# Development of an advanced frontal dummy thorax demonstrator

Paul Lemmen[1], Bernard Been[1], Jolyon Carroll[2], David Hynd[2], Johan Davidsson[3], Eric Song[4], Erwan Lecuyer[4]

***Abstract*** Thoracic injuries are one of the dominant causes of fatalities and severe injuries in car crashes today. THORAX-FP7 is a collaborative medium scale project under the Seventh Framework which focuses on reduction and prevention of thoracic injuries through an improved understanding of the thoracic injury mechanisms and the implementation of this understanding in an updated design for the thorax-shoulder complex of the THOR dummy as well as in human boy models.

The models and dummy will enable the design and evaluation of advanced restraint systems for a wide variety (gender, age and size) of car occupants. This paper presents results achieved during the first three years of the project related to dummy hardware developments. The hardware development involved five steps: 1) Identification of the dominant thoracic injury types from field data, 2) Specification of biomechanical requirements, 3) Identification of injury parameters and necessary instrumentation, 4) Dummy hardware development and 5) Evaluation of the demonstrator dummy.

The accident surveys were reported in a previous IRCOBI paper. This paper describes the selection of human response data suitable for assessment of frontal dummy performance, studies into the injury criteria which are independent of the loading type and the dummy developments done so far.

*Keywords* **Biofidelity, Dummy development, Frontal impact, THOR dummy, Thorax.**

## I. INTRODUCTION

Around 41,600 people were killed and more than 1.7 million injured in European road accidents in 2005 [1]. Although data from the European Road Safety Observatory show that the number of road fatalities declined down to 34,817 in 2009 and the injured declined to less than 1.6 million, further efforts are needed to make European roads safer. This may be particularly challenging taking into account the growing transportation needs of the elderly and the recent expansion of the EU with countries that historically lacked effective safety standards.

While efforts are needed on all levels of road safety, the EC 7th Framework project THORAX (Thoracic injury assessment for improved vehicle safety) is focused on the reduction and prevention of thoracic trauma from frontal impact accidents. As depicted in Fig. 1, thoracic injuries are one of the leading causes of severe injuries and fatalities in car crashes. Compared with older analyses (e.g. [2]) it is now clear that the thorax has superseded other body regions in terms of the number of occupants receiving an injury, particularly at the severe MAIS ≥ 3 level.

The general objectives of THORAX are to develop required understanding in thoracic injury mechanisms and to implement this into numerical and experimental tools that will enable the design and evaluation of advanced vehicle restraint systems that offer optimal protection for a wide variety of car occupants. In order to maximise the safety benefits gained from new vehicle and restraint technology for various genders, ages and sizes of occupants, these tools will have to be much more sensitive to the in-vehicle occupant environment than what is the case today.

P. Lemmen is Coordinator of the THORAX Project, Humanetics Europe. (+31 6 227 56 277, plemmen@humanetics.eu). B. Been is responsible for the THOR dummy developments at Humanetics Europe, the Netherlands. J. Carroll is a Senior Researcher at TRL, United Kingdom. D. Hynd is Head of Biomechanics at TRL. J. Davidsson works in the Vehicle Safety Division of Chalmers University of Technology, Sweden. E. Song and E. Lecuyer both are Senior Researchers at LAB PSA Peugeot Citroën Renault, France.

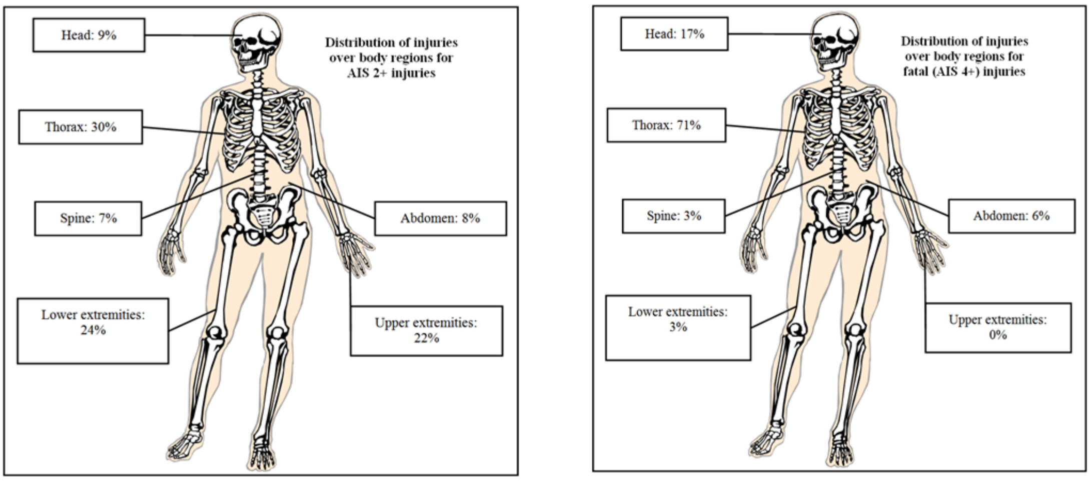


Fig. 1. (a) Distribution of AIS ≥ 2 and (b) AIS ≥ 4 injuries over body regions to car occupants sitting in front seats in frontal impacts for cars manufactured between 1996 and 2004 [3].

Specific objectives of the THORAX Project are:

- Identification of the two most relevant thoracic injury types for car occupants in view of societal relevance, taking into account user diversities like age, gender and size.
  - Output of the project towards this objective was reported at a previous IRCOBI conference [4].
- Development of a mechanical demonstrator consisting of a new dummy thorax and shoulder design
  - This paper describes Project progress towards this objective.
- Derivation of injury risk functions differentiating between genders, age groups and sizes
- Evaluation of the sensitivity of the demonstrator to modern vehicle safety systems
  - These last two objectives are still in progress and, as such, not ready for publication at this time.

As noted above, the accident analysis tasks of the THORAX project have already been completed. These were undertaken with close collaboration between efforts in the THORAX Project and the COVER Project. The surveys into real world accidents provided detailed information on the type and severity of injuries in relation to impact type (severity, overlap, intrusion), restraint type (airbag deployment, load limiter, pre-tensioner), and occupant characteristics (age, size, sex).

