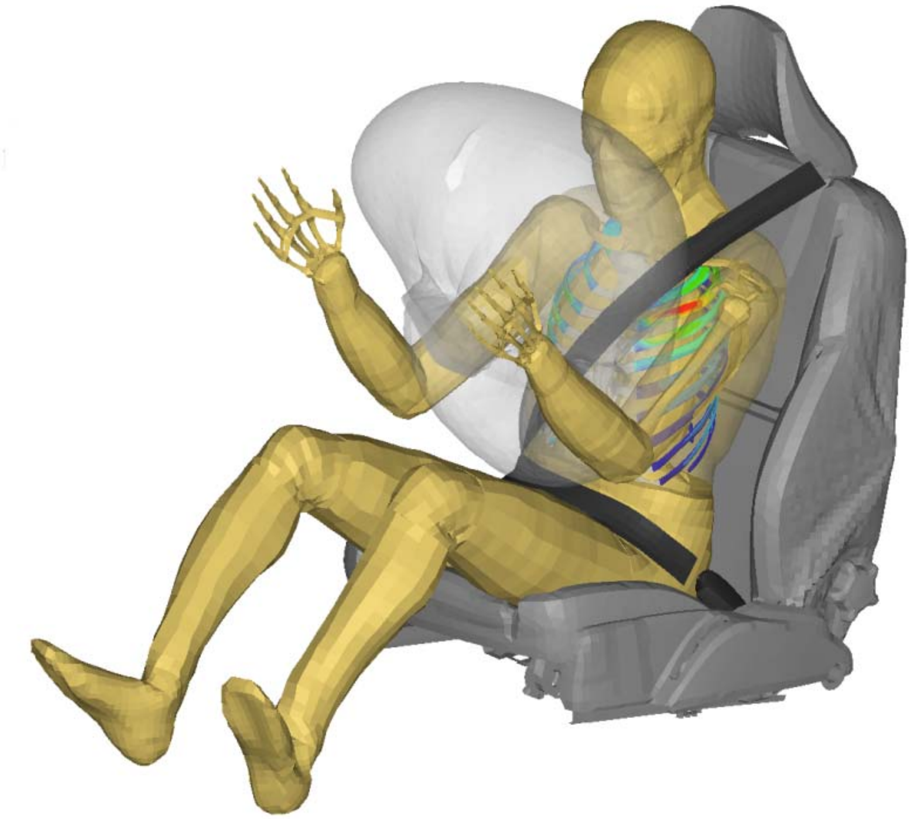
Improved injury prediction using HBM, step 2



Project within Vehicle and Traffic Safety

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Date: 2015-03-05

FFI

Content

FFI in short

FFI is a partnership between the Swedish government and automotive industry for joint funding of research, innovation and development concentrating on Climate & Environment and Safety. FFI has R&D activities worth approx. €100 million per year, of which half is governmental funding. The background to the investment is that development within road transportation and Swedish automotive industry has big impact for growth. FFI will contribute to the following main goals: Reducing the environmental impact of transport, reducing the number killed and injured in traffic and Strengthening international competitiveness. Currently there are five collaboration programs: **Vehicle Development, Transport Efficiency, Vehicle and Traffic Safety, Energy & Environment and Sustainable Production Technology.**

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1. Executive summary

Thoracic injuries are one of the main causes of fatalities and serious injuries in car crashes. This calls for improved restraints which, to date, are developed using virtual as well as physical crash test dummies. Virtual crash test dummies can only be used in specific crash scenarios, whereas virtual models that represent the human, commonly referred to as Human Body Models (HBMs), have the potential to simulate all crashes that occur in real world situations, including complex crashes with combinations of loads, e.g. oblique and small overlap crashes. Moving towards the goal of Vision Zero, there is an increased need of omnidirectional, human-like occupant tools to be used in these complex crash configurations, as well as for tuning collision mitigating and occupant restraint systems. However, there is a lack of well-defined and accepted criteria to predict thoracic injury and threshold when using these HBMs. This project focused on injury criteria for the thorax in frontal impact loading scenarios using the HBM Total Human Model for Safety (THUMS).

Firstly, THUMS was used to evaluate injury criteria at the global, structural and tissue level and to develop injury risk curves for AIS2+ thoracic injury. Risk curves were generated based on post mortem human data from six different loading conditions. When the quality of the risk curves and how well they represented the post mortem human data were evaluated, the criteria for ‘shear stress’ in two ribs and ‘DcTHOR’ were most promising. Secondly, THUMS was used to simulate a representative statistical selection of real world frontal impacts and risk curves for five criteria were compared to the risk curves developed based on the real world outcome. The comparison displayed that THUMS with the developed risk curves consistently over-predicted the injury risks. As a complement to the statistical evaluation, THUMS was used for in-depth reconstructions of five real-world frontal impacts, illustrating that tissue level injury have a great potential to provide omnidirectional model specific criteria, but that they require a high model detail and are dependent on material properties and mesh quality to match real world data.

This project has evaluated injury criteria for an HBM and developed risk curves for thoracic AIS2+ injuries. It has improved the knowledge about injury criteria for HBMs through active discussions and collaborations between the industrial and academic partners within the environment of the SAFER Vehicle and Traffic Safety Center at Chalmers, and through several scientific publications and presentations. The project has resulted in one doctoral thesis.

2. Background

Thoracic injuries are one of the main causes of fatally and severely injured casualties in car crashes. Current Anthropomorphic Test Devices (ATDs) have a limited sensitivity to advanced restraint systems for the thorax (Forman 2005, Kent 2003), therefore a more advanced tool is urgently needed to develop and assess future restraint systems with the purpose of reducing the risk of thorax injuries. New vehicle models are developed mainly in a virtual environment. Any design change must be introduced at an early stage. To assess the safety potential of these vehicle designs and their restraint systems at an early stage in development, it is essential to have access to virtual tools that can predict injury risk for occupants in simulated crashes. The virtual ATDs are limited to a few specific crash scenarios, for example frontal crashes, and cannot predict the occupant responses in more complex crash scenarios. Virtual Human Body Models (HBMs) have the potential to predict kinematics and injury outcomes for these more complex scenarios. Therefore, it is expected that HBMs will play an important role in future vehicle and safety system projects. Hence, to be competitive, Swedish vehicle industries need access to HMBs that can predict injury outcome in complex load scenarios.

State-of-the art numerical HBMs are now available to academia and industry. These are well suited to parametric studies and, as such, suitable for virtual testing and assessment of the safety potential of future vehicles. Currently, families of HBM are being developed; Toyota supply different sizes of the Total HUman Model for Safety (THUMS, Toyota 2008) and eventually the Global Human Model Consortium will supply models in more sizes than the average male. HBMs offer possibilities to understand injury mechanisms on a detailed level and to determine injury criteria. These criteria can be used to develop assessment methods of new restraint systems. However, there is a lack of well-defined and accepted criteria to predict thoracic injury with HBMs, hence making this difficult to use in vehicle development.

For ATDs, the most widely used injury criteria in frontal impacts are the maximum chest compression (‘Cmax’), defined as the ratio of chest deflection to initial chest depth (Kroell et al., 1974), and the viscous criterion (‘VCmax’), defined as the maximum of the product of the chest compression and the derivative of deflection with respect to time (Lau and Viano, 1986). Recently, the combined deflection criterion (‘DC’) was proposed by Song (2011), taking into account the sternal compression and the difference in deflection between the left and right sides of the ribcage. Due to limitations in instrumentation of ATDs these criteria cannot effectively differentiate between modern restraint systems (Petitjean et al., 2002) and with HBMs there is a possibility to use far more refined criteria.

In THUMS, the bone failure criterion used is plastic strain in the cortical bone of the ribs. Here, all rib finite elements in which the strain reaches a predefined value are removed and do not contribute to the stiffness of the rib cage in the remainder of the simulation. Song et al (2011) proposed to use plastic strain without element erosion to assess the

number of rib fractures. A probabilistic method to predict the rib fractures risk was developed by Forman et al (2012) who compared the greatest strain for every rib with a distribution of ultimate strain values obtained from tensile tests. It is questionable if strain is an appropriate injury criterion for HBMs available today, as the element size in the models may be too large to adequately capture the strain distribution. Therefore, there is a need to explore new thorax criteria on global, structural and material level and develop corresponding injury risk functions for the THUMS in crash simulations.
In previous projects (SAFER funded project B7: *Improved injury prediction using HBM* and the EU FP7 project *Thorax*), the partners of this project initiated the research on thoracic response and injury criteria for HBMs. A thorough validation of the THUMS thorax model was carried out by Pipkorn et al (2011). THUMS has a thoracic response that is sensitive to advanced restraint systems, such as belt pre-tensioners, load limiters and airbags (Mendoza-Vazquez 2012). Global injury criteria were suggested based on research carried out using various HBMs and simulations were carried out with the purpose of suggesting improvements for the THOR-NT dummy (Brolin 2012). Hence, THUMS versions 1.4 and 3 were used in this study and the thorax mesh and material properties were improved and validated by Chalmers and Autoliv.

3. Objective

The objective of this project was to propose and evaluate thoracic AIS2+ injury criteria and risk curves for a state-of-the art HBM, the Total Human Model for Safety (THUMS). Focus was on the 50th percentile male, taking age into account during risk curve generation. This was done by: identifying injury criteria in a literature review (task1), developing injury risk curves for THUMS by reconstructing tests with post mortem human subjects (task 2), assessing the quality of the risk curve with statistical methods and robustness simulations (task 3), compiling real world in depth data (task 4) to evaluate the predictability of THUMS with the proposed injury criteria in simulations compared to individual (task 5) and generic (task 6) frontal accidents, and assess the usability of the model compared to HIII (task 7) and for in-house projects at Autoliv and VCC (task 8). This project has provided the Swedish automotive industry with knowledge of injury prediction using HBM in crash simulations and enhanced the tools in use today for restraint evaluation.

4. Project realization

The project was realized through intense collaboration between the partners Autoliv Research AB (Autoliv), Chalmers University of Technology (Chalmers), Volvo AB (Volvo), and Volvo Car Corporation (VCC) from April 1st 2013 until December 31st 2014. It has encompassed numerical simulations with HBMs and analyses of real world crash data. A core group of 7 senior researchers from the partners and one Chalmers' Ph.D. student actively participated in the project.

The Ph.D. student, Manuel Mendoza-Vazquez, was involved in planning simulation activities, selecting the evaluated thoracic injury criteria with support from the industrial partners, simulating post mortem human tests to create risk curves, and the evaluation of these by simulating typical frontal collisions compared to real world data. Volvo supplied the computer resource for all simulations performed by Chalmers. VCC supplied the real world data and contributed to the analysis and planning of the injury risk evaluation. Autoliv contributed with THUMS enhancement and numerical simulations of the in-depth accident cases. Many work meetings, with participation from all partners, have been held to analyse, discuss and learn from the numerical in-depth reconstructions.

Collaboration with international partners was an essential part of this project. Manuel Mendoza-Vazquez visited the University of Virginia, USA, during late spring 2013 to study the experimental setup for the post mortem human tests used to create injury risk curves for THUMS. The Japan Automotive Research Institute (JARI) were active speaking partners during the analyses of real world data, offering an FE model of a small passenger vehicle that potentially could be used with selected accident data from NASS. When the project decided to proceed with data from VCC on Volvo cars, the NASS data that had been compiled was sent to JARI for future collaborative studies into thorax injury criteria and risk curve developments for FE-HBMs.

5. Results and deliverables

In this project, Manuel Mendoza-Vazquez completed a doctoral degree at Chalmers University of Technology (Mendoza-Vazquez 2014), and this project contributed to 6 publications. The project results are presented in this chapter with reference to the tasks defined in the application, together with a brief description of the methodology. For a complete description of methods and results, please see the doctoral thesis (Mendoza-Vazquez 2014).

5.1 Identification of injury criteria (task 1)

A literature review was performed to identifying injury criteria that can predict thoracic AIS2+ with an HBM. Criteria were selected based on if they were measurable with THUMS, there was a suggested coupling to injury mechanisms, and there were no known dependence on restraint systems. The result was the identification of 24 candidate injury criteria, of which the following where chosen for simulation in subsequent tasks:

The global level criteria were ‘Cmax’ (Kroell et al. 1974), ‘VCmax’ (Lau and Viano 1986), chest deflection ‘Dmax’(Kleinberger et al. 1989), ‘DC’(Song et al. 2011), a combined deflection of multiple points on the chest originally developed for THOR ‘DcTHOR’ (Davidsson et al. 2014), and ‘total internal energy’ for the cortical bone of all ribs.

The structural level criteria were ‘rib end-to-end displacement’, ‘change in rib curvature’, and ‘internal energy’ for the cortical bone in each rib.

The material level criteria for the rib cortical bone were 'principal strain', 'principal stress', 'plastic strain', 'shear stress' and 'von Mises stress'.

5.2 Injury risk curves for THUMS (tasks 2, 3)

The HBM used in this study was a modified THUMS v3 (Mendoza-Vazquez et al. 2013, Figure 1). The trabecular rib bone was modelled with hexahedral elements and the cortical bone with shell elements (elastic modulus of 13 GPa, yield stress of 93.5 MPa). The pre- and post-processors used were LS-PREPOST (v2.4, LSTC, Livermore, CA, USA) and Primer (v10.0, Oasys Ltd., UK). The finite element solver was LS-DYNA (version 971 R4.2.1, LSTC, Livermore, CA, USA). Data was analyzed using an in-house code developed in MATLAB (R2007b, The Math Works Inc., Natick, MA, USA).
A total of twenty-three PMHS tests (average stature of 1.77 m, average weight of 70.2 kg and average age of 61 years at time of death) were reproduced with the modified THUMS. The injury risk curves were constructed using parametric survival analysis, where a PMHS test was considered injurious if the number of fractured ribs (NFR) was two or more. The simulation results were matched to the respective PMHS test. For the global injury criteria, the maximum value was used. For the structural and material criteria, the maximum value in the rib with the second highest maximum value was used. All injurious tests were considered as left censored and all non-injurious tests as right censored during the parametric survival analysis. Figure 2 shows five of the developed injury risk curves. As a basis for selection, the Akaike information criterion (AIC) provided a value for the relative quality and fit of the data (Table 1). The injury risk curves with the lowest AIC were developed with the criteria 'DcTHOR' and 'shear stress' with age adjustment.

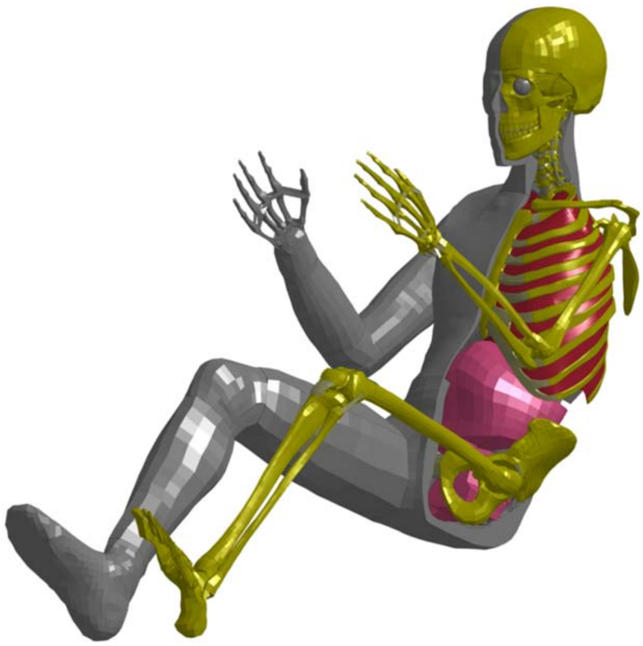

Figure 1: The modified THUMS (Mendoza-Vazquez et al. 2013), skin is blanked on the left side to show the ribcage and internal soft tissues.

Table 1. Akaike information criterion (AIC) values and the chosen distributions for survival analysis, with and without age adjustments.

Level	Injury criterion	Without age adjustment		With age adjustment	
		Distribution	AIC	Distribution	AIC
Global	Cmax [%]	Log-logistic	26.9	Log-logistic	28.8
	VCmax [m/s]	Log-logistic	31.9	Log-logistic	33.8
	Dmax [%]	Log-logistic	25.1	Log-normal	26.4
	DC	Log-normal	23.3	Log-normal	23.8
	DcTHOR	Log-logistic	19.0	Weibull	16.3
	TIE [mJ]	Log-logistic	26.4	Log-logistic	28.1
Structural	E2E [%]	Log-logistic	32.8	Log-logistic	34.7
	IE [mJ]	Log-logistic	23.6	Log-normal	24.1
	Angular change [%]	Weibull	25.9	Weibull	27.4
Material	Max principal strain [%]	Log-logistic	26.5	Log-logistic	28.4
	Plastic strain [%]	Weibull	22.7	Log-normal	24.1
	Max principal stress [MPa]	Log-logistic	24.1	Log-normal	25.2
	Shear stress [MPa]	Log-normal	20.0	Weibull	15.6
	von Mises stress [MPa]	Log-logistic	24.7	Log-normal	26.0

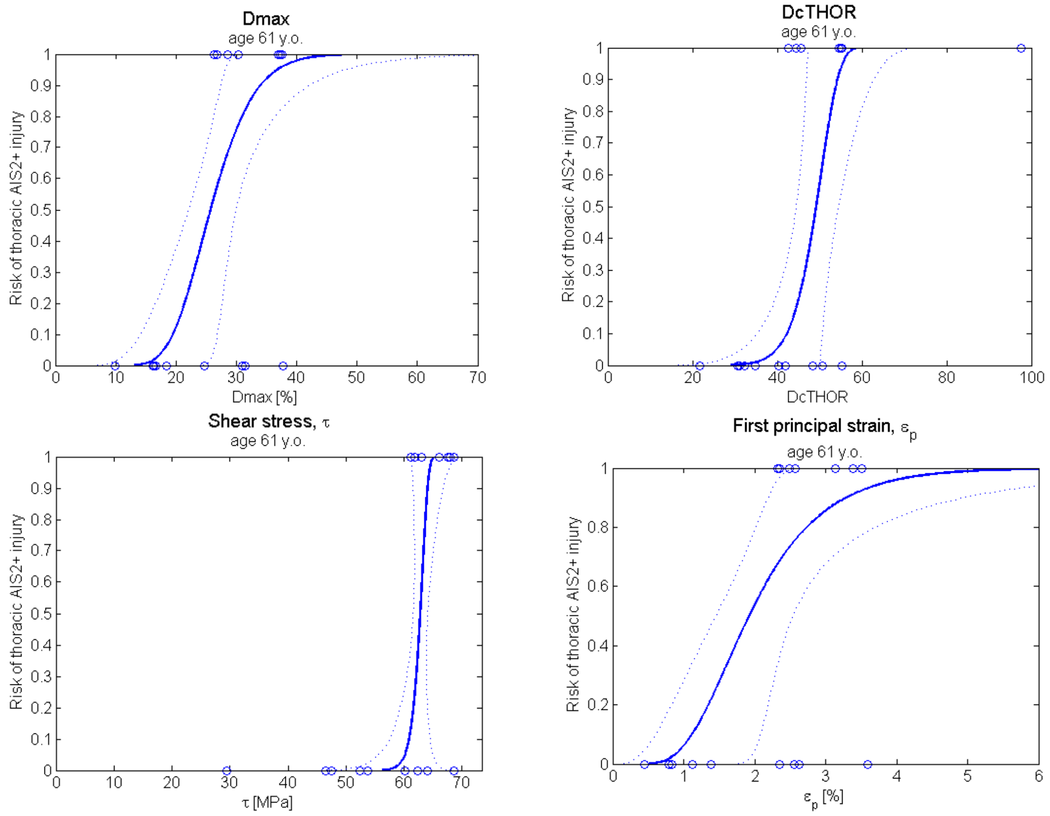

Figure 2. AIS2+ injury risk curves for THUMS, from upper left to lower right: ‘Dmax’, ‘DcTHOR’, ‘shear stress’, and ‘first principal strain’.

5.3 Real world data (task 4)

Data searches were carried out to identify relevant real world data. Inclusion criteria were discussed and decided, with the focus on accidents with Volvo cars or Ford Taurus 4th generation, for which there were available FE models of the vehicle interiors. The data bases studied were CIREN, NASS, INTACT, GIDAS, STRADA and those provided by Folksam and VCC. CIREN, INTACT, GIDAS, STRADA and Folksam databases did not contain a large enough number of accidents with cars of relevant make and occupant injuries. Attempts to combine two or several databases were tried. However, the accident and injury scoring systems used in the different databases did not enable such a merger. The NASS database contains a limited number of accident cases for each vehicle make, model and accident configuration. These cases are then scaled to establish a database that is representative of the accidents that occur in the US. Hence, the number of Taurus accidents identified in the NASS database was limited. Therefore, the Volvo Cars' Traffic Statistical Accident Database (VCTAD) was used as the basis for real world data throughout the project. The database contains data on Volvo passenger cars in Sweden in which the repair cost due to a crash exceeds a specified level. Injuries are coded according to the AIS. The main crash severity measure used in frontal impacts is the Equivalent Barrier Speed (EBS), calculated using an energy absorption matrix, together with the residual deformation of the front structure of the car in question. Additional in-depth information is available for a limited number of cases in the database, including acceleration versus time data from the Digital Accident Research Recorder (DARR).

To compare the injury risk curves developed for THUMS (section 5.2) with real word injury risk (section 5.4), a subset was selected with the following inclusion criteria:

- restrained drivers with known injury outcome,
- involved in a single frontal impact during 2002-2012,
- car year models 1999-2012,
- with a direction of impact 11-1 o'clock, and
- a horizontal overlap of 2/3, central overlap of 1/3 or full overlap.

Thirteen out of a total 1007 drivers sustained a thoracic AIS2+ injury. Parametric survival analysis was performed on the subset using software R [21] to establish thoracic AIS2+ thoracic injury risk curves for real world data, using EBS as the predictor variable and age as a covariant. The Weibull distribution with age adjustment provided the best fit for the data and resulted in the thoracic AIS2+ injury risk curve in Figure 3. Method and results are further described in Mendoza-Vazquez et al. 2014.

Five cases were selected from VCTAD for in-depth reconstructions using THUMS (section 5.5). Cases were selected based on other criteria besides the subset for the statistical analysis:

- frontal impacts without limitations in angle or overlap,
- availability of DARR data,
- limited interior intrusion,
- detailed description of the crash event,
- detailed injury information, and

- vehicle models where a validated interior CAE model was available for the reconstruction.

All cases were drivers; four of them in newer Volvo vehicle models years 2008-2009 and one in an older Volvo V70 model year 1997. Only one driver (the older vehicle from 1997) sustained injuries to the thorax with fractures of the ribs and sternum.

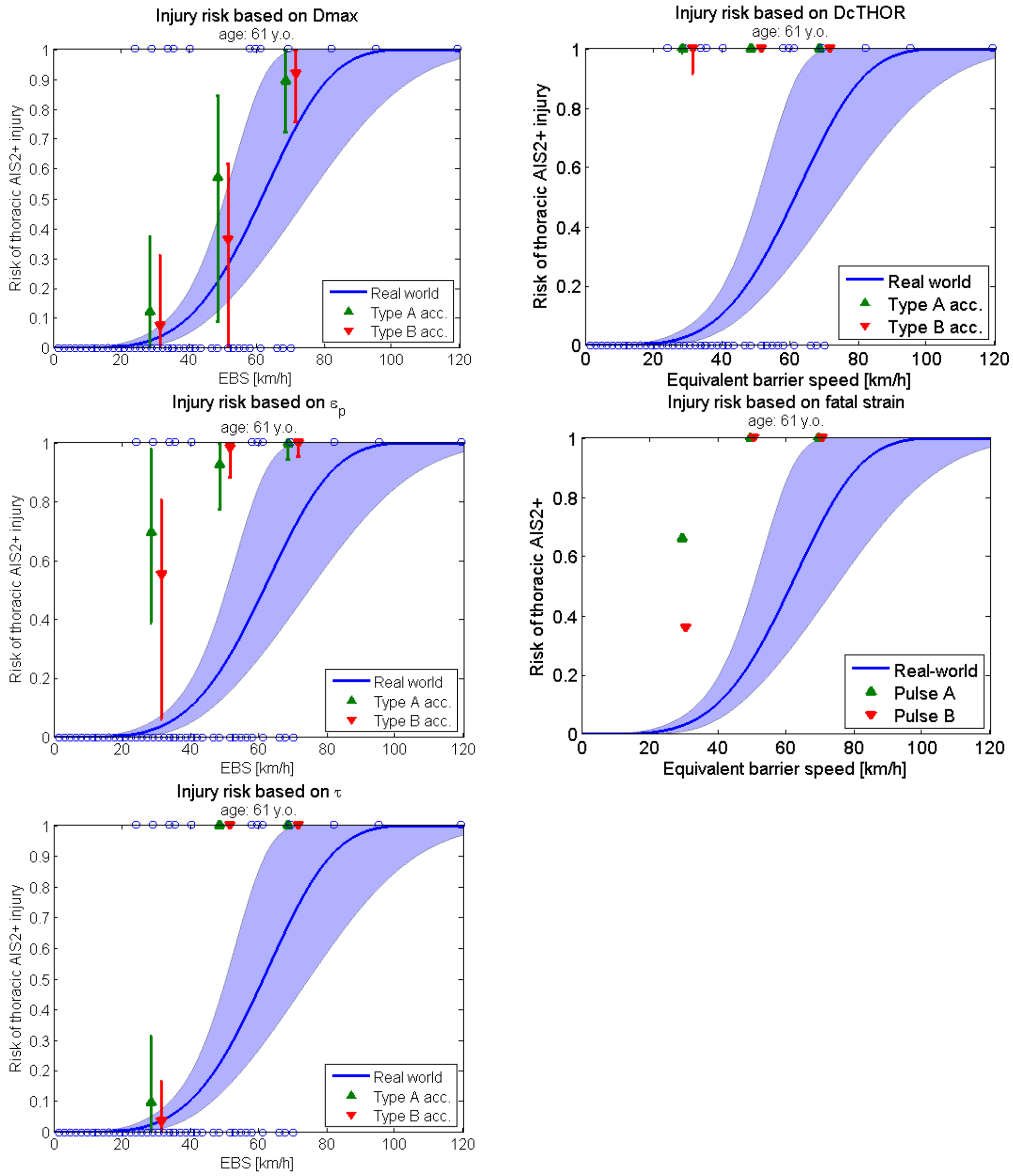

Figure 3: Injury risks predicted with 'Dmax', 'DcTHOR', 'first principal strain' (ε_p), 'fatal strain', and 'shear stress' (τ), (from upper left to lower right) in THUMS simulations of three equivalent barrier speeds (EBS) with two acceleration pulses (red and green triangles) compared to the injury risk curves based on real world data age adjusted for 61years (blue corridor).

5.4 Comparing THUMS injury risks to real-world data (task 6)

THUMS was positioned in the driver seat of the vehicle interior model (validation described briefly in section 5.5 and in detail in Mendoza-Vazquez 2014, appendix A). Method and results are described in detail in Mendoza-Vazquez et al.2014. In short, two different acceleration pulses were applied to the interior vehicle model for each of three chosen EBS values; 30, 50 and 70 km/h. The risks predicted by the modified THUMS, and the corresponding age adjusted injury risk over-predicted the injury risks compared to the real-world data (Figure 3). The injury criterion closest to the real world data risks was ‘Dmax’, where the confidence intervals overlapped for all tested EBS and acceleration pulses. The ‘shear stress’, ‘first principal strain’, and ‘fatal strain’ criteria predicted higher risks more rapidly than ‘Dmax’; the stress and strain criteria indicated a risk higher than 90% at an EBS of only 50 km/h. The ‘DcTHOR’ criterion predicted risks over 95% as early on as an EBS of 30 km/h. These results indicate there are many challenges to be met when injury criteria developed with post mortem human data are compared to real world data, and that further work is needed to explore how injury criteria for HBMs should best be developed to predict real world risks.

5.5 In-depth accident reconstructions using THUMS (tasks 5, 7, 8)

The five in-depth cases that were chosen for reconstruction (section 5.3) were run with THUMS in the driver position. The vehicle interior models were validated using data from a physically reconstructed frontal collision, between the older vehicle and one of the newer vehicles, using HIII 50%-ile ATDs performed by Volvo Cars in 2010. This reconstruction was simulated using virtual HIII 50%-ile ATDs, where the resulting output in terms of kinematics and accelerations were compared to the corresponding experimental data. This is described in further detail in Mendoza-Vazquez 2014, appendix A.

The crash pulse for each reconstruction case was collected from the real world crash (DARR), except for the two cases physically reconstructed in a crash test. For these two cases, the crash pulses from the crash test were used. The thoracic injury criteria selected for evaluation were ‘DcTHOR’ and ‘Dmax’ for two or more fractured ribs (NFR2+) and ‘fatal strain’ for three or more fractured ribs (NFR3+). The results from these initial simulations show that none of the criteria were completely consistent in reflecting the injury outcome in all cases, Figure 4. ‘DcTHOR’ and ‘fatal strain’ criteria predicted the outcome in the older vehicle, while ‘Dmax’ gave a lower risk. For the newer vehicle cases the injury risk was over-predicted, primarily by the ‘fatal strain’ criteria. The local rib strain distribution was not completely in line with the fracture pattern of the injured driver, which effected the injury prediction by ‘fatal strain’ more than ‘DcTHOR’ and ‘Dmax’.

These initial steps of in-depth reconstructions using THUMS illustrate that tissue level injury criteria have a great potential to provide omnidirectional model specific criteria, but that they require high model detail and are dependent on material properties and mesh quality to match real world data. Further steps, including more cases as well as modified set-ups in the initial cases, are needed to truly evaluate the robustness of each criterion, and to choose among different types of criteria for industrial implementation. In the current study, no modifications were made to the set-up (sitting posture, belt position etcetera). Ongoing activities include additional reconstructions, especially for the injured driver, to reconstruct the fracture pattern more precisely.

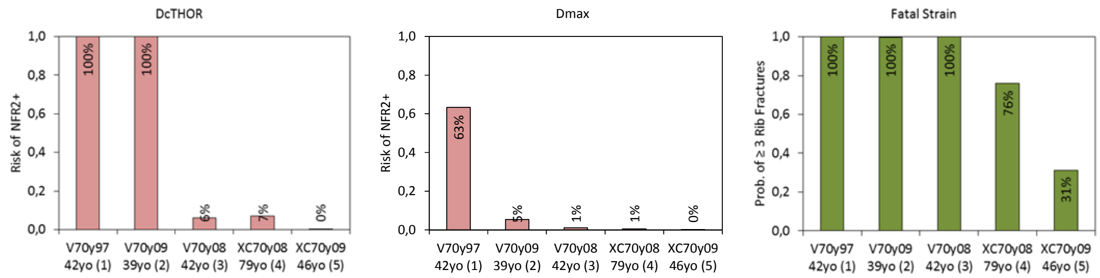

Figure 4: Injury risks predicted with ‘DcTHOR’, ‘Dmax’, and ‘fatal strain’ in THUMS simulations of five reconstruction cases: (1) Volvo V70 model year 1997, 42 year-old driver with fractures to ribs and sternum, (2) Volvo V70 model year 2009, 39 year-old driver without thorax injuries, (3) Volvo V70 model year 2008, 42 year-old driver without thorax injuries, (4) Volvo XC70 model year 2008, 79 year-old driver without thorax injuries, and (5) Volvo XC70 model year 2009, 46 year-old driver without thorax injuries.

Beside the advances in thoracic injury evaluations, this part of the project served an important objective in evaluating the model and criteria in an industrial application environment. During the project, numerous issues were identified, discussed and modified, striving towards simplifications and acceptance of the model, including criteria within the industrial process.

When comparing the reconstructions of the HIII 50%-ile and THUMS, in the two cases where these were made, it was clear that THUMS provides far more information and detail. This information and the additional details are important ingredients when addressing complex crash situations, including oblique frontal impacts. It is of outmost importance to both industrial developments of occupant restraints and active safety systems. Hence, this study illustrates the benefit of introducing THUMS as a tool in the development of new vehicle models and restraints.

5.6 Delivery to FFI-goals

The results of this project will contribute to the reduction of chest injuries sustained by vehicle occupants and help towards the goal of reducing fatalities and injuries in traffic. Enhanced injury prediction using HBMs will enable higher precision in the development of vehicle safety, including high risk situations in modern vehicles. These situations typically include complex crash situations and the influence of individual differences. This is especially important to the development in collision mitigation systems, where critical decisions regarding vehicle interventions are taken influencing impact configurations. With the developed thorax injury risk functions, simulations with THUMS have the potential to introduce significant design improvements due to the

HMB's omnidirectional capabilities. The THUMS biofidelity, and large number of details modelled, will give the industry a significant opportunity to design countermeasures enhancing real world safety, including development of both active safety systems and enhanced restraint systems.

The knowledge gained in this project will increase the competitiveness of the Swedish vehicle industry. New knowledge has been generated in regard to injury risk curves and thresholds for AIS2+ thoracic injury and implemented in an existing HBM. This knowledge was transferred to the THUMS HBM used by Autoliv and Volvo Cars, and implemented to study chest injuries in frontal impacts. The in-depth studies of real world data have generated new knowledge as to the usability of the HBMs for thoracic injury prediction and evaluation of restraint systems and safety assessment of vehicles. Hence, this project contributes to maintaining the world leading position within traffic safety that Swedish industry has today.

6. Dissemination and publications

6.1 Knowledge and results dissemination

There are many initiatives world-wide focused on generating injury criteria for HBMs and improving their biofidelity, which can benefit from the results of this project. Specifically, the results from this project form an important pillar in the SAFER HBM competence arena. Development of the new THOR dummy is another ongoing activity that has strong connections to the results from this project. Project partners have presented results and knowledge at international meetings and conferences.

6.2 Publications

The publications written in this project are listed here, including the Chalmers Publication Library (CPL) reference number. Two peer-reviewed publications, one manuscript, one doctoral thesis, and there conference presentations:

Mendoza-Vazquez M, Jakobsson L, Davidsson J, Brolin K, Östmann M (2014) Evaluation of Thoracic Injury Criteria for THUMS Finite Element Human Body Model Using Real-World Crash Data, *IRCOBI Conference Proceedings - International Research Council on the Biomechanics of Injury,* 10-12 September, Berlin, Germany. IRC-14-62:528-541. [CPL 203161]

Mendoza-Vazquez M, Brolin K, Davidsson J, Wismans J (2013) Human rib response to different restraint systems in frontal impacts: a study using a human body model. *International Journal of Crashworthiness* 18(5):516-529. [CPL 185861]

Mendoza-Vazquez M, Davidsson J, Brolin K (2014) Construction and evaluation of thoracic (NFR2+) injury risk curves for an FE-HBM in frontal crashes. Manuscript submitted to *Journal of Accident Prevention and Analysis*, September 2014.

Mendoza-Vazquez M (2014) Thoracic injuries in frontal car crashes: risk assessment using a finite element human body model, *Doctoral thesis*, Department of Applied

Mechanics, Chalmers University of Technology, Gothenburg, Sweden, ISBN/ISSN: ISBN 978-91-7597-097-4. [CPL 205139]

Brolin K, Gras LL, Östh J, Mendoza-Vazquez M, Ólafsdóttir J, Davidsson J. (2013) Human Body Modeling for Integrated Safety Analyses, Adult and Child Models, Presentation at the *4th International Symposium on Human Modelling and Simulation in Automotive Engineering*, Aschaffenburg, Germany, May 13-14. [CPL 192673]

Brolin K, Mendoza-Vazquez M, Östh J, Ólafsdóttir J, Paas R, Davidsson J. (2013) Human body modeling for integrated safety analyses using THUMS, Presentation at the *THUMS European Users' Meeting*, Manchester, England, June 6. [CPL 192670]

Brolin K, Östh J, Nydahl M. (2014) Evaluation at low g-level loading. Presentation at the *5th International Symposium on Human Modelling and Simulation in Automotive Engineering*, Munich, Germany, October 16-17. [CPL 205756]

7. Conclusions and future research

This project has evaluated injury criteria for an HBM and developed risk curves for thoracic AIS2+ injuries. A first step was taken with respect to checking robustness and applicability in oblique and more complex loading scenarios, which proved to be the strength of the THUMS compared to HIII. The injury risk curves developed with THUMS that best captured the PMHS data were calculated with age adjustment for the global injury criterion 'DcTHOR' and the material level injury criterion 'shear stress', in the rib cortical bone. These injury risk curves over-predicted the risks as compared to real world data, and the global injury criteria 'Dmax' was found to be closest to real world data. The in-depth reconstructions pointed in the same direction, where the injury risk was over-predicted by both the 'DcTHOR' and 'fatal stain' criteria. Additional cases are needed to analyze the injury risk predictions with a higher degree of certainty.

This project has taken important steps to improved knowledge about injury criteria for HBMs and served as one of the pillars of SAFER's HBM competence platform. The project has combined academic research and industrial implementations, providing a good foundation for future work in the area.

Future research in this area is very essential, as the industry needs a human-like occupant tool that can predict injuries in omnidirectional loading events in order to develop efficient restraint systems for future vehicles. This need is growing with the developments in active safety vehicle systems. In the developments of collision avoidance and mitigation systems, it is of outmost important to be able to evaluate occupant loading in different directions and severity levels, and to make comparisons between these aspects. Taking steps towards autonomous driving, biofidelic real world injury prediction capability is one of the key areas that will enable this journey.

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