 2008 (Pipkorn et al. 2023). The baseline SAFER HBM corresponds to a 50%-ile male, with a weight of 77 kg and stature of 175 cm (Schneider et al. 1983). The development of the model started with modifications to the THUMS v3, for instance updated material properties for low-g events (Östh et al. 2012) and modifications to the ribcage (Mendoza-Vazquez et al. 2013) that were carried out in the FFI financed projects (Diarienr: 2010-02860) Active *human body models for virtual occupant response, step 2* (“A-HBM 2”) and (Diarienr: 2013-01287) *Improved injury prediction using HBM, step 2* ("I-HBM 2”).

A head model developed at the Royal Institute of Technology (Kleiven 2007) was integrated into the SAFER HBM in the FFI project (Diarienr: 2010-00764) *Human body model with active neck and detailed head - for neck and brain injury prediction* ("Pedestrian-HBM I"). In the FFI project (Diarienr: 2015-04864) "*Development of implementable omni-directional chest and spine injury criteria for human body models ("I-HBM III")* SAFER HBM v8 was updated with a new detailed generic rib cage model, including an updated sternum (Iraeus et al. 2020, Iraeus et al. 2019). A strain-based probabilistic method to predict rib fracture risk (Forman et al. 2012) with whole-body FE models was implemented and validated. Furthermore, the forearms (radius, ulna, carpals, metacarpals, phalanges, and ligaments) were replaced with a new model (Bayat and Pongiaporte 2020) in the FFI project (Diarienr: 2017-03070) *Identification and prediction of injuries with long-term consequences* ("Long-term"). Injury risk functions for the new arm models to assess radius and ulna fractures were developed to improve the capability of SAFER HBM to assess injuries with frequent long-term consequences.

The current version of the SAFER HBM is considered a world leading, efficient, and biofidelic tool, with injury prediction capabilities for development and validation of protection systems for road users inside and outside the vehicle (Pipkorn et al., 2023). The SAFER HBM is capable of predicting occupant kinematics and injury risk at a level of biofidelity beyond the capability of other HBMs and current ATDs.

3 Aim, Research Questions and Method

3.1 Aim and Research Questions

The main aim was to enhance methods used in the assessment of car occupant protection in typical and alternative seating positions for the diverse population. Three subgoals were defined. The first included development and validation of a new generic morphable pelvis capable of predicting submarining risk fractures. The second was development of a lumbar spine model including a fracture risk function and the third to apply the model to demonstrate seat and restraint system developments.

In addition to these aims, the following research questions were formulated:

- How can pelvis to lap belt, pelvis to seat, and pelvis to car interior interactions be predicted for a population of female and male car occupants with various body compositions for various seating positions; upright and reclined in current and future crash scenarios?
- How can pelvic skeletal injuries and submarining be predicted using HBMs?
- How can lumbar spine fractures be predicted using HBMs?

3.2 Methods

The project was a collaboration including medical and engineering competences. Partners were several senior researchers from the university, a car manufacturer, a restraint developer and a university hospital. In addition, a PhD student was tied to the project. included development of body part models and injury risk functions. It also included whole-body model integration for model robustness evaluations and applied studies. In addition, a sled test series was undertaken with the aim to enable further improvements of the model and refinement of the restraint models. The applied studies focused on submarining evaluations and countermeasure development.

Pelvis Model

The development of the new detailed morphable pelvis finite element model was based on five steps (Figure 1), including activities such as; landmarking of subjects and template, registration with Generalized Procrustes Analysis (GPA), morphing of the template mesh to each subject geometry using landmarks to create corresponding node sets, performing Sparse Principal Component Analysis (SPCA) on morphed subject-specific models and generating a morphometric model. This is further described in Brynskog et al. (2021). Based on the average pelvic shape defined with the statistical model, a detailed pelvis finite element model was built as the baseline. This new pelvis finite element model can be morphed to different pelvic shapes using the statistical model predictions. The coupling of the finite element model with the statistical model prediction is further described in Brynskog et al. (2022). Calibration and validation of the pubic symphysis and sacro iliac joint of the new pelvis finite element model was carried out by means of published physical tests, see Brynskog et al. (2022). The model of the pubis symphysis was calibrated by reconstructing quasi static axial compression and tension tests by Miller et al. (1987). The model of the sacro iliac (SI) joint was calibrated by reconstructing force and moment loads through three orthogonal directions through the centre of the sacrum, based on tests by Dakin et al. (2001). The complete pelvis model was validated by means of quasi-static and dynamic lateral loading experiments on denuded pelvic bones (Guillemot et al. 1998). Both the pubis symphysis and the SI joint were calibrated for an average male and an average female, while the complete model validations were carried out for the average male and female.

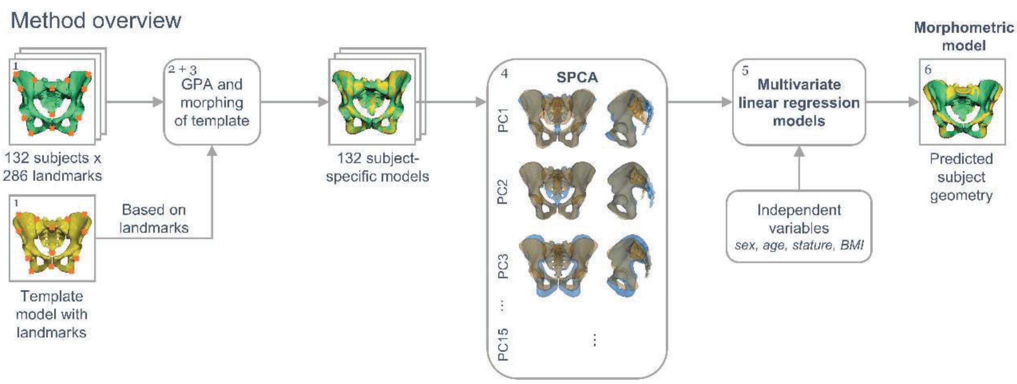


Figure 1. Schematic overview of method used. (1) Landmark subject geometries and template model, (2) align and scale subject geometries to the template model using GPA on landmarks, (3) morph template model to scaled subject geometries using landmarks to create corresponding node sets, (4) perform SPCA on morphed subject-specific models, (5) perform multivariate linear regression analysis using overall anthropometric variables on GPA and SPCA results, (6) predict subject geometries using morphometric model.

Spine Models

A detailed lumbar spine finite element model, as well as a cervical and thoracic spine model were created. They were based on a geometry of an average sized female (Gayzik et al. 2009) and later morphed to an average sized male. The work with the lumbar spine was done partly in collaboration with the EU Projects OSCCAR and SAFE-UP, while the cervicothoracic spine was done within the current project using the same method as developed for the lumbar spine.

The material model parameters used were either from the literature or were manually tuned to past experimental data. As there was no data on initial unstretched ligament length for a spine in neutral posture, the unstretched ligament lengths were reverse engineered. This was done by simulating the stepwise removal of the ligaments of L4-L5 FSU in tests reported in Heuer et al. (2007) and Jaramillo et al. (2016).