It was concluded that rib fractures are the most common injury followed by lung injuries [5]-[6]. These two types of injury should be considered in the THORAX project. Moreover it was found that older occupants have a substantially higher risk of sustaining a torso injury than younger occupants, with a particular susceptibility to rib fractures when compared with younger occupants [7]. The younger occupants were more likely to suffer a lung injury without serious rib fractures than were the older occupants. Finally the effectiveness of load limiters in seat belts was shown in the reduction of torso injury severity [8].

In crash tests, instrumented physical human surrogates, known as crash test dummies, are used to estimate a human's injury risk. The dummy must possess the general mechanical properties, masses, joints and joint stiffness of the humans of interest. In addition, they must possess sufficient mechanical impact response similitude and sensitivity to cause them to interact with the vehicle's interior in a human-like manner. For the thorax, appropriate construction, behaviour and injury measurement of the dummy is particularly critical as the human chest during a crash may be subjected to a complex loading environment that comprises both localized (belt -like) and distributed (airbag-like) loading types.

Detailed studies [9]-[10] have shown that the currently used Hybrid III dummy as well as its intended successor, the THOR dummy, lack sensitivity to relevant injury parameters like sternal displacement under realistic restraint loadings when belt and airbag loading is superimposed on the chest. In particular, it has been shown that the relationship between injury risk and the injury criteria measured by the dummies is sensitive to experimental parameters such as the apportionment of seatbelt and airbag loading. This is a problem both of measurement (the dummy does not measure the same thoracic response as a human) and of interpretation (lack of knowledge to understand the underlying mechanisms of thoracic injury).

## II. Biomechanical requirements

Biofidelity requirements are used to ensure that a crash test dummy loads the vehicle and restraint system in a similar way to the human. In addition, these are used to ensure that the response of the dummy to this loading is relevant to be used in prediction of injury risk in simulated crashes. Biofidelity requirements may be derived from human volunteer, PMHS, or animal tests and the test conditions should be representative of real-world accidents. In THORAX a literature survey and analysis of existing datasets was conducted to define biomechanical requirements and to identify gaps in the existing datasets. For the analysis of the existing data the load cases used were compared with the loads in actual collisions to prioritize the available information.

From a literature survey a first set of thoracic biofidelity target corridors for a 50th percentile male frontal impact dummy was presented [11]. The biomechanical references used to define the targets and which are most reasonable to reproduce are summarised in Tables A**Error! Reference source not found.** to AIII. From these tables it is clear that to ensure good performance under various loading conditions a much broader set of requirements was proposed when compared with those from the EEVC and NHTSA.

It should be noted that the biofidelity conditions shown in Tables AI to AIII represent the highest priority data sets from the literature survey. To be included in this list, the requirements were considered as suitable for defining biofidelity requirements and suitable for replication within the THORAX project (or at any well-equipped crash test or biomechanics laboratory). Further potential conditions were identified which could either be used in the future, subject to further information about the test set-up or requirements being presented, or which offer engineering guidance as to expected thoracic behavior. Data sets which provided only limited information on biofidelity but which would be more useful in the development of injury risk functions were noted and flagged for use later in the project; but are not included in the tables in the Appendix.

In searches to determine the baseline performance of the THOR against these requirements [35], it was found that, generally, the THOR dummy matches the human response much better when compared with the Hybrid III dummy e.g. [22], [39]-[40]. The THOR also offers more humanlike anthropometry of the chest and rib orientation. The THOR dummy exhibits a human like seating position and dynamic upper body kinematics. Its chest sensitivity is dependent on loading type (hub impact, belt load, airbag). However, for a human, distribution of the chest load was found to be effective to mitigate chest injury. With the THOR dummy it appears that injury risk predictions do not decrease as would be expected with distributed loads. This finding creates a target for improvement.

Another important conclusion from the biofidelity requirements review [35] was that the 6.7m/s hub impact, a test condition where the loading object has high mass and produces a high chest deformation and high rate, is not representative of the rate or type of loading to which a human chest will be subjected in a modern vehicle under belt and airbag restraint e.g. [17], [41]-[45]. Note that when Neathery [36] defined the response corridors, he increased the force with 667N to correct for the lack of muscle tension in the test subjects. Recent work done by Lebarbe and others suggest that this increase due to muscle tension can no longer be defended, so the impact force in the corridors was reduced to the original PMHS levels [51]-[53]. With the reduction of the load and omission of the high speed test conditions, the rigid chest impact test was found to be representative of the highest level of restraint loading cases. Also indications were found that the shoulder belt interaction with the THOR dummy is not human-like and should be improved [16], [46]. Here it is noted that there were no biomechanical requirements on the shoulder for the original THOR, even though shoulder and clavicle play an important role to distribute belt loads further into the human chest.

## III. Injury criteria

Sternal deflection is an injury criterion used in current regulatory and consumer tests worldwide to assess thoracic injury risk. However, this criterion has some limitations when applied to the Hybrid-III dummy: the risk curve based on the criterion is restraint dependent, and it does not allow discrimination between some advanced restraint systems e.g. [9]-[10], [42]-[43]. The THOR dummy, despite its improved biofidelity, is confronted with similar limits when assessing injury risk through sternal deflection. THORAX Task 2.3 aims at identifying more robust approaches. A human body FE model-based approach was used to achieve this objective. The Radioss™ HUMOS 50th percentile male human model, depicted in Fig. 3 (a), was updated and

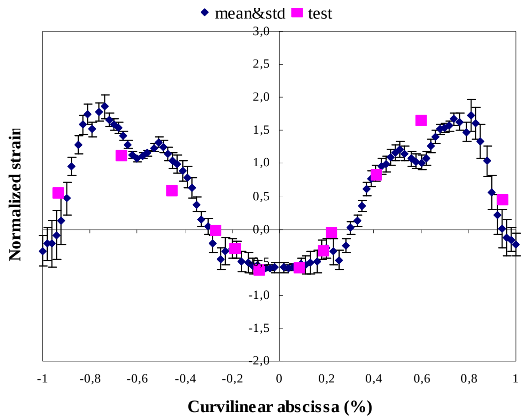


Fig. 2a Comparison of the strain profile for the 5th rib between the HUMOS2LAB model and the cadaver tests under static airbag loading performed by Trosseille et al. 2009 [47].

