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FRONTAL AND OBLIQUE COLLISIONS: EVALUATION OF INJURY RISK AND RESTRAINT PROTECTION SYSTEM FOR UPGRADED THOR DUMMY

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Content

1. Executive summary

This project aimed to understand the thoracic loading of the upgraded THOR crash test dummy in frontal and oblique loading conditions using current and state-of-the-art restraint systems. In addition, the project aimed to evaluate and rank proposed injury criteria in terms of real life relevance and capability of countermeasure differentiation. In order to understand potential benefits and limitations of the THOR dummy, a Finite Element (FE)-model was needed. This led to that a large part of the project focused on developing the FE-THOR since an updated and valid model was not available at the project start. In addition, The FE human body model THUMS was used to relate the FE-THOR crash test findings to humanlike responses.

For a detailed evaluation of the thoracic response, the physical THOR dummy was subjected to quasi-static loading. A probe was pressed down on the thorax to check if localized loading was picked up by the four IR-Traccs measuring chest deflection in three directions. The thorax´s capability of identifying variations due to belt routing was checked by pulling the belt in different angles across the thorax (table top tests). Sled tests using a body-in-white (BIW) was performed to evaluate if the head and chest responses in a complete vehicle oblique impact crash test method (proposed by NHTSA), could be replicated in a sled test environment. Additionally, generic sled tests were performed to check variations to different types of restraints. For the development and validation of the FE-THOR, all the physical tests were replicated virtually. In addition, thoracic responses and overall kinematic of the occupant models were compared using FE-THOR and THUMS in the generic sled setup using ten different restraint configurations.

The quasi-static tests showed that the THOR thorax is sensitive enough to detect localized loading and that repeatability for the chest deflection measured by the IR-Traccs is acceptable in x-direction but questionable for the resultant deflection. The different belt routing positions from the quasi-static tests were replicated in the generic sled tests, and variations in dummy response due to belt routing was detected. Restraint variation in the generic sled tests did result in different dummy response showing that a firm restraint of pelvis or low or distributed loading of the thorax results in low thoracic deflection.

Correlation of the FE-model to physical tests with the THOR was good in the quasi-static tests, generic sled test and the complete vehicle tests. The FE-THOR showed similar kinematic behaviour as THUMS although the less flexible spine resulted in slightly smaller excursion and, as a result of that, different interaction with the restraint systems in terms of head contact to driver airbag and area and shoulder belt deformation. In the comparison of FE-THOR and THUMS, the thoracic response to the different restraint variations was compared using injury criteria with corresponding injury risk functions developed for AIS2+ injuries. For all restraint variations, as well as for two different ages, THOR predicted a lower injury risk compared to THUMS. For the THOR, NHTSA proposed criteria showed more age dependency than the other criteria.

One of the main achievements for this project is the availability of a FE model of the THOR dummy, and specifically the most recent version of the dummy (THOR-M). THOR is the most advanced crash test dummy, enabling higher flexibility in loading directions (oblique to frontal crashes) and higher quality in real world resemblance and responses. A FE model is of outmost importance for using a crash test dummy in vehicle development, due to the need of virtual tools in early phases. The tool and the knowledge gained in this project is of high importance for the partners (Chalmers, Autoliv and Volvo Cars); as restraint system development tool, but also as knowledge base positioner internationally. The knowledge and experiences from dummy handling, response and positioning, together with other results from the project, are disseminated in discussions with NHTSA as well as input to the EEVC working group on the THOR dummy. Using the FE THOR and the THUMS in back-to-back comparison has resulted in a deeper understanding on potentials and limitations for each of the tools available for occupant protection.

2. Background

To further reduce fatal and serious injuries, and to reach Vision Zero, efforts are needed to improve occupant protection. The THOR 50 percentile male dummy, recently upgraded within the European project THORAX and in collaboration with NHTSA, has been shown to be more biofidelic and more sensitive to different restraint systems than currently used Hybrid III dummy (HIII). Even though still a 50 percentile male, this improvement is an important addition to the toolbox needed for development of more sophisticated restraint systems for frontal and possibly also oblique impacts. To cover a wider range of crashes observed in the field data, evaluation of occupant protection using simulation is a must. This requires a valid FE-model of the physical dummy, and although the development of THOR has been ongoing for several years, this was not available at the start of this project.