Kinematic and kinetic whole lumbar spine validation was performed by comparing the predictions from the complete lumbar spine model to two published data sets of physical tests (Yamamoto et al. 1989 and Demetropoulos et al. 1998). The two data sets provide setups with complementing boundary conditions, shown in Figure 2. In the Yamamoto setup, the pure moment loads (extension-flexion, lateral bending, and axial rotation) were applied separately to the superior potting, and rotations were recorded at each vertebrae level. In the Demetropulos setup, the T12 vertebrae was constrained in epoxy (superior potting) and rigidly attached to the test fixture. The L5 was also potted in epoxy (inferior potting) and displacements was applied.

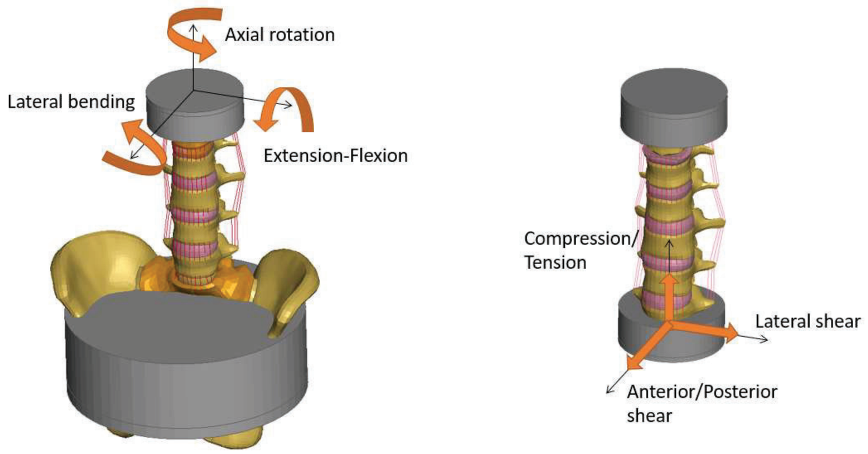


Figure 2. Illustration of the validation setups for the lumbar spine validation. Left: Yamamoto et al. (1989). Right: Demetropoulos et al. (1998). The orange arrows show the directions of the displacements applied.

Injury Risk Function Development

An injury risk function was developed for lumbar spine vertebra fracture predictions (Iraeus et al. 2023). The injury metric used for assessing the fracture risk was trabecular compressive strain in the superior-inferior direction. The risk function was based on trabecular strains predicted in reconstructions of published component tests with lumbar spines and injuries observed after the component tests were carried out. In these tests two and three vertebral body functional spinal units (FSUs) were loaded in compression or combined flexion-compression. The selected tests were presented in Brinkman et al. (1989), Duma et al. (2006), Granhed et al. (1989), Hutton and Adams (1982) and Tushak et al. (2022) (see Figure 3). The selected injury metric was the inferior-superior compressive strain in the trabecular bone of the vertebrae body.

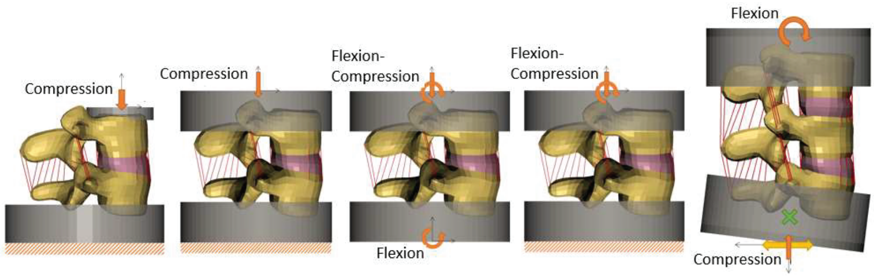


Figure 3. Schematics of the reconstructions of the FSU tests used to create injury risk functions (Iraeus et al. 2023). From left to right; Brinkman et al. (1989), Duma et al. (2006), Granhed et al. (1989), Hutton and Adams (1982), and Tushak et al. (2022). The orange arrows show the directions of the displacements applied. The green cross marks show the rotation centre. The yellow arrows indicate that the end was free to translate in that DOF, and the orange diagonal patterns mark that these ends were fixed.

Holländer and Riazi (2023) investigated if the new lumbar spine model and associated injury risk function successfully predicted lumbar spine fractures in reconstructions of two subsystem tests, one injurious (Stemper et al. 2018) and one non-injurious (Ortiz-Paparoni et al. 2020), one whole-body sled test (Richardson et al. 2020) and a real-world car crash (Pipkorn et al. 2019).

With the purpose to develop an injury risk function, iliac wing fractures from lap belt loading were analyzed in a Master thesis work (Umapathi Bhat 2023). In the thesis, FE simulations were used to reconstruct experiments conducted by the University of Virginia (Moreau et al., 2023). These experiments included 22 tests and each test was simulated by a subject specific model using the morphable pelvis model developed in the project.

Whole-Body Model Integration and Validation

The new pelvis, the lumbar and cervicothoracic spine models, being results from this project, will be integrated into the SAFER HBM V11 model planned for late 2023 (an integration of earlier versions of the new models was carried out within one of the MSc-thesis).

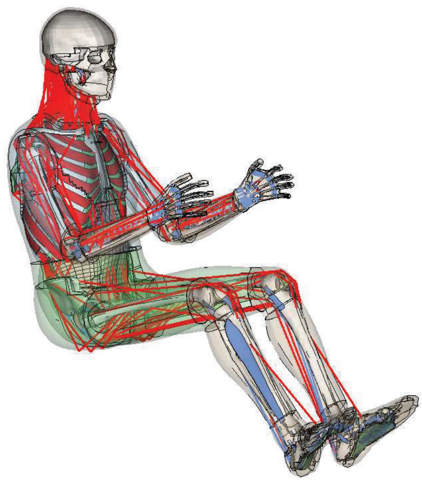


Figure 4. The SAFER HBM v10.0 with soft tissues made transparent to show the skeletal structure and muscle elements.

In 2020 the SAFER HBM V10.0 (Figure 4) was compiled based on the prior version (SAFER HBM V9 from 2018). The modifications include a generic rib cage, a refined torso and extremity soft tissue hexa-mesh, a new 50th percentile male pelvis, new leg models, new shoulder girdle joints, updated muscle control system and pre-and post-processing tools, from the prior joint “I-HBM III” project. The modification also included an updated head and new upper extremity models, these were taken from the prior “Long-Term” project.

The SAFER HBM v10.0 was validated for Far-Side impact kinematics (Pipkorn et al. 2021) for a generic sled environment and for one vehicle-based setup, shown in Figure 5. In addition, to further evaluate the capability to predict injury risk for the population of vehicle occupants, the 20 detailed accident reconstructions as used for SAFER HBM v9 (Pipkorn et al. 2019) were replicated with the SAFER HBM v10.0. These real-world crashes include a range of frontal impact situations. The capability of the model to predict rib fracture risk, using a tissue-based criterion, and lumbar spine fracture risk, using a force-based criterion, was focused.