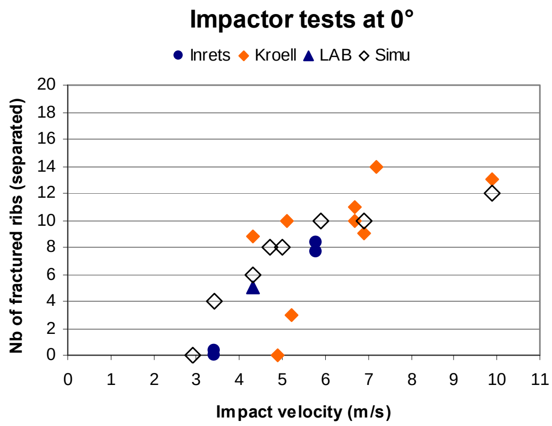


Fig. 2b. Number of fractured ribs versus loading severity for impactor tests: comparison between the HUMOS2LAB model and the experimental data (Kroell et al. 1974 [49], Bouquet et al. 1998 [47], Trosseille et al. 2009 [48]).

validated for frontal impact simulation, not only in terms of its gross motion response, but also in terms of its capability to predict rib fractures [37]-[38]. Figure 2 provides examples of validation of the updated model: one is relative to rib strain profile comparison under static airbag loading; the other is relative to comparison of number of fractured ribs for impactor test.

Once validated, the model was submitted to a wide range of loading types: impactor, static airbag, belt only restraint, airbag only restraint and combined belt and airbag restraint. For each loading type, different loading severities were applied to generate different levels of rib fracture: from the absence of fractures to numerous fractured ribs. Fig. 3 (b) shows examples of ribcage deformation shape under different loading types. From the simulations bending was identified as being the main loading resulting in rib fracture. Two injury criteria representing this pattern were formulated, the first one being the Combined Deflection (Dc):

$$Dc = Ds + Cf \times \left[(dD - Lc) + \left|(dD - Lc)\right|\right] \quad (1)$$

Where:
- Ds = sternal deflection
- dD = differential deflection
- Lc = characteristic length for the differential deflection
- Cf = contribution factor

The sternal deflection Ds (the X-component of the mid-sternum displacement relative to the spine in A-P direction) reflects the amplitude of the symmetric part of the ribcage deflection while dD is the difference between right and left deflections of the lower ribcage measured at the joint between the 7th ribs and the cartilage (the X-components in A-P direction). The characteristic length Lc serves to amplify the differentiation effect of the term “dD – Lc” between different types of asymmetric loadings. Finally the contribution factor Cf is a coefficient to weight contributions of the differential deflection to the Dc.

Fig. 3a. HUMOS 50$^{th}$ percentile male human model

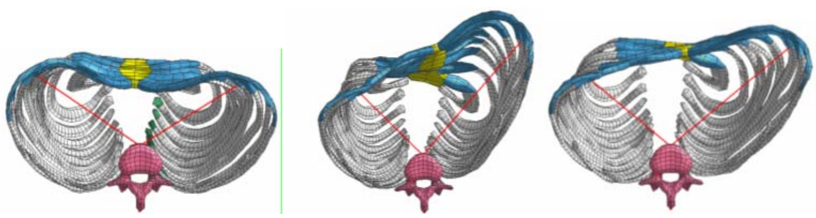

Fig. 3b. Examples of ribcage deformation shape under different loading types based on the HUMOS2LAB simulations. From left to right: airbag only, 6kN load limiter only, 4kN load limiter + airbag,

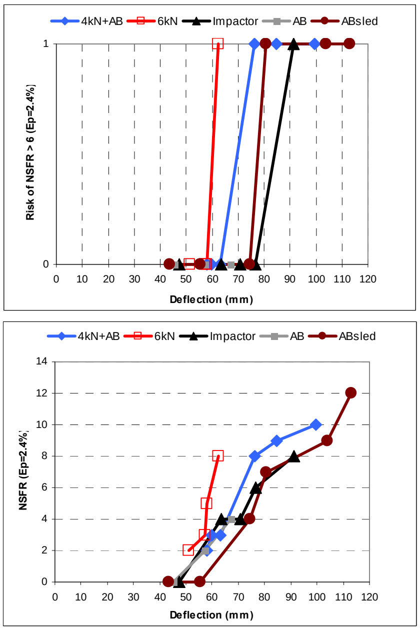


Fig. 4a. Risk curves (top) and injury curves (bottom) of Number of Fractured Ribs > 6 with sternal deflection as injury criterion. Results obtained with HUMOSLAB2 model assuming a plastic strain failure threshold of 2.4% representing a stronger subject.

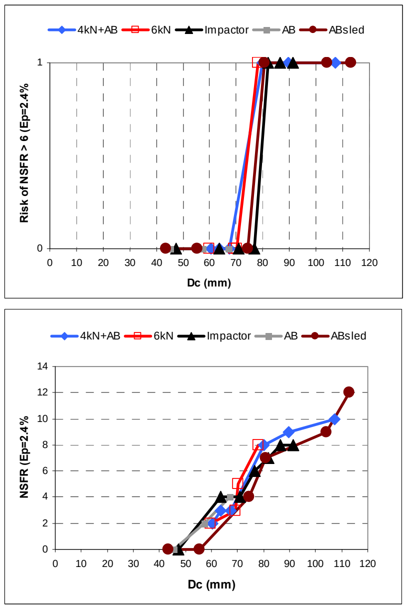


Fig. 4b. Risk curves (top) and injury curves (bottom) of Number of Fractured Ribs > 6 with Dc as injury criterion. Results obtained with HUMOSLAB2 model assuming a plastic strain failure threshold of 2.4%, representing a stronger subject.

Simulations with the Dc criterion showed that Lc should be around 24 mm, and Cf about 0.15 to give the most consistent results with respect to independence to the various loading types [38], [50]. These values need to be confirmed in future studies with the THOR dummy. Fig. 4 shows injury curves and risk curves corresponding to different loading types for a stronger subject represented by a large failure strain of the ribs. The results in this figure are generated using the HUMOSLAB2 model. Results are shown for the chest deflection criterion (a) and the Dc criterion (b). It can be observed that the injury curves relating the metrics to the number of fractured ribs, become independent from the loading type when using the Dc. Also the risk curves of NSFR > 6 become reasonably close, especially when only sled tests are considered. Note that both types of curves are built on only 1 subject, being the human body model used. As a consequence the injury risk curves become a straight vertical line. Also no goodness of fit was applied to the injury curves for this reason. Although it would smooth the curves, the fitted result would not pass through the actual raw points leading to some accuracy loss. The above simulations were repeated for different strain thresholds representing weaker and stronger subjects. An identical outcome was obtained in these cases [38], [50]. This result encouraged the THORAX team to further explore the Dc criterion in future experimental studies with hardware dummies. For this purpose four 3-D IR-TRACCs will be implemented in the thorax, measuring relative displacements in three directions.