3. Objective

This project aimed to understand the thoracic loading of the upgraded THOR in frontal and oblique loading conditions using current and state of the art restraint systems. The project also aimed to evaluate and rank (in terms of real life relevance and countermeasure response) the injury criteria presented by the EU-THORAX project. In order to understand potential benefits and limitations of the THOR dummy, a Finite Element (FE)-model was needed. This led to that a large part of the project focused on developing the FE-THOR since an updated and valid model was not available at the project start. In addition, there is a need to relate to humanlike responses, which can be done through comparison to the FE human body model THUMS.

4. Project realization

4.1 Method

To understand the thoracic loading to the THOR the physical dummy was subjected to a number of test scenarios. In parallel to the physical evaluation, the FE-THOR was developed and correlated. Due to the lack of a reliable FE-model of the THOR dummy, focus was shifted during the project and more efforts were put in developing a validated FE-THOR, than evaluating the FE-THOR response compared to the human like response using the FE human body model THUMS.

4.1.1. Quasi-Static tests

For the response to localized impacts, two types of quasi-static tests were performed; indentor tests and table top tests. In the indentor tests, a probe was used to press different points on the thorax according to Figure 1. The setup was similar as previously used in the THORAX project (Carrol et al. 2013)
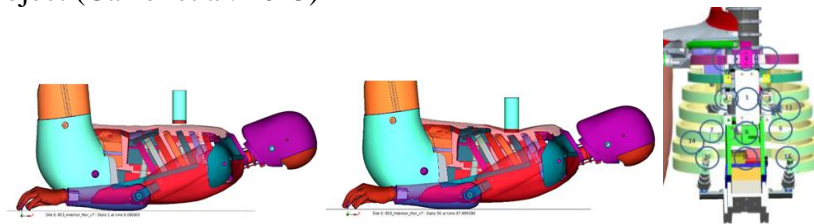

Figure 1. Indentor test setup (left) and indentor location on thorax (right).

In the table top tests, a seat belt was routed in different ways over the dummy thorax. The test setup used is a replica to the method described in Carrol et al. 2013. The setup and the different belt routings are shown in Figure 2.
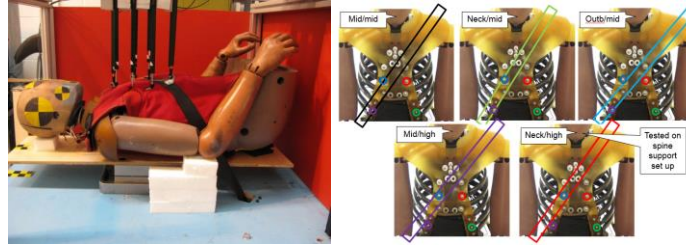
Figure 2. Table top test setup (left) and the different belt routing tested (right).

4.1.2. Sled tests – Body-in-White (BIW)

Six sled tests were performed using a BIW reflecting the proposed NHTSA Oblique Impact. The sled tests were performed in a Volvo S60 BIW and correlated using data from a complete vehicle crash test of the Volvo S60 published in the open database of NHTSA. All interior components were vehicle specific and changed for each test. To replicate correct occupant kinematics and head measurements, two different setup angles were tested; 20 and 25 degrees. The used crash pulse came from the vehicle acceleration in x-direction and all restraint were initiated at the same time as in the crash test. Iterations with modifications of the airbags were made to achieve an understanding of variation in correlation to the crash test.

4.1.3. Sled tests – Generic setup

For evaluation of repeatability and thoracic response to different restraint systems, a total of 61 sled tests were performed using a simplified generic setup, illustrated in Fig 3. In this setup (according to UN ECE R16), a rigid seat was used and belt routing and crash pulse was set to represent a mid-size modern vehicle. To understand the effect on restraint performance and interaction with the THOR, different seat belt systems were compared. Crash Locking Tongue (CLT), was used to prevent belt slip between diagonal and lap belt. Shoulder pre-tensioner was used with a load limiter of 4kN. Pelvis pre-tensioner, PLP, was compared to double PLP. Multipoint belts (criss-cross and backpacker belt) was also evaluated as well as belt bag and a wider webbing for load distribution covering a larger part of the thorax. Interaction with a driver airbag (DAB) was also investigated in two tests. The DAB was a standard driver airbag not optimized for the setup but used to see the influence of distributed thoracic loading.
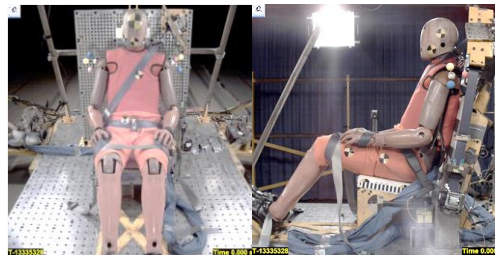

Figur 3. Generic sled test setup. Front view (left) and lateral view (right).

4.2 THOR FE Development

Large part of the efforts within this project was made to develop a stable and valid FE-Model representing the updated THOR (THOR-M).

4.2.1 Chalmers SD3 FE-model development

The shoulder complex is of vital importance for the loading conditions to the chest, in particular when a three-point safety belt is used. Therefore, Törnvall et al. (2006) developed a mechanical shoulder that had humanlike anthropometry and ranges-of-motions and that could be retrofitted the Upper Thoracic Spine weldment of the THOR NT dummy. The new design was denoted Shoulder Design 1 (SD1). Its range-of-motions were updated in SD2. For improved durability and test reproducibility the SD2 was updated within the THORAX project (Lemmen et al 2012 and 2013a and 2013b), and the new shoulder was denoted SD3.

The SD3 shoulder model was created from geometries obtained from NHTSA 3D CAD drawings, and physical measurements on the dummy. Once the model was created, the validation focused shoulder range-of-motion and stiffness evaluation and static shoulder loads focusing on the shoulder only. CAE shoulder response was found to be in alignment with the physical shoulder tests.

4.2.2 NHTSA FE-THOR

The FE-THOR developed by NHTSA did not have the SD3 shoulder at project start. Once the SD3 FE-model was created, the shoulder model was implemented in the NHTSA FE-THOR version 2.0.5. The NHTSA FE-THOR response was evaluated using physical test results from Kroell pendulum tests (ref) and Gold Standard sled tests (ref) to evaluate shoulder and thorax kinematic and measurement responses. The NHTSA FE-THOR was unstable and showed a poor correlation to the physical tests. Due to the vast number of problems identified it was decided to go for a licensed model provided by Humanetics.

4.2.3 FE-model Collaboration and Correlation

A collaboration with Humanetics was established where test results from the physical tests (quasi-static as well as generic sled tests) was provided to Humanetics for model update. Once updated, Autoliv and Volvo Cars evaluated the model in vehicle tests as well as sled tests (generic and BiW). After three iterations the model was replicating kinematic behavior as well as loading response well enough for continuing evaluation with comparison to THUMS. Due to the many iterations during model development the restraint optimization using FE-THOR was not managed within the project time frame or budget.

Correlation between physical test and virtual tests was done with FE-THOR model 0.6.2 in a full vehicle simulation of NHTSA Oblique Impact crash test, and the generic sled test using the reference restraint system. The correlation in the simulated crash test was mainly

focusing on kinematic behavior and head measurements (especially BrIC). THUMS was included to check a humanlike response. The correlation in the generic sled tests focused on overall kinematics, belt forces, accelerations and displacements.

4.3 FE-THOR comparison to THUMS

To evaluate overall occupant kinematic behavior, thoracic deformation and injury risk the FE-THOR was compared to the finite element human body model THUMS in a full vehicle simulation, as well as for the generic sled setup using different restraints. The evaluation of kinematic behavior was made by video analysis. The thoracic deformation was investigated both by deflection measurements in the four thoracic quadrants as well as from animations. Injury risk for THOR was calculated using four different injury criteria; Peak deflection for any of the 4 IR-Traccs (x-direction), Combined deflection, DC, calculated using all four IR-Traccs, Number of fractured dummy ribs (NFS) using strain and Peak resultant deflection (from any of the 4 IR-Traccs). The Dmax, DC and Strain criteria is further explained in Davidsson et al. 2014. For THUMS a strain based injury criteria (fatal strain) was used as well as DC_THOR. The strain based method is described in Foreman et al. 2012, and the DC_THOR is explained further in Mendoza-Vazquez et al. 2015.

5   Results and deliverables

5.1 Test results

In this section physical test results are summarized, followed by comments on the FE-model correlation, the FE-THOR versus THUMS evaluation and the deliverables to the overall FFI goals

5.1.1   Quasi-Static Tests

Spread between similar tests: The set up and the dummy are repeatable enough to make observations and conclusions. Chest deflection in x-direction vs resultant can sometimes explain the variation observed. Temperature effect: Dummy temperature has to be taken into account. After this test loop three temperature sensors were installed (head, neck and chest). Belt position at the shoulder: Small effect on max chest deflection when belt is place on the lower right position. But significant effects could be seen with belt on the upper left position. Belt position at pelvis: The belt position has no or limited effects of the max deflection. But mid/high increase the upper chest deflection.

5.1.2   Sled tests – Body in White

In comparison, the THOR head impacts the DAB later, slides off the driver airbag, and impacts the interior more to the outboard left side in the sled tests versus the complete vehicle test. Sliding off the DAB lower the head rotation around the z-axis resulting in

lower BrIC values than observed in the crash test. HIC on the other hand was found to be higher in the sled tests due to impact to vehicle interior. The femur forces did not match the complete vehicle test due to the lack of instrument panel intrusion. The chest deflection measured in x-direction was highest in the upper and lower right quadrant but peak values were lower in the sled tests compared to the complete vehicle test. Resultant deflection, which might be more appropriate in oblique loading was very different in the sled tests compared to the complete vehicle test. Overall, the sled correlation was not sufficient enough for injury prediction or countermeasure optimization using physical sled tests. CAE evaluation was needed to understand the lack in correlation, but due to the delay in FE-THOR availability further activities on the oblique loading was cancelled.

5.1.3 Sled tests – Generic setup

Spread between tests: The test set up is known and proved to be repeatable. Repetitive test in the series lowered the spread. Diagonal belt position at the shoulder: Neck/mid does not in general decrease resultant deflection as it did for the x-direction only, which correlates to the table top results. Outboard/mid does not affect max deflection which also correlates to table top results. Diagonal belt position at lower thorax: Mid/high in general increase resultant deflection (but no effect in x-direction) as seen in the table top results. Neck/high in general increase resultant deflection (but decrease in x-direction), which does not correlates to table top results. Temperature effect: No obvious increase of deflection with higher temperature. Results were considered as within normal spread. For high repetitiveness in a test loop using THOR, warm up tests is recommended.

For the restraint evaluation, an overview of performance results with different belt systems can be found in Figure 4, where yellow color code denotes reference results, green better results and red worse results compared to reference. The evaluation is based on chest deflection results as well as thorax and pelvis excursion.

0-100ms	Std Ref	No PLP	Pre pt	Dual buckle	2xPLP	DAB	Std LLA	Chris X	Backpack
Cd res.	yellow	orange	light green	green	orange	orange	orange	light green	light green
Cd x-dir	yellow	yellow	yellow	green	light green	yellow	orange	light green	light green
DC, Defl-Comb, x-dir	yellow	orange	yellow	green	light green	yellow	red	green	green
Chest forw disp	yellow	orange	yellow	orange	light green	green	orange	green	green
Pelvis forw disp	yellow	red	yellow	light green	light green	light green	light green	yellow	yellow

Figure 4. Comparison of dummy measurements from the different restraint systems. Yellow for similar measurements, red for increased values and green for lower values.

5.2 FE-Evaluation

5.2.1 FE-model Correlation

In the comparison of the NHTSA complete vehicle test using THOR and the virtual version of the test, using FE-THOR and THUMS showed a good correlation between physical THOR and FE-THOR. Left shoulder and head movement similar and belt slides off right

shoulder in a similar way. An observation during the simulations was that the model is very sensitive to small changes in the setup. Considering the humanlike THUMS, left shoulder movement is similar to the physical THOR test with belt sliding off right shoulder as in the test but still with a different head movement. For future evaluation of oblique impacts, THOR and THUMS are suitable tools to use.

In the generic sled tests the FE-THOR model showed similar kinematics with the physical THOR dummy. Belt forces, accelerations (head, thorax and pelvis) and chest deflections were replicated well in the CAE model compared to the physical tests. When it comes to chest deflection, the measured chest deflections are a result of the forces the dummy are subjected to and the material models used, given that the virtual model is geometrically correct. Users to the licensed model, Autoliv and Volvo Cars, can only control the applied forces and the surrounding systems and only feedback to the CAE dummy distributor (i.e. Humanetics) if the CAE model response is incorrect. One observation is that the belt in the physical and virtual tests, respectively, does not behave exactly the same. In several of the tests, the belt slips off the shoulder towards the neck which it does not do in virtual setup. This may have a slight effect on dummy kinematic, belt forces and dummy responses.

5.2.2   FE-THOR versus THUMS

In the generic sled test set-up, the THUMS model showed a more flexible spine, resulting in more forward excursion and rotation compared to the FE-THOR. THUMS pelvis rotation is also different compared to the FE-THOR, see Figure 5.
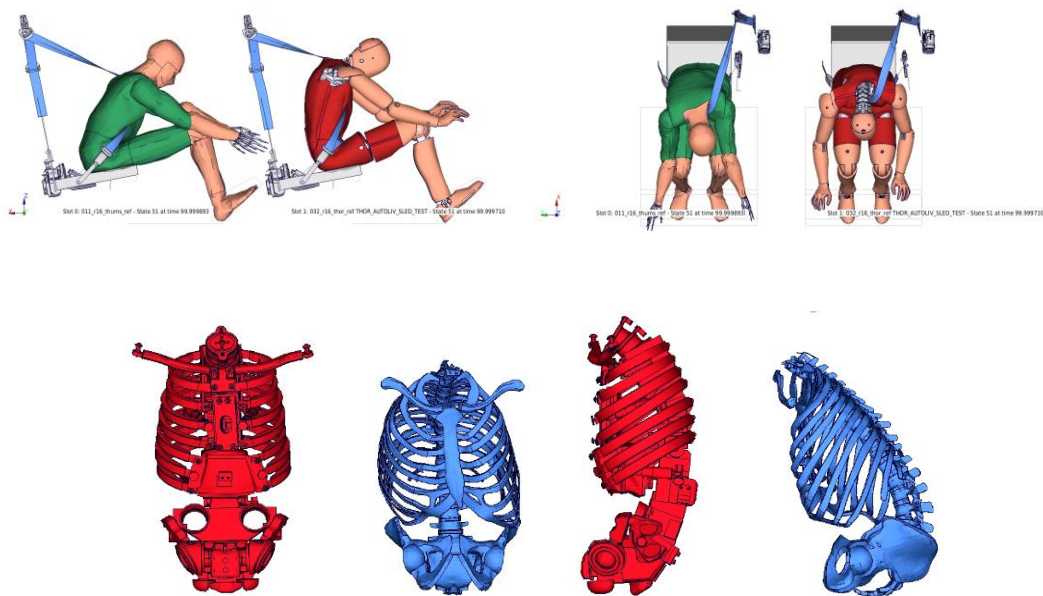

Figure 5. Kinematic comparison of FE-THOR (red) and THUMS (green and blue). Overall kinematic (top) and detailed kinematic (bottom).

Thoracic AIS2+ injury risk for THOR as a 45 and a 65 year old occupant are shown in Figure 6. For a 65 year old occupant the NHTSA developed injury risk curve show a higher

age dependency than the criteria from EU-THORAX. The prediction of two or more rib fractures based on strain, and AIS2+ injury risk derived from DC-THOR for a 45 year old and 65 year old THUMS are shown in Figure 7. For both ages the THUMS predict significantly higher injury risk than the THOR.
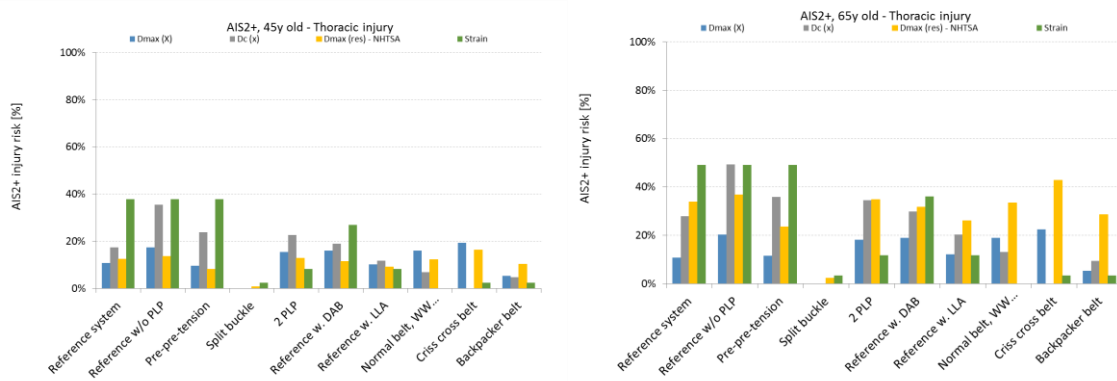

Figure 6. AIS2+ injury prediction based on THOR injury criteria and risk functions.
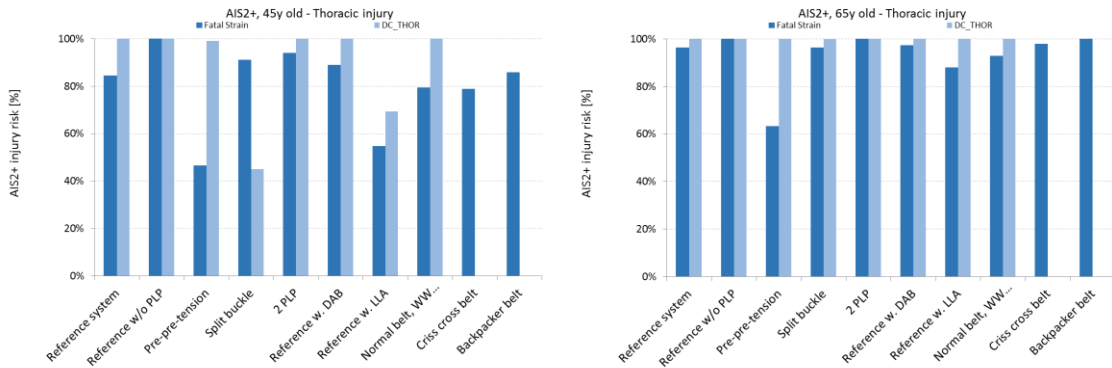

Figure 7. AIS2+ injury risk prediction based on THUMS injury criteria and risk functions.

As injury critera, Dmax either x-direction as proposed by THORAX project or the resultant proposed by NHTSA, is believed to be a good criteria. The high risk of injury predicted by THUMS does seem unrealistic and to further understand the injury prediction levels obtained by these tools more research is needed. To better understand the injury response using advanced restraints and injury mechanisms in oblique impact more research is also needed on the rib cage deformation and spine kinematics in THUMS in order to validate the model.

5.3 Delivery to FFI-goals

The project has contributed with several new research results providing the project partners with enhanced and internationally attractive knowledge. This contributes to perceiving the Swedish industry and academia as very experienced in dummy handling, response and positioning.

One of the main achievements for this project is the now available FE version of the most advanced crash test dummy for frontal and oblique impacts, THOR-M. A FE model is of outmost importance for the possibility of using a crash test dummy in vehicle development, due to the need of virtual tools in early phases.

Results from this project are disseminated in discussions with NHTSA as well as input to the EEVC working group on the THOR dummy, providing evidence of the global significance of Swedish industry and academia.

Using the FE THOR-M and the THUMS in back-to-back comparison has resulted in a deeper understanding on potential and limitation for each of the tools available for occupant protection. THOR is the most advanced crash test dummy, enabling higher flexibility in loading directions (oblique to frontal crashes) and higher quality in real world resemblance and responses. Using the most advanced tools will help Swedish industry to maintain the safety leadership as well as contribute to the reduction of injured and killed car occupants.

Thanks to the now available FE-model of THOR-M, the THOR is now being used to a greater extent in product development projects. Designing restraint systems using the THOR-M will enhance occupant protection designs and contribute to the Zero Vision.

6 Dissemination and publications

6.1 Knowledge and results dissemination

The results obtained within this project has increased the knowledge on the updated THOR dummy that is suggested for evaluating occupant protection in oblique impact as a first step and them probably a candidate of replacing the HIII dummy. The detailed level of knowledge on handling, dummy response and the comparison to THUMS gives a world leading role for the project partners. The knowledge will be very valuable as input for the EEVC working group evaluating the THOR for EuroNCAP.

The results from this project will be directly transferred into other collaboration projects for research such as the FFI project application "Development of Implementable Omni-Directional Chest and Spine Injury Criteria for Human Body Models", and internal product development projects at Autoliv and Volvo Cars.

6.2 Publications

This project has generated a lot of results which has been disseminated mainly through oral presentations. The project has also enabled collaborations with other partners resulting in a number of written and oral publications.

6.2.1 Reports

Holmqvist K. and Davidsson J. *Development of a Finite Element Model of the SD3 Shoulder.* Chalmers internal report.

6.2.2 Presentations directly related to the project

M Dahlgren. *THOR test vs CAE, restraint parameter study*. Oral presentation at the Humanetics Crash Meeting in Heidelberg 2015.

M Dahlgren. *NHTSA oblique generic CAE study*. Oral presentation at the Humanetics Crash Meeting in Heidelberg 2015.

M Östmann. *Comparison of Occupant Behaviour (CAE-HIII, Thums, CAE-Thor and Physical Thor) in NHTSA Oblique Test*. Oral presentation at the Humanetics Crash Meeting in Heidelberg 2015.

M Panzer. *Evaluation of the NHTSA THOR Finite Element Model*. Oral presentation at the THOR Public Meeting at NHTSA, Washington DC, 2015.

C Sunnevång. *FFI-THOR - Repeatability and sensitivity of the THOR dummy,* presented at the EEVC Kick off meeting July 9th 2015.

6.2.3 Publications associated with this project:

F. J Lopez-Valdes, O Juste, B Pipkorn, I Garcia-Muñoza, C Sunnevång, M. Dahlgren & J. J Alba. *A Comparison of the Performance of Two Advanced Restraint Systems in Frontal Impacts*. Traffic Injury Prevention, 2014:15 pp 119-125.

F. J Lopez-Valdes, O Juste. *Innovative Restraints to Prevent Chest Injuries in Frontal Impacts*. ESV Conference 2015 Gothenburg.

B Pipkorn, F.J Lopez-Valdes, C Lundgren, D Bråse, C Sunnevång. *Innovative Seat Belt System for Reduced Chest Deflection*. ESV Conference 2015 Gothenburg.

C Sunnevång, E Lecuyer, D Hynd, J Carroll, D Kruse & O Boström. *Evaluation of Near-Side Oblique Frontal Impacts Using THOR with SD3 Shoulder*. Traffic Injury Prevention, 2014:15 pp 96-102.

C Sunnevång, D Hynd, J Carroll, M Dahlgren. *Comparison of the THORAX Demonstrator and HIII sensitivity to crash severity and occupant restraint variation*. IRCOBI Conference 2014.

7 Conclusions and future research

7.1 Conclusions

An FE-THOR version 1.0 (representing physical dummy THOR-M) is now available to use for product development.

Injury risk prediction using THOR (FE and physical dummy) offers increased possibilities to address senior occupant protection, as well as non-senior occupants.

Injury prediction using THOR and THUMS in the same loading conditions resulted in different risk levels where THOR showed lower risk of AIS2+ thoracic injury. Chest deformation was found to be larger in the THUMS compared to THOR and in some cases the thorax deformation was different due to different kinematic behavior of the spine.

All the injury criteria for THOR showed similar trends although the peak values were different. The strain based NFR criteria for THOR is a step function resulting in very large differences. The results from this study showed that peak deflection from one of the IR-Traccs (Dmax) is as good for risk prediction as using the DC (Combined Deflection using all four IR-Traccs).

7.2 Future Research

With the different injury predictions obtained by THOR and THUMS it is important to establish which levels are correct. It is also important to understand the limitations with the THOR dummy when it is being used for product development. To do this more research is needed to ensure the THUMS biofidelity in terms of spine kinematics and ability to predict rib fractures. One way to establish the injury prediction for THUMS (and THOR) is to reconstruct real life crashes.

As injury criteria Dmax, either x-direction only or the resultant proposed by NHTSA, is believed to be a good criteria. The high risk of injury predicted by THUMS do seem unrealistic and to further understand the injury prediction levels obtained by these tools more research is needed. To better understand the injury mechanisms using advanced restraints and also in oblique impact more research is also needed on the spine kinematics in THUMS in order to validate the model.

Due to the late availability of FE-THOR, limited comparison to THUMS was performed in oblique loading conditions. To understand injury prediction under oblique loading and with possible deformation from belt as well as door side more research is needed to evaluate the validity of proposed injury criteria for thoracic injury in this loading condition.

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