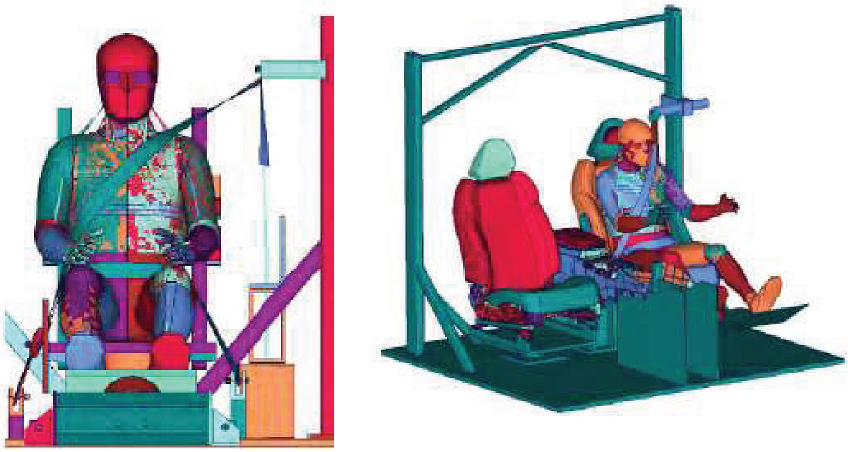


Figure 5. The SAFER HBM v10.0 Far-Side impact validation study based on Pipkorn et al. (2021). Left: generic lab environment Far-Side test setup. Right: Vehicle-based Far-Side test setup.

Enabling the development of the capability of SAFER HBM to predict submarining a number of modifications to the model were found necessary. These modifications were:

- Updating the lumbar spine and pelvis orientations to match available literature.
- Update the outer skin geometry based on the data from HumanShape.org
- Update the buttocks/thigh geometry to represent uncompressed geometry
- Update soft tissue thickness over ASIS
- Include fat and muscle distribution
- Update coupling between bone and soft tissue

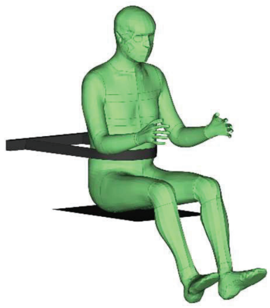
A development version of the model, SAFER HBM v10.1.x was compiled by integrating these modifications.

Whole-body validation of the SAFER HBM v10.1.x model was carried out focusing on submarining related loading scenarios. In the validation focused on the average male subject, simple boundary conditions were used to avoid additional validation of e.g. seat models and include both stationary and moving (sled tests) PMHS. These submarining related validation scenarios were:

- ‘Free-back, mid-abdomen, rigid-bar impact’ (Hardy et al. 2001), see Figure 6a
- ‘Abdominal seatbelt loading’ (Ramachandra et al. 2016), see Figure 6b
- ‘Pelvis seatbelt loading’ (Uriot et al. 2006), see Figure 6c

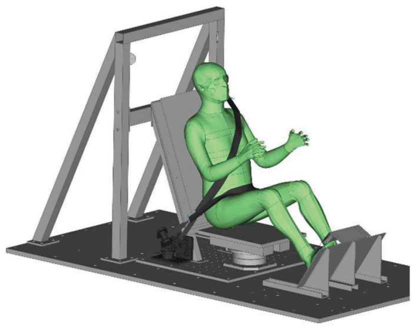
- ‘Sled tests with rigid seat’ (Luet et al. 2012), see Figure 6d)
- ‘Sled tests with semi-rigid seat’ (Uriot et al. 2015b)
- ‘Sled tests with a semi-rigid seat, reclined occupants’ (Richardson et al. 2020)
- ‘Quasi-static lumbar flexion tests’ (Uriot et al. 2015a)

a) ‘Free-back, mid-abdomen, rigid-bar impact’



b) ‘Abdominal seatbelt loading’

c) ‘Pelvis seatbelt loading’



d) ‘Sled test with rigid seat’

Figure 6. Four examples of the scenarios for submarining validation of the SAFER HBM v10.1.x.

With the purpose to further develop the capability of the SAFER HBM to predict submarining and enable assessment of submarining and injury risk in upright as well as in reclined seating position in vehicle environment a basic vehicle interior model was developed comprising a real vehicle seat and a state-of-the art seatbelt system. To validate the interior model, mechanical sled tests were carried out. Tests with two different seat back angles and three different seat pan angles (Figure 7), two different types of seat (a production seat and a lab seat called semi-rigid seat) were carried out. In addition, tests were carried with an anti-submarining system mounted in the production seat (Figure 8). The THOR dummy was used as human substitute in the sled tests. In total 22 tests were carried out. The tests carried out covered a wide range of seating positions such as upright as in today’s vehicles to various degrees of seatback and seat pan recline angles as in the future vehicles in which the occupants have a greater freedom to choose seating position. The validated vehicle interior model with be used with morphed versions of the SAFER HBM to evaluate and develop protection system for the population of vehicle occupants.

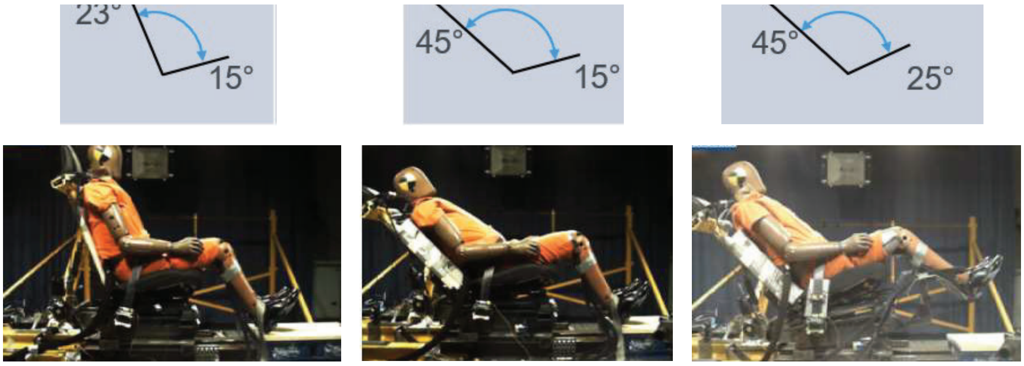
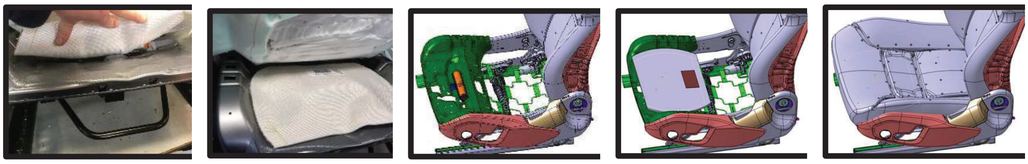


Figure 7. Schematics and photos of test with crash test dummies showing the three seating positions used in the tests. Left: seatback angle upright, middle: seatback angle reclined, right: seat pan angle raised.



Inflator and bracket | PRC (white) and seat pan | Inflator (orange) mounted on the seat pan (green) | PRC (blue) mounted on the seat pan (green) | Seat with foam

Figure 8. Photos and finite element models of the pelvis restraint cushion

Two seat and seatbelt models were developed, one production seat model and one model of a semi-rigid seat with deformation properties corresponding to the properties of average vehicles seats (Figure 9). A state-of-the-art seatbelt system was included for both seat models. A model of the THOR dummy (THOR-50M EU 1.8.1) was positioned and belted on the seat models (Figure 10) and sled simulations with an impact velocity of 50km/h and peak acceleration of 30g were carried out.

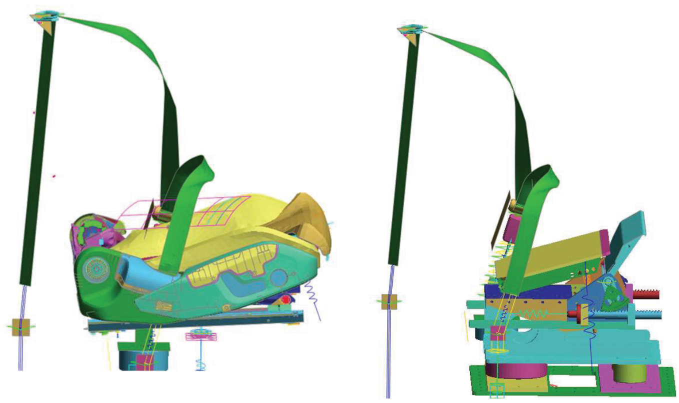


Figure 9. The models of the production seat (left) and the semi-rigid seat (right)

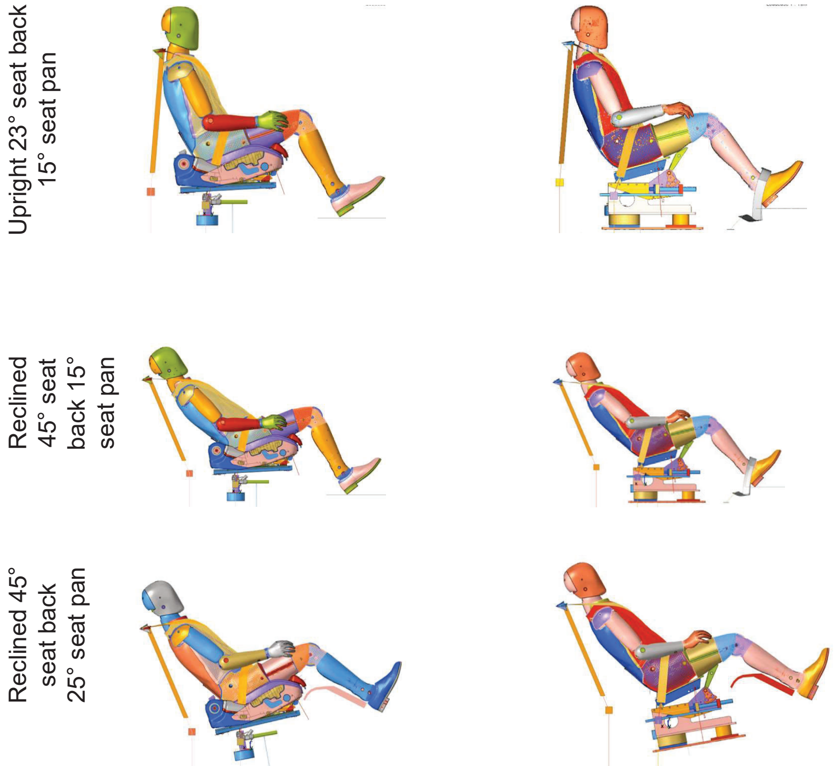


Figure 10. The THOR model in the production seat and the semi-rigid seat models

Using the results from the sled tests, the seat and seatbelt model was validated. The agreement between the predictions of the model and results from the mechanical tests were evaluated by means of CORrelation and Analysis (CORA) (Gehre et al. 2009). This analysis compares the time-history signals from a model to experimental data. Three cross-correlation measures, phase, shape/slope, magnitude/size, are weighted equally to calculate a CORA score on a scale from 0 to 1, with 1 being a perfect match. The analysis is divided into two sections, a boundary and a model prediction section. The WIAMan biofidelity rating system was used to assess the level of biofidelity of the model predictions (Pietsch et al. 2016).

To evaluate the numerical reproducibility of SAFER HBM repeated simulations were carried out quantifying the variation in model predictions for diverse computer systems at different sites and settings (Östh et al. 2021). Repeated simulations, with varying number of Central Processing Unit (CPU) cores and model decomposition, of four high severity load cases – a full frontal, near-side frontal oblique and side impact with a full set of driver restraints, as well as a full frontal with a seat belt only restraint. To analyze the variation in simulation responses of the six repeated FF simulations, Shapiro-Wilk tests were used to assess normality of the analyzed data. Each sample was assessed for equal variances using an F-test, and lastly a one-way analysis of variance was carried out to assess if the mean values from each computer system were different. For the simulation responses analyzed, the Coefficient of Variation (CV) was calculated as the Standard Deviation (SD) divided by the mean.

4 Goal

The project delivered on the goals to develop and validate a generic and injury predicting model of the human pelvis and adjacent body parts for SAFER HBM. The updated SAFER HBM is now capable of predicting risk of submarining, lumbar spine vertebra fracture risk, in addition to estimating iliac wing fracture risk. The model was successful in demonstrating seat and restraint system development assessment. Although, project duration was extended in time by 14 months (due to paternal leave and effects of the COVID-19 pandemic), the majority of the project plans were followed and met. Some deviations are described here.

During the project it was realized that more work was needed for the development of the body part models. Due to this, it was decided that the industrial partners took a larger share of the model development, exemplified by meshing of the cervicothoracic spine, a body part which was not included in the initial plan. The developments of the lumbar spine model and injury risk function were carried out in cooperation with the EU project SAFE-UP. Thanks to this, the current project could deliver beyond the initial plan; i.e. including a more advanced pelvis model than initially planned for, a refined femur and pelvis mesh in addition to an improved torso model and the cervicothoracic spine model.

The initial plan included two full scale crash tests as part of demonstrating HBM versus ATD capabilities. These tests were excluded and transferred into other activities, e.g., a more extensive sled series than originally planned, additional model refinements such as remeshing the upper torso and improvements to the mobility of the shoulder were carried out. Instead, the HBM versus ATD capabilities could be covered by published activities by the partners in parallel research projects and included within the whole-body application part of the report.

5 Results and Goal Fulfillment

The project has taken important steps in developing tools to assess safety for all vehicle occupants by addressing injuries that are expected to be more frequent in crashes with future vehicles. Pelvis spine models with geometry of humans of various sizes for prediction of humanlike kinematics were developed. Risk functions for predictions of lumbar spine and iliac wing fracture risks were developed. With the new injury criteria and risk functions the SAFER HBM will be able to predict injury risk for injuries that are expected to increase in future vehicles with increased levels of automation.

The new pelvis and lumbar spine models were integrated in the whole-body SAFER HBM development version (v10.1.x) and will later be integrated in SAFER HBM v11 (planned release late 2023), making it a biofidelic and efficient tool to assess injury risk. The SAFER HBM can be morphed into populations of female and male car occupants enabling development of protection systems that can provide males and females of various sizes as far as possible equal level of protection. The capabilities of SAFER HBM to predict injury risk for the population of vehicle occupants was demonstrated by reconstructing accidents from the field. This enables steps towards safe equitable transport solutions which can significantly reduce the number of seriously injured and killed vehicle occupants.

In future vehicles in which the occupants have the freedom to select seating positions with a more reclined posture assessment of submarining risk will be important. In the current project, the capability of SAFER HBM to predict submarining was developed and validated. This capability is an important contribution due to a potential increased risk of submarining for occupants in future vehicles, in which the vehicle occupants may want to sit with a more reclined posture than in the vehicles today.

This project has in combination with a series of successful FFI financed projects since 2008, provided the Swedish researchers, automotive industry and suppliers with a unique biofidelic and advanced tool. The state-of-the-art human body model, SAFER HBM, provides a competitive edge and enables development of first to market products. The industrial partners will use SAFER HBM to develop and evaluate countermeasures that will allow women and men of varying ages, height, and weights to ride safe in both upright and reclined seating positions in future vehicles with high degree of automation. SAFER HBM is a world leading tool for injury assessment and protection system development for all road users inside as well as outside the vehicle such as pedestrians, motorcycle riders, bicyclists etc.

Some results are summarized below.

5.1 Pelvis Model

The morphometric model was able to significantly capture eight of the 15 identified population pelvis bone shape variance components. The morphometric model prediction obtained by changing each variable individually shows that sex mainly affects the shape of the inferior-anterior regions, age affects scale and shape along the iliac crest, stature mainly affects scale, while BMI has almost no effect on the pelvic bone geometry.

The mesh of the new generic pelvis finite element model was made entirely of hexahedral solids (n = 23,926), quadrilateral shells (n = 10,984), and 1-D cable (n = 318) elements, with a target element side length of 3 mm. The high-quality mesh was prioritized to allow morphing of the model without risking severely distorted elements, this is important for both the robustness of the model and the capability to predict injury risk. The morphed female/male baselines showed a minor decrease in mesh quality compared to the average geometry. Two examples of the morphed finite element models, predicting shapes of a 50th percentile female (50 years, 162 cm, and 63 kg) and male (50 years, 175 cm, and 77 kg), are displayed in Figure 11.

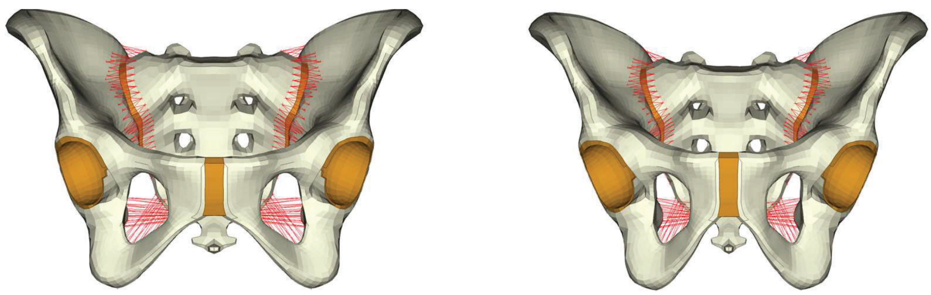


Figure 11**.** The pelvis finite dlement models for the 50th percentile female (left) and male (right).

The calibration of the pubis symphysis and sacro iliac joint properties, based on the tests by Miller et al. (1987) and Dakin et al. (2001), respectively, resulted in acceptable compressive and bending stiffnesses of the joints. In the validation of the complete pelvis based on the tests by Guillemot et al. 1998 there was good agreement between the predictions from the model and results from the tests for both the male and female subjects. Detailed description can be found in Brynskog et al. (2022).

The generic pelvis finite element model corresponding to a 50%-ile, 45 year old, 175cm tall and 77kg heavy male was successfully integrated into the SAFER HBM V10.0. The model was used to evaluate the interaction between the seat belt, and seat. The pelvis will in the future be morphed to shapes corresponding to males and females of various sizes. This enables seat belt and seat interaction and submarining analysis for the population of vehicle occupants. It will also provide a tool that is capable of predicting injury risk for the pelvis.

5.2 Spine Models

The new lumbar spine FE model is shown in Figure 12. It consists of about 10 000 quadrilateral shell elements with an average side length of 3.2 mm, 15 000 solid hexahedral elements with an average side length of 2.8 mm, and 300 beam elements.

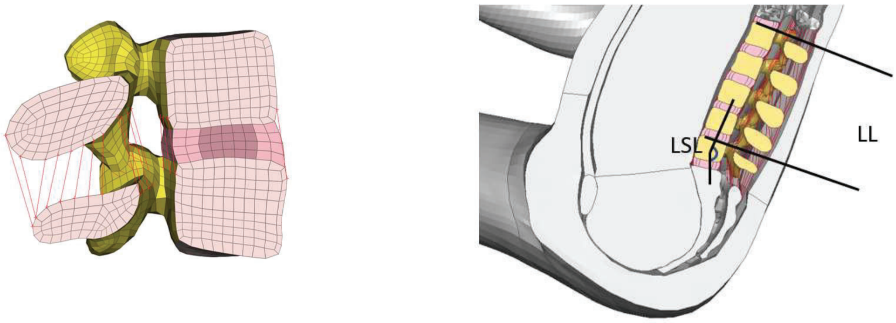


Figure 12. Images of the developed lumbar spine.

The kinematic and kinetic whole lumbar spine validation showed that the model predictions were reasonably close to the published physical tests. The major deviation was observed for the posterior shear, where the model predicted a weaker response. The model predictions for the lateral bending stiffness were on the high side and for the axial rotation on the low side. The model can be considered suitable for the development of a risk function for prediction of lumbar spine vertebra risk.

The cervicothoracic spine was modelled using 12 000 and 13 400 shell elements, and 26 100 and 16 800 solid elements for the cervical and thoracic spine, respectively (Figure 13).

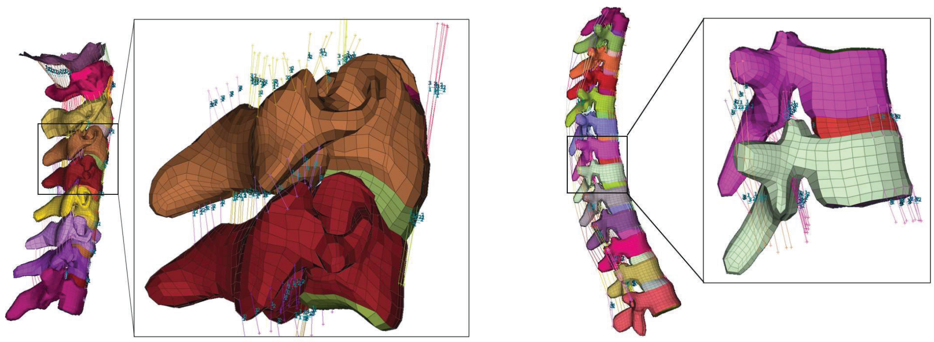


Figure 13. Images of the developed cervical (left) and thoracic (right) spine.

Material data for the cervicothoracic spine model was based on previously developed spine models, and its response was verified with respect to physiological range of motion tests data from human subjects. The model compared well for most responses and captured trends of varying stiffness along the spine.

5.3 Injury Risk Function Development

The lumbar spine injury risk function is based on maximum inferior-superior compressive strain in the trabecular bone and was developed using published component tests. It predicts vertebra endplate fracture risk, with age as covariates (Figure 14). Even though it was found that the onset of fracture risk was somewhat overpredicted, it was judged that the injury risk function can be used to estimate the risk for lumbar spine compression fractures, with the knowledge that these estimates are most likely somewhat conservative.

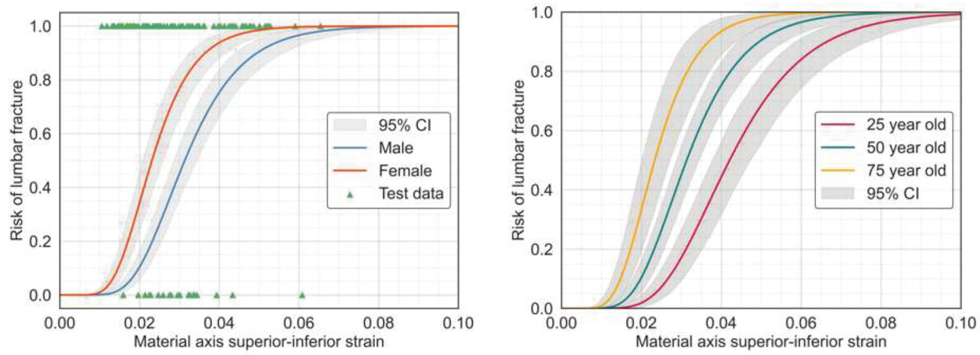


Figure 14. Injury risk functions recommended for use with the developed lumbar spine model and for a 50-year-old male and female (left) and for a male 25, 50 and 75 years of age (right).

In the evaluation of the lumbar spine risk function (Figure 14) it was found that when reconstructing the published injurious subsystem drop test (Stemper et al. 2018), the injury risk function (Iraeus et al. 2023) predicted 98% risk of L1 lumbar spine fracture. While when reconstructing the published non-injurious drop test, the injury risk function predicted close to zero risk. For the published whole-body sled test a 93% risk for L1 fractures was predicted, while in the PMHS sled test series L1 fractures was observed for 3/5 specimens (Richardson et al. 2020). In the accident reconstruction in which the driver sustained a compression fracture at L5 a 70% risk of fracture was predicted. The new lumbar spine risk function has the potential to identify the risk for lumbar spine fracture with good precision (Holländer and Riazi, 2023).

Although the master thesis study on Iliac wing fractures from lap belt loading showed a fair match between the model and the published tests for force and displacement, a satisfactory injury risk function suitable for practical applications could not be determined (Umapathi Bhat 2023). Nevertheless, the project resulted in valuable insights regarding the experimental setup, limitations when replicating the experiment in FE, the complexity of the injury, and statistical considerations that could be made in future work.

5.4 Whole-Body Model Validation and Application

The SAFER HBM v10.0 was able to predict the occupant shoulder belt interaction in six of the eight simulated configurations of the Far-Side impact configurations in Pipkorn et al. (2021) with CORA scores of 0.65–0.74 for the evaluated kinematic variables. In two of the simplified configurations, the SAFER HBM slid out of the belt while none of PMHS in the corresponding published tests (Forman et al. 2013) did.

The detailed accident reconstructions based on Pipkorn et al. (2019) provided insight into the predictive capability of the SAFER HBM V10.0. In general, the rib fracture risks were higher for v10.0 than with the previous v9 model, increasing the overprediction of rib fracture risk which seems to be present for the SAFER HBM (Figure 15)

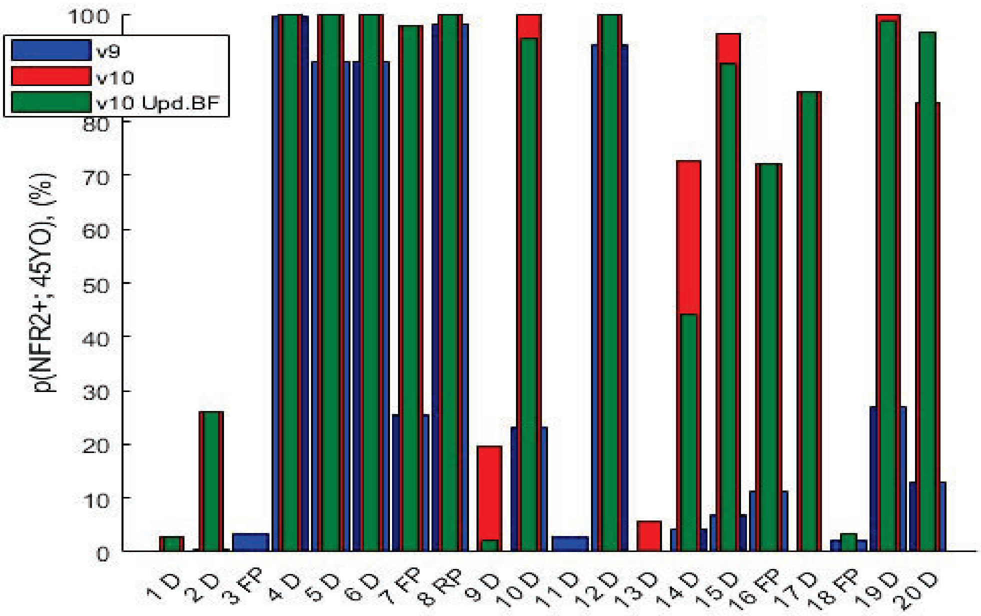


Figure 15. The risk for two or more rib fractures (NFR2+) for a 45 year old occupant in the detailed accident reconstructions. For information on the cases, see Pipkorn et al. (2019)

The lumbar spine forces, which were perceived as underpredicted in the SAFER HBM v9 due to too much load reacted through the torso soft tissues (Pipkorn et al. 2019), were higher for most simulations with the SAFER HBM v10.0, both for the peak compressive Fz force and flexion moment My (Figure 16).

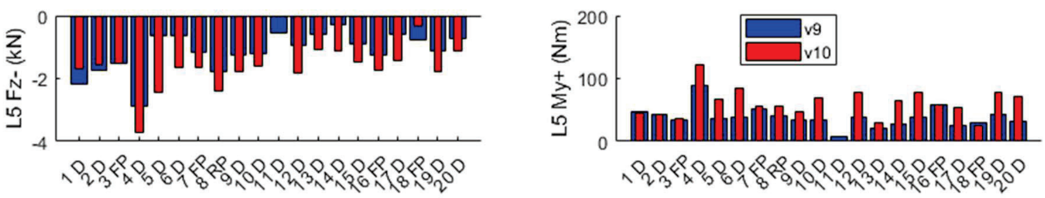


Figure 16. Peak L5 Fz compression forces and flexion moment in the detailed accident reconstruction simulations for SAFER HBM v9 and v10.0. For information on the cases, see Pipkorn et al. (2019)

Focusing submarining related loading, the predictions from the whole-body validation of the SAFER HBM v10.1.x development model generally showed agreement with the published experiments, in the seven validation scenarios. For the ‘Free-back, mid-abdomen, rigid-bar impact’ scenario (Hardy et al. (2001), the predicted responses were mainly within the experimental corridors. For the ‘Abdominal seatbelt loading’ scenario (Ramachandra et al. 2016), the model predicted smaller abdominal penetration than what was obtained in the testing. However, the mechanical test results were found to be less reliable than for the other cases and therefore less attention was assigned to this load case. For the 'Pelvis seatbelt loading’ scenario (Uriot et al. 2006), greater compression of the soft tissue was seen in the SAFER HBM V10.1X model than for the PMHSs in the published experiments. Despite this difference in penetration, the submarining angle matched well and the general trend of the experiments was captured. For the

‘Sled test with rigid seat’ (Luet et al. 2012), the SAFER HBM v10.1.x reconstructed the submarining in the experiments in two out of three test configurations, with a rigid seat. While in the third configuration, one of three PMHS submarined while the SAFER HBM v10.1.x did not, although the belt slipped over the iliac wings in the rebound phase. For the ‘Sled tests with semi-rigid seat’ (Uriot et al. 2015b), all PMHS in the rear seat configuration in the experiments submarined and so did the SAFER HBM v10.1.x., while in the front seat configuration, no PMHS submarined in the experiments and neither did the SAFER HBM v10.1.x. For the ‘Sled tests with a semi-rigid seat, reclined occupants’ (Richardson et al. 2020), the SAFER HBM v10.1.X did not submarine, while one of five PMHS in the experiments had a partial submarining on one side while the others did not submarine. For the “Quasi-static lumbar flexion tests’ (Uriot et al. 2015a) and the dynamic sled tests (Uriot et al.2015b) the model follows the average response of the PMHS well.

The validation sled tests with the THOR-50M showed good repeatability between the tests. General observation on the influences of the varied parameters in the sled tests, revealed e.g. that for larger seatback angle, the belt pay-out was shorter and for larger seat pan angle, additional reductions in belt pay-out was obtained. The shoulder belt force was 4.5kN for all configurations, since a seatbelt system with 4.5 kN load limiting at the retractor was used. The lap belt forces were generally high. However, the forces were lower for the larger seat pan angle. Pelvis displacement and rotation was greater for the reclined relative to the upright occupant, with a 15-degree seat pan angle. This difference was even greater in the 25-degree seat pan angle comparison.

In the validation of the seat and seatbelt system models generally according to the WIAMan biofidelity rating the agreement between the model predictions and the test results was rated as good or fair with a few signals rated as marginal and unacceptable (Table 1). The score for the model varied between 0.63 and 0.68. For the semi rigid seat reclined with 15- and 25-degree seat pan angle the pelvis y-acceleration was rated as unacceptable. However, pelvis y-acceleration is of minor importance when evaluating frontal loading. Therefore, the models are considered valid and applicable for evaluating submarining risk with SAFER HBM.

Table 1 WIAMan Biofidelity Rating System.

WIAMan Biofidelity Rating	**Weighted Average Score**
Excellent	0.85 <= Score <= 1.0
Good	0.65 <= Score <0.85
Fair	0.44 <= Score <0.65
Marginal	0.26 <= Score <0.44
Unacceptable	0.0 <= Score <0.26

To evaluate occupant protection systems in crashes with todays and future vehicles, with increased level of automation, validated and biofidelic models are needed. The human body models have to be validated for upright as well as for reclined seating positions and for predicting injury risk for the population of vehicle occupants. The ATDs are only available in limited sizes, have limited biofidelity and do not represent the population of vehicle occupants. Human body models, such as SAFER HBM, have potential to predict injury risk at a level of detail, organ level, that is not possible with ATDs and can be morphed to represent the population of vehicle occupants. In addition, due to the greater level of anatomical detail the human body models are able to predict human like interactions between the vehicle interior and body e.g. shoulder to shoulder belt interaction. However, the HBMs and the vehicle interior models that will be used with the HBM need to be thoroughly validated for new seating positions as well as for injury prediction.

The importance of using human body models, such as SAFER HBM, in evaluation and development of occupant protection systems has been demonstrated in numerous studies. The SAFER HBM was applied in an evaluation of a seat track load limiter (i.e., reducing the crash severity by adding an energy absorbing element in the seat track). A substantial reduction in rib fracture risk was obtained with SAFER HBM while the THOR-50M model indicated an increased thorax injury risk despite a reduction in lower shoulder-belt force with the presence of a seat track load limiter (Östling et al., 2021, Östling et al., 2022). It was stated that SAFER HBM with a human like design and rib strain as metric for rib fracture risk is likely to be more biofidelic than THOR and rib deflection to evaluate human rib fracture risk for upright and reclined seating positions. In addition, the performance of the load limiter is dependent on the mass of the occupant. Due to the fact that human body models are morphable to occupants of various sizes and the ATDs only are available in three sizes, HBMs can be considered to be the most applicable tools for development of seat track load limiters.

In another study, the potential injury reducing effects of lap belt load limiting was evaluated. With the detailed pelvis model a human body was considered to be an applicable tool for such a study. Both SAFER HBM and the 50% HIII dummy was used in the study. It was found the lap-belt load limiter did not only reduce the risk for iliac wing fracture, but also limited forward-downwards head excursion and thereby a reduced likelihood for head-to-thigh contact. Despite fundamental different designs, both tools (ATD vs HBM) indicated similar effect on the occupant kinematics (Östling and Lubbe, 2022, Östling and Eriksson, 2022). However, the performance of the lap belt load limiter and iliac wing fracture risk is dependent on the mass and shape of the occupant. Therefore, the SAFER HBM with a morphable pelvis can be an applicable tool to evaluate the load limiter for the population of vehicle occupants.

In a third study, the potential injury reducing effects of air belts in frontal impact was evaluated (Jakobsson et al. 2023). The air belt distributes the load from the belt on a larger area of the chest than only belt. Due to the detailed representation of the thorax in the HBM in which each rib is individually modelled while only a few ribs are represented in the ATDs the HBMs are considered to predict a more human like chest response when loaded by an air belt than the ATDs. However, no significant benefits from the air belt were obtained with neither the HBM nor the ATD. The reason can be that the increased loaded area of the chest from the air belt relative to the seat belt was too small to reduce the injury risk. A bigger air belt that loads an even larger area of the chest is likely to result in reduced predicted rib fracture risk with the HBM while the ATD is likely to predict the same injury risk as for the seatbelt.

In the numerical reproducibility evaluation (Östh et al. 2021), it was found that the SAFER HBM responses vary randomly with the Number of CPU cores (NCPU), but not due to different hardware or message parsing interface software at each computer system used. When the NCPU used was fixed, identical results were obtained from all computer systems. This means the variation of HBM responses is due to the model decomposition.

6 Dissemination and Publications

The project partners have continuous interactions and cooperations with international researchers in which results from the project are discussed and evaluated. In a joint publication with University of Virginia the biofidelity of SAFER HBM was compared to other state-of-the art human body models and SAFER HBM came out on top (Gepner et al., 2022). SAFER HBM was presented in a network (HBM4VT) for making human body models ready for use in consumer testing programs such as Euro NCAP. The project has generated six scientific publications with peer review, one conference publication without peer review, one licentiate degree and five master's theses. The licentiate presentation had a high attendance and was well received by the audience.

At the 27th ESV conference in April 2023 the development of SAFER HBM from 2008 until today was presented (Pipkorn et al. 2023). The presentation included the development steps, refinements, and validation of the different versions of SAFER HBM. The SAFER HBM research was presented in a public lecture by one of the Chalmers PhD Students, at the SAFER Day 230310 which is a public event.

The SAFER HBM was used by the industrial partners for internal research and development projects. The results from those projects were continuously presented and discussed with the cooperation partners. In addition, the model was used by the academic partner in teaching and student assignments.

For the development of the morphing capability, the project partners interacted with researchers from University of Michigan Transport Research Institute (UMTRI) and for the development of the iliac with risk function, data was shared by researchers at University of Virginia (UVA).

How will or are the project results used and disseminated?	Mark with an X	Comment
Increase knowledge in the area	X	The project has generated important knowledge that will enable development of tools to assess pelvis and lumbar spine injury risk for the population of vehicle occupants.
Forwarded to other advanced technical development projects	X	The updated SAFER HBM will be included in development project for protection systems for todays and future seating positions.
Forwarded to product development projects	X	The SAFER HBM validated for submarining risk prediction will be used in ongoing development of products to mitigate submarining risk.
Introduced on the market	X	The ambition is to make the SAFER HBM globally available during 2024.
Used in investigations/regulatory/permissions/political decisions	X	The publications from the project and results from evaluations carried out by the project partners with the model are used for information in the development of global standards, regulatory framework and consumer information programs such as Euro NCAP

The project was part of a cluster of research projects within SAFER with the focus to develop virtual human body models to fulfill the current and future needs of detailed humanlike tools that are able to predict injury risk and can be used to develop protection systems. This cluster collaborates with international researchers. This project has benefitted from being part of the cluster, as well as contributed to spread knowledge, clearly contributed to demonstrate the high international level of Swedish research within this area.

6.1 Publications

Peer Review Conference and Journal Publications

Brynskog E, Iraeus J, Reed M, Davidsson J, (2021). Predicting Pelvis Geometry Using a Morphometric Model with Overall Anthropometric Variables, *Journal of Biomechanics* 126: 110633.

Brynskog E, Iraeus J, Pipkorn B, Davidsson J, (2022). Population Variance in Pelvis Response to Lateral Impacts – A Global Sensitivity Analysis, P*roceedings of the IRCOBI Conference*.

Östh J, Nylund M, Olofsson N, Iraeus J, Jakobsson L (2023). Assessment of THOR-50M Thoracic Injury Criteria by Population-based Accident Reconstructions. *Proceedings of the IRCOBI Conference*.

Östh J, Pipkorn B, Iraeus J, Forsberg J, (2021). Numerical Reproducibility of Human Body Model Crash Simulations, *Proceedings of the IRCOBI Conference*.

Östh J, Bohman K, Jakobsson L (2023). Head Injury Criteria Assessment using Head Kinematics from Crash Tests and Accident Reconstructions. *Traffic Injury Prevention* 24(1): 56–61.

Pipkorn B, Östh J, Brynskog E, Larsson E, Rydqvist L, Iraeus J, Perez-Rapela D, Jakobsson L (2021). Validation of the SAFER Human Body Model Kinematics in Far-Side Impacts, *Proceedings of the IRCOBI Conference.*

Conference Publications without Peer Review

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, Paper Number 23-0242, *Proceedings of the International Technical Conference on the Enhanced Safety of Vehicles*.

Licentiate and Master Thesis

Brynskog E (2022). *Towards the Inclusion of Pelvis Population Variance in Human Body Models*, Licentiate Thesis, Machine and Vehicle Systems, Chalmers University of Technology

Fernández, P-M, Todorovic I (2020). V*ehicle Crash Reconstructions Using FE Human Body Model to Improve Injury Predictions*. MSc Thesis, Chalmers University of Technology, Gothenburg, Sweden.

Holländer N, Riazi A (2023). *Validation of a Lumbar Spine Fracture Injury Criterion for Finite Element Human Body Simulations*. MSc Thesis, Chalmers University of Technology, Gothenburg, Sweden.

Nylund M, Olofsson N (2022). *Rib Fracture Injury Risk Function Assessment for the THOR-50M using Population-based Finite Element Crash Reconstructions*. MSc Thesis, Chalmers University of Technology, Gothenburg, Sweden.

Umapathi Bhat S (2023). *Iliac Wing Fracture from Lap Belt Loading*. MSc Thesis, Chalmers University of Technology, Gothenburg, Sweden.

7 Conclusions and Future Research

In the project, a morphable biofidelic pelvis model and new spine models (lumbar and cervicothoracic) were developed for the SAFER HBM. The pelvis model was integrated into SAFER HBM v10.0. The pelvis, and spine models were integrated in the development version SAFER HBM v10.x and they will later be integrated into the next version of SAFER HBM that is planned to be released in December 2023. SAFER HBM can be morphed to represent women and men of various heights and weights. Therefore, the model can be used to develop protection systems that provides vehicle occupants equal protection regardless of sex, height and weight. The model can also be used to evaluate protection for road users outside the vehicle such as pedestrians, motorcycle riders, bicyclists etc. This enables the progression towards safe equitable transport solutions which can significantly reduce the number of seriously injured and killed vehicle occupants.

The SAFER HBM updated with the morphable pelvis and lumbar spine model is a biofidelic and efficient tool to assess submarining and lumbar spine fracture. The tool will be used by the industrial partners to assess injury risk when developing protection systems for future vehicles that will allow alternative seating positions and postures. The pelvis and lumbar spine models were thoroughly correlated and validated by means of reconstructing available and published tests with PMHS from component to whole-body sled tests. The capability to predict submarining is an important contribution due to increased risk of submarining for occupants in future vehicles, for which the vehicle occupants are expected to sit with a more rearward leaning posture than today.

The pelvis model can be morphed geometrically to correspond to women and men of varying height and weight. However, due to limited availability of biological data, the updated SAFER HBM was so far only validated for prediction of submarining risk for average males using available published studies. In particular there is a need for data for reclined occupants for configurations that results in submarining. Research is needed to extend the scope of submarining risk prediction to include additional portion of the population of vehicle occupants. Therefore, data is needed for humans with both higher and lower BMI than the 50%-ile male vehicle occupant. In addition, there is a need for biological material data specifically for males and females that can be used to develop sex specific risk assessment.

The updated lumbar spine model and accompanied risk function is a biofidelic and efficient tool to assess lumbar spine vertebra fracture risk. The risk function enables assessment of vertebra fracture risk for different age categories. To also enable assessment for women and men separately, additional data is needed. The risk function enables assessment of injury risk for the most vulnerable vehicle occupants, the elderly. Injury risk can also depend on the spine posture of the occupant in a crash. Little is known about the spine posture of vehicle occupants. Therefore, research is needed to define spine posture of vehicle occupants and how to integrate alternative spine postures in the human body models, such as the SAFER HBM. In addition, the lumbar spine injury risk function could most likely be extended to predict thoracic vertebra fracture for the new thoracic spine model.

In addition to generate knowledge regarding protection of women and men, the project has generated experience in development of morphable human body model parts. To achieve a fully morphable human body model there is a need to develop additional morphable body parts, such as upper and lower extremities.

Morphed SAFER HBMs positioned in the validated seat and seatbelt model enables detailed investigations and time efficient large parameter studies for evaluation of submarining risk for the population of vehicle occupants in different seating positions. The seat and seatbelt models were validated for the pelvis restraint cushion making the model a suitable tool for evaluation and development of anti-submarining mitigations systems built into the seat. In addition, the model can be used to demonstrate the applicability of using SAFER HBM as a tool for evaluation of safety systems for women and men of various sizes.

The project was a cooperation between industry and academia. The cooperation made the transfer of research results and knowledge exchange between academia and industry rapid and efficient. Furthermore, it enabled the industry to use early versions of the tools to develop and evaluate concepts of new protection systems. This gives the industrial partners an opportunity to develop market leading protection systems for current and future vehicles.

The project has generated unique knowledge regarding injury prediction with SAFER HBM. The project has generated six scientific publications with peer review, one conference publication without peer review, one licentiate degree and five master’s theses. The project has provided the Swedish automotive industry and suppliers a unique biofidelic and advanced tool, SAFER HBM, that gives a competitive edge. The SAFER HBM enables development of first to market products for all road users and strengthen the strong reputation that the Swedish automotive manufacturers and suppliers are world leading safety system developers.

8 Partners and Contact Persons

The project partners are Autoliv, Volvo Cars, Sahlgrenska University Hospital / Västra Götalandsregionen (VG Region) and Chalmers. The contact persons for the different partners are:

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