The second injury criterion advanced is a rib strain based one: the Number of Fractured Ribs (NFR). In fact, the validation process of the model showed that rib fractures can be explained by excessive strain level. By measuring rib strain on a dummy, the NFR can be determined and used as a global injury criterion. Besides, the NFR intrinsically reflects the injury level for the ribs and is independent of loading type. Figure 5 illustrates a possible approach to use this criterion. The key point is to determine, for a given dummy, a strain threshold. For each rib of the dummy, once its maximal peak strain reaches the threshold, the rib is considered as fractured.

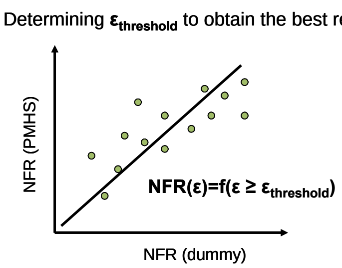


Fig 5. Scheme of possible approach to apply the NFR as an injury criterion to dummies

In this way, the NFR for the dummy in question can be determined for each test. A three-step approach can be used to determine the strain threshold. First, PMHS-dummy matched tests should be gathered, where we know rib fracture outcome of all PMHS tests and where the strain distribution of each rib is measured. Then, the NFR-PMHS should be plotted versus the NFR-dummy determined by supposing a strain failure threshold. Finally, we should vary this strain failure threshold until the best correlation is identified. This strain threshold will be the threshold for this specific dummy. For another dummy, we can apply the same method to identify its proper strain threshold. Once the strain threshold has been determined, the NFR can be derived easily and be used as an injury criterion in the same way as a traditional one.

It should be stated that the NFR is still hypothetical as no data have been collected so far. As a consequence it is not possible at this stage to identify a preference for either one of the proposed criteria. It is one of the goals of future testing in the THORAX project to provide required information for recommendations on this. More details on the Dc and the NFR can be found in the work of Song et al. [38] and [50].

## IV. Thorax demonstrator design

Based on the findings of the accident surveys and the outcome of the biomechanical work so far, a demonstrator dummy has been designed. Extensive design and prototyping efforts were made to realise three demonstrator dummies for evaluation testing and restraint sensitivity testing later in the project. Key points of attention were the rib response tuning to new corridors, updates of the SD2 shoulder in relation to durability and functionality and implementation of instrumentation to capture newly propose injury parameters.

***Rib cage design and initial response tuning***

During the THORAX project the existing THOR FE computational model was evaluated [48, 49]. Initial comparison with experimental sled data showed that both spine and shoulder kinematics were very different from those of the mechanical counterparts [48]; the authors suggested that additional material characterization should be carried out and it was recommended to perform additional evaluations using various loading conditions. Although further studies indicated that the lack of correlation was also partially due to modelling errors of the test setup [49] it was decided not to use the model for fine tuning the chest impact response. Because of the complex structure of the upper body of the THOR NT preference was given to experimental investigations (Fig. 6a). For the initial design realisation pendulum impactor tests representing the low-speed NHTSA [13] and ISO (also referred to as Lebarbe) [14] requirements for the thorax were performed. Both are partially based on the same biomechanical background data, but Lebarbe included results from newer data sets. Also, Lebarbe’s corridor is based on a newly developed mathematical methodology [14], which includes a different normalisation process, subset selection based on response shape and corridor calculation based on standard error. The NHTSA corridors are developed with a subjective methodology by ‘eye-balling’ constructing and envelop of straight lines around the responses. Fig. 6b shows that the NHTSA and Lebarbe corridors cannot be compared directly as the latter allows for larger deflection. Apart from the above mentioned differences Lebarbe’s corridors represent external compression, as the original data only included pendulum penetration. As such they do not allow for direct comparison of the dummy instrumentation output, which measures skeletal deformation only. During NHTSA corridor development, the external soft tissue deformation was roughly estimated at 1/2” (12.7mm) and was distracted from pendulum penetration to represents internal skeletal deformation, which does allows direct comparison to the output of the chest compression measurement system inside the dummy.

In order to optimise the THOR rib cage response a large test matrix was completed to investigate the influence of various components in the dummy thorax. Sensitivities to rib metal stiffness, influence of the jacket and effect of fine tuning in the sternum area were studied as well as the influence of rib damping material. Over 100 tests were conducted. The rib metal stiffness was gradually reduced by stepwise cutting of the height of rib metal. The final result is a rib cage optimised for pendulum impact corridors applied by NHTSA as well as ISO. It is noted that a compromise was necessary and agreed between THORAX members and NHTSA, as the peak force was still slightly outside the upper boundary (Fig. 7). Test data indicated that the peak deflection increases at a much higher rate than peak force reduction with gradual stiffness reduction. Further peak force reduction

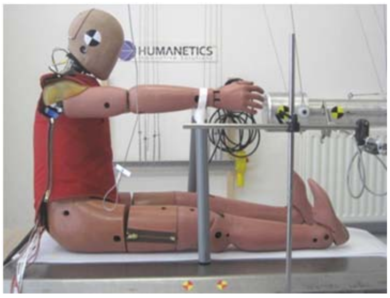


Fig. 6a. Set-up frontal impactor test

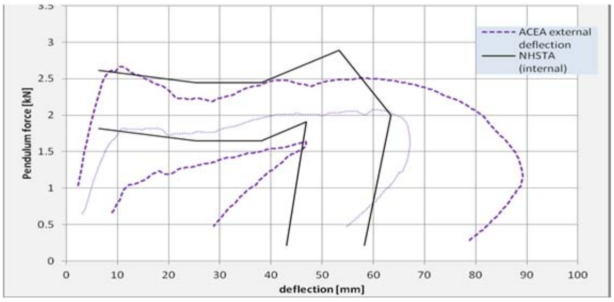


Fig. 6b. Comparison of NHTSA and Lebarbe corridors for 4.3m/s 23.4kg pendulum test

would have been possible but not pursued as the peak compression would potentially rise beyond the range of the full dummy compression. Based on the outcome of the tests 3 rib sets were made with 9mm damping 1.6mm rib metal gage. Inside the front jacket an additional 6mm foam pad was added to slightly increase the external deflection and reduce vibrations in the platform of the force deflection response. The performance of the rib cages is shown in Fig. 7. Note that for the comparison against the Lebarbe corridor, the measured internal chest deflection was corrected for the external soft tissue deformation, by adding up jacket compression based on jacket force-deflection characteristics. Note that the responses shown are from a dummy with standard THOR-NT shoulders, which was used as test bed for performance tuning.

***Shoulder and arm design***

In addition to the rib cage extensive efforts were made to update the THOR SD2 shoulder which was originally developed by Törnvall [46]. The sterno-clavicular joint was redesigned to meet anthropometry requirements for the 50 %-ile male described in [47]. See Fig. 8a. The original SD2 design did not meet the anthropometric target position of ±20mm lateral from mid saggital plane (it was ±44mm). The sternum and clavicle design were updated accordingly.

Of particular importance is the update of the shoulder cover (Fig. 8c). As the SD2 design allows a complex and large range of shoulder motion, the original design applied left and right soft foam shoulder mouldings inside a dedicated jacket. The position and shape of the foam was not well defined and did not provide a repeatable position of and interaction with the belt. The updated SD shoulder employs a solid elastomer moulding, which is closer to the original NT part in geometry and firmness. The original THOR jacket is used with the updated SD shoulder, slightly modified to allow for the larger range of shoulder motion.

In addition to the above, weak spots previously identified in tests by UVA were addressed and updates realised. The changes include going back to a spherical joint for the clavicle (Fig. 8a), introduction of adjustable joint friction to obtain a more reproducible dummy seating position (Fig. 8b), geometric simplification of components for ease of manufacturing (Fig. 8b), etc.. The humerus joint, originally a universal joint, was replaced by a metric version Hybrid III style joint, to address lack of joint friction and durability problems (Fig. 8a). Finally a clavicle load cell has been implemented that allows measurement of vertical and interior-posterior loads in both ends of the clavicles (Fig. 8a). The updated shoulder design is being referred to as the SD3 shoulder.

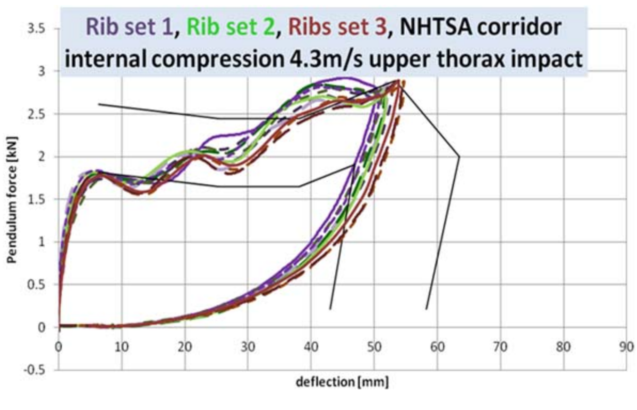


Fig. 7a. Test results compared to NHTSA corridors

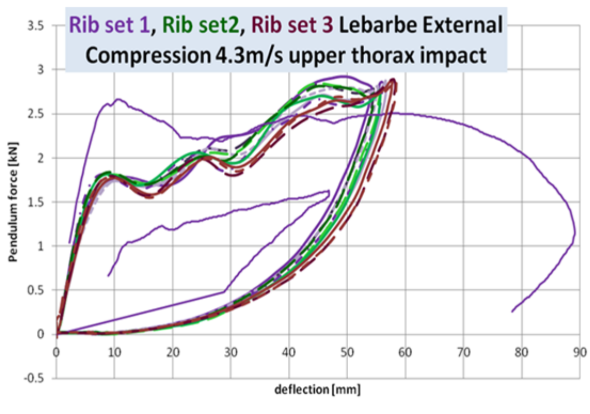


Fig. 7b. Test results compared to Lebarbe corridors

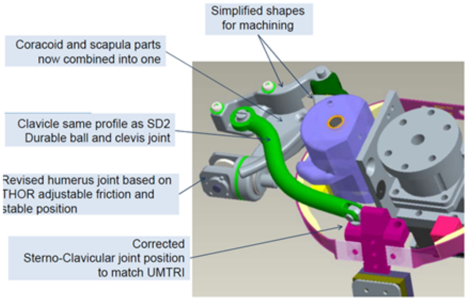


Fig. 8a. Shoulder updates

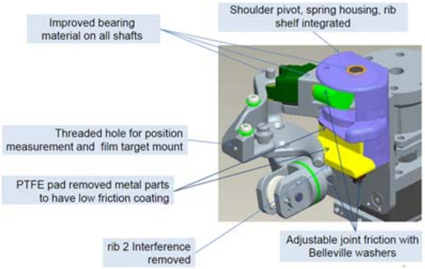


Fig. 8b. Details pivot region

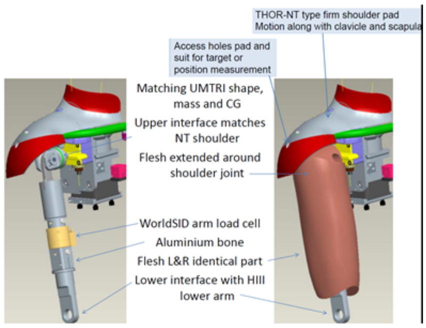


Fig. 8c. Shoulder cover and arm

The THOR dummy applied HIII arms which were not matching anthropometry requirements in [47]. Moreover the arms were not well integrated in the SD2 shoulder design. To make up for this discrepancy, a new upper arm was developed which is compatible with the shoulder design and meets the anthropometric targets (Fig. 8c). The design includes load measurement capabilities at mid humerus.

***Instrumentation***

In conjunction with the injury criteria proposed, four 3-D IR-TRACCs in the thorax were adopted from the THOR mod-kit. Their output provides required input for the Dc criterion. The IRTRACCs are installed at identical positions as proposed by NHTSA in the mod-kit to harmonise the design. As input to the NRF criterion two of the demonstrator dummies are equipped with a total of 72 strain gages on the ribs (Fig. 9). The 72 gages are implemented such that the influence on the chest dynamic response is negligible. From the second rib down, all 6 lower ribs have 6 strain gages on both sides equally spaced in ratio to the length of the ribs (Fig. 9c). The dummies with gages are equipped with a 96 channel digital on board Data Acquisition System, to minimise influence of electrical cables to the kinematic behaviour.

***Pelvis-Femur-Knee***

Outside of the THORAX Project dummy parts like Pelvis, Femur and Knee were updated and address issues raised by the SAE THOR Evaluation. Two out of the three dummies tested in THORAX have these updates included to allow for direct comparison of test data with others.

## V. Discussion

It is well known that thoracic trauma from frontal impact accidents is one of the leading causes of severe injuries and fatalities in car crashes e.g. [12]. Accident surveys in THORAX and COVER concluded that rib fractures are the most important source of injuries followed by lung injuries [5]-[6]. Age was seen to influence the common patterns of thorax injury; older occupants have a substantially higher risk of sustaining a torso injury than younger occupants, with a particular susceptibility to rib fractures [7]. The younger occupants were more likely to suffer a lung injury without serious rib fractures than were the older occupants. Finally the effectiveness of load limiters in seat belts was shown in the reduction of torso injury severity [8].

Fig. 9a. Example of rib with gages

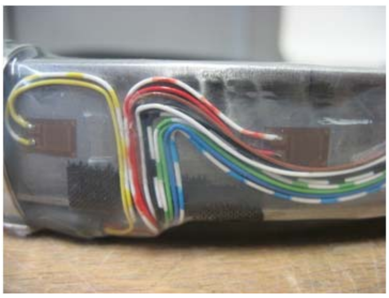

Fig. 9b. Detail of gage implementation

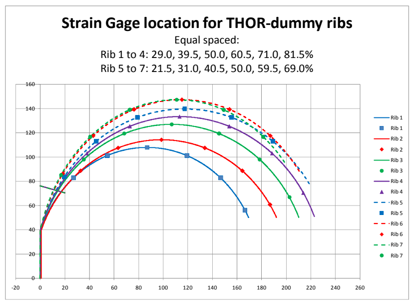


Fig. 9c. Gage positions (only left half)

An update of the thorax / shoulder complex of the THOR dummy is being developed to address these observations. In searches towards the baseline performance of the THOR [35], it was found that, generally, the THOR dummy matches the human response from PMHS tests much better when compared with the Hybrid III [22], [39]-[40]. The THOR also offers more humanlike anthropometry of the chest, rib orientation and a human like seating posture. Its chest sensitivity is dependent on loading type (hub impact, belt load, airbag). However, for a human, distribution of the chest load was found to be effective to mitigate chest injury. With the THOR dummy it appears that injury risk predictions do not decrease as would be expected with distributed loads. This finding creates a target for improvement.

A first set of biofidelity target corridors for a 50th percentile male frontal impact dummy has been presented. These represent the priority test conditions against which the new thorax demonstrator dummies should be evaluated. A broader set of requirements has been produced than was included in previous thorax biofidelity requirements. This reflects the expected conditions in which an advanced frontal dummy is expected to be used and continuing efforts throughout the research community to define relevant and reproducible biomechanical data sets. It also reflects the well known fact that the hub impact is not representative of the type and rate of loading to which a human chest will be subjected in a modern vehicle under belt and airbag restraint [17], [41]-[45]. Moreover it includes requirements related to more realistic shoulder belt interaction [16, 46]. Here it is noted that there were no requirements on the shoulder for the original THOR, even though the shoulder and clavicle play an important role to distribute belt loads further into the human chest.

Sternal deflection is an injury criterion used in current regulatory and consumer tests worldwide to assess thoracic injury risk. However, this criterion has limitations in the fact that the related risk curve is restraint dependent and it does not allow discrimination between some advanced restraint systems [9]-[10], [42]-[43]. The THOR dummy, despite its improved biofidelity, is confronted with similar limits when assessing injury risk through sternal deflection. A human body FE model-based approach was used to identify more robust approaches. Rib fractures were simulated for a wide range of loading types and severities. Bending was identified as being the main loading type resulting in rib fracture and two injury criteria representing this pattern were formulated. The first one is the Combined Deflection (Dc) which is a global criterion that combines sternal displacement information with data from the joints of the 7th rib and the cartilage. The second criterion is indicated as Number of Fractured Ribs (NFR). It combines local strain information at ribs 2 – 7 to establish a relation between risk for rib fracture and peak strains measured. Both were evaluated using human body models but further assessment based on hardware testing is needed. For this purpose an extensive test series is currently ongoing in the THORAX project. The tests are defined to relate outcomes of Dc and NFR on the THOR dummy to the injury outcome of the corresponding PMHS tests and as such meant to provide recommendations for the use of either one of these proposed criteria.

The shoulder/thorax complex has been developed to be capable of representing the older occupants identified in the THORAX accident analyses. The biofidelity requirements are naturally biased towards older subjects, because the available test data is biased to older subjects. However, the nominal age of occupant represented by the dummy and, in particular, of the injury risk functions used may be dependent on the application of the dummy. Therefore, it is planned that the THORAX project will deliver injury risk functions for a range of occupant groups, including older occupants, so that the end user can select the appropriate risk function and performance requirement for their application.

In summary the new dummy thorax / shoulder complex should be largely based on the THOR design, but optimised for interaction with load limiting belts and airbags (reducing overall rib stiffness), the rib stiffness distribution over the chest height should be reviewed, shoulder and clavicle should be more human like, and instrumentation should be implemented to detect localised chest deformation. Based on the wish list a new design was realised. Experimental investigations were carried out to fine tune the chest impact response to impactor loading. A design was accomplished that matches hub impactor requirements both from NHTSA and ISO as closely as possible. Also the previously proposed SD2 shoulder was updated, addressing remarks on anthropometry, durability and handling. Three demonstrator dummies are being realised. Two of these also include updates to pelvis, femur and knee as proposed by NHTSA. The dummies will be subjected to an extensive test program over the next months including reproductions of all biomechanical tests included in the requirements. Body in white tests with various restraint systems in a sled environment will be conducted to study the dummy's sensitivity to restraint settings. Test data and experiences will be shared with other regions, for instance the US, to collate a comprehensive set of information on the dummy performance. In addition injury risk curves will be constructed for the dummy. Curves will be generated with respect to different users. In particular this involves the age effect found to be predominant in the accident studies.

## VI. Conclusions

THORAX is a collaborative medium scale project under the Seventh Framework, Theme 7 Transport. The general objectives of THORAX are to develop required understanding in thoracic injury mechanisms and to implement this into numerical and experimental tools that will enable the design and evaluation of advanced vehicle restraint systems that offer optimal protection for a wide variety of car occupants. The project started February 1st 2009 and will continue until March 2013. During the first period of the project accident studies were completed identifying rib fractures as the most important source of thoracic injuries followed by lung injuries. Related to these injuries an extensive set of PMHS tests, representing various relevant loading conditions, was selected and described for future access. A study into injury mechanisms was performed resulting in proposals for new injury assessment criteria that predict rib fracture under different loading conditions. The Number of Fractured Ribs criterion uses strains over the different ribs whereas the Combined Deflection criterion uses multiple point chest deflection measurements. Both criteria are considered in an update of the thorax / shoulder complex of the THOR dummy by including appropriate measurement devices for displacement and strain measurements.

Three prototype shoulder / thorax complexes are being realised and implemented in THOR NT dummies for extensive evaluation testing against the biomechanical requirements over the next months. In addition over 90 tests with various restraint systems in a sled environment are planned,

## VII. Acknowledgements

The authors would like to thank the European Commission for commissioning and funding this research and the UK Department for Transport for providing supporting funding. Thanks are also extended to the providers of the accident case data: the CCIS, the GIDAS and GIE RE PR as well as to the on board DAS systems providers for the dummies, Hentschel and Messring.

## VIII. References

[1] European Commission, Mid-term review of the European Commission's 2001 transport White Paper, *Office for Official Publications of the European Communities,* Luxembourg, 2006

[2] Beusenberg M, Wismans J, Faerber E, Lowne R, Cesari D, *et al.*, EEVC recommended requirements for the development and design of an advanced frontal impact dummy, *EEVC Working Group 12 Report, European Experimental Vehicles Committee,* 1996.

[3] Cuerden R, Damm R, Pastor C, An estimation of the costs and benefits of improved car to car compatibility on a national and European scale, *VC Compat Growth project GRD2-2001-50083,* Deliverable D24, 2006.

[4] Carroll J, Adolph T, Chauvel C, Labrousse M, Trosseille X, Overview of serious thorax injuries in European frontal car crash accidents and implications for crash test dummy development, *Proceedings of IRCOBI Conference,* Hannover, Germany, pages 217-234, 2010.

[5] Carroll J, Matrix of serious thorax injuries by occupant characteristics, impact conditions and restraint type and identification of the important injury mechanisms to be considered in THORAX and THOMO, *COVER project GA No. 218740,* Deliverable D5-Main summary report, 2009.

[6] Adolph T, Eggers A, Pastor C, Matrix of serious thorax injuries by occupant characteristics, impact conditions and restraint type and identification of the important injury mechanisms to be considered in THORAX and THOMO, *COVER project GA No. 218740,* Deliverable D5-Annex II, 2009.

[7] Carroll J, Cuerden R, Richards D, Smith S, Cookson R, *et al.*, Matrix of serious thorax injuries by occupant characteristics, impact conditions and restraint type and identification of the important injury mechanisms to be considered in THORAX and THOMO, *COVER project GA No. 218740,* Deliverable D5-Annex I, 2009.

[8] Chauvel C, Labrousse M, Matrix of serious thorax injuries by occupant characteristics, impact conditions and restraint type and identification of the important injury mechanisms to be considered in THORAX and THOMO, *COVER project GA No. 218740,* Deliverable D5-Annex III, 2009.

[9] Kent R, Patrie J, Benson N, The Hybrid III dummy as a discriminator of injurious and non-injurious restraint loading *Annual Proceedings of the Association for the Advancement of Automotive Medicine (AAAM),* volume 47, pages 51-75, 2003.

[10] Forman J, Kent R, Ali T, Crandall J, Boström O, *et al.*, Biomechanical Considerations for the Optimization of an Advanced Restraint System: Assessing the Benefit of a Second Shoulder Belt. *Proceedings of IRCOBI Conference*, Prague, Czech Republic, pages 337-353, 2005.

[11] Hynd D, Carroll J, Davidsson J, Vezin P, Biofidelity requirements for the THORAX project, *THORAX project GA No. 218516,* Deliverable D2.1, 2010.

[12] EEVC WG12, Biofidelity impact response requirements for an advanced mid-sized male crash test dummy, *EEVC WG12 Public Document,* European Enhanced Vehicle-safety Committee, Internet: www.eevc.org, 1996.

[13] GESAC, Biomechanical response requirements of the THOR NHTSA Advanced frontal dummy (Revision 2005.1), *GESAC Inc., GESAC-05-03,* Boonsboro, MD, U.S.A., 2005.

[14] Lebarbé M, Contribution to the Definition of Biofidelity Corridors in Frontal Impact for an Adult Male 50th Percentile - Thorax Impactor Report – April 2010. *Frontal Biofidelity Specification International Task Force, ISO/TC22/SC12 – Working Group 6,* Unpublished, CEESAR, Nanterre, France, 2010.

[15] Vezin P, Bruyere-Garnier K, Bermond F, Human response to a frontal sled deceleration. *Proceedings of IRCOBI Conference,* Munich, Germany, pages 84-98, 2002.

[16] Törnvall F, Holmqvist K, Davidsson J, Svensson M, Gugler J, *et al.*, Evaluation of dummy shoulder kinematics in oblique frontal collisions, *Proceedings of IRCOBI Conference,* Bern, Switzerland, pages 195-210, 2008.

[17] Shaw G, Parent D, Purtsezov S, Lessley D, Crandall J, *et al.*, Impact response of restrained PMHS in frontal sled tests: skeletal deformation patterns under seat belt loading. *Proceedings of 53rd Stapp Car Crash Conference,* Savannah, Georgia, U.S.A., Paper number 2009-22-0001, 2009.

[18] Kroell C, Schneider D, Nahum A, Impact tolerance and response of the human thorax, *Proceedings of 15th Stapp Car Crash Conference,* San Diego, California, U.S.A., Paper number 710851, pages 84-134, 1971.

[19] Yoganandan N, Pintar F, Kumaresan S, Haffner M, Kuppa S, Impact biomechanics of the human thorax-abdomen complex, *IJCrash* 2(2), Pages 219-228, 1997.

[20] Bolton J, Kent R and Crandall J, Passenger Air Bag Impact and Injury Response using a Hybrid III Test Dummy and Human Surrogates. *NHTSA Biomechanics Test Database, Tests 8377-8379*, 2006.

[21] Forman J, Lessley D, Kent R, Bostrom O, Pipkorn B, Whole-body kinematic and dynamic response of restrained PMHS in frontal sled tests. *Proceedings of 50th Stapp Car Crash Conference,* Dearborn, MI, U.S.A., Paper number 2006-22-0013, pages 299-336, 2006.

[22] Shaw G, Crandall J and Butcher J (2000). Biofidelity evaluation of the THOR advanced frontal crash test dummy. *Proceedings of the IRCOBI Conference,* Montpellier, France, pages 11-29, 2000.

[23] Yoganandan N, Pintar F, Skrade D, Chmiel W, Reinartz J, *et al.*, Thoracic biomechanics with air bag restraint, *Proceedings of 37th Stapp Car Crash Conference,* San Antonio, Texas, U.S.A., Paper number 933121, 1993.

[24] Rouhana S, Bedewi P, Kankanala S, Prasad P, Zwolinski J, *et al.*, (2003). Biomechanics of 4-point seat belt systems in frontal impacts, *Proceedings of 47th Stapp Car Crash Conference,* San Diego, California, U.S.A., Paper number 2003-22-0017, pages 367-399, 2003.

[25] Schneider L, Ricci L, Salloum M, Beebe M, King A, *et al.*, Design and Development of an Advanced ATD Thorax System for Frontal Crash Environments, Volume 1, *UMTRI-92-22-1 / DOT HS 808 138. Michigan: University of Michigan Transportation Research Institute,* 1992.

[26] Cesari D, Bouquet R, Behaviour of human surrogates thorax under belt loading, *Proceedings of 34th Stapp Car Crash Conference,* Orlando, Florida, U.S.A., Paper number 902310, pages 73-81 1990.

[27] Kent R, Lessley D, Sherwood C, Thoracic response to dynamic, non-impact loading from a hub, distributed belt, diagonal belt, and double diagonal belts. *Proceedings of 48th Stapp Car Crash Conference,* Nashville, Tennessee, U.S.A., Paper number 2004-22-0022, pages 495-519, 2004.

[28] Shaw G, Lessley D, Evans J, Crandall J, Shin J, et al., Quasi-static and dynamic thoracic loading tests, cadaveric torsos, *Proceedings of IRCOBI Conference,* Maastricht, The Netherlands, 2007.

[29] Cesari D., Bouquet R., Comparison of Hybrid III and human cadaver thorax deformations, *Proceedings of 38th Stapp Car Crash Conference,* San Antonio, Texas, U.S.A., Paper number 942209, pages 65-76, 1994.
[30] L'Abbé R, Dainty D, Newman J, An experimental analysis of thoracic deflection response to belt loading, *Proceedings of IRCOBI Conference,* Cologne, Germany, pages 184-194, 1982.
[31] Riordain S, Ramet M, Cesari D, Bouquet R, A comparison of Hybrid III and cadaver thorax response under diagonal belt loading, *Proceedings of 13th International Conference on Experimental Safety Vehicles (ESV),* Paris, France, pages 860-862, 1991.
[32] Fayon A, Tarriere C, Walfisch G, Got C, Patel A, Thorax of three-point-belt wearers during a crash (experiments with cadavers), *Proceedings of 19th Stapp Car Crash Conference,* San Diego, California, U.S.A., Paper number 751148, pages 195-223, 1975.
[33] Lessley D, Salzar R, Crandall J, Kent R, Bolton J, *et al.*, Kinematics of the thorax under dynamic belt loading conditions, *International Crash Worthiness Conference,* Kyoto, Japan, 2008.
[34] Salzar R, Bass C, Lessley D, Crandall J, Kent R *et al.*, Viscoelastic response of the thorax under dynamic belt loading, *Proceedings of IRCOBI Conference,* Bern, Switzerland, pages 73-85, 2008.
[35] Been B, Dummy Concept Specifications, *THORAX project GA No. 218516*, Deliverable D2.5, 2010.
[36] Neathery R, Analysis of Chest Impact Response Data and Scaled Performance Recommendations, *Proceedings of the 18th Stapp Car Crash Conference*, 1974.
[37] Song E, Trosseille X, Baudrit P, Evaluation of Thoracic Deflection as an Injury Criterion for Side Impact Using a Finite Elements Thorax Model, *Stapp Car Crash Journal*, Vol. 53, pp. 155-191, 2009.
[38] Song E, Lecuyer E, Trosseille X, Development of Injury Criteria for Frontal Impact Using a Human Body FE Model, *Proceedings of the 22nd Int. Tech. Conf. on the Enhanced Safety of Vehicles*, Washington D.C., 2011.
[39] Kent R, Patrie J, Poteau F, Matsuoka F, Mullen C, Development Of An Age-Dependent Thoracic Injury Criterion For Frontal Impact Restraint Loading, Paper No. 72, *Proceedings of 18th International Conference on Experimental Safety Vehicles (ESV)*, Nagoya, Japan, 2003.
[40] Vezin P, Bruyere-Garnier K, Bermond F, Verriest JP, Comparison of HIII THOR-alpha and PMHS response in Frontal Sled Tests, *Proceedings of 46th Stapp Car Crash Conference,* paper 2002-22-0001, November 2002.
[41] Petitjean A, Lebarbe M, Potier P, Trosseille X, Lassau JP, Laboratory Reconstructions of Real World Frontal Crash Configurations Using the Hybrid III and Thor Dummies and PMHS, *Proceedings of 46th Stapp Car Crash Conference*, paper 2002-22-0002, 2002.
[42] Kent R, Shaw G, Lessley D, Crandal J, The Utility of HIII and THOR Chest Deflection for Discriminating Between Standard Belts and Force-Limiting Belt Systems, *Proceedings of 47th Stapp Car Crash Conference*, 2003.
[43] Kent R, Murakami D, Kobayashi S, Frontal Thoracic response to dynamic loading: the role of superficial tissue, viscera, and the rib cage, *Proceedings of IRCOBI Conference*, Prague, Czech Republic, 2005
[44] Lebarbe M, Potier P, Baudrit P, Petit P, Trosseille X, Vallancien G, Thoracic Investigation using PMHS in Frontal Airbag Out-of-Position Situations, *Proceedings of 49th Stapp Car Crash Conference*, November 2005.
[45] Trosseille X, Baudrit P, Leport T, Vallancien G, Rib Cage Strain Pattern as a Function of Chest Loading Configuration, *Proceedings of 52th Stapp Car Crash Conference,* November 2008.
[46] Törnvall F, A New Shoulder for the THOR Dummy Intended for Oblique Collision, Vehicle Safety Division, Department of Applied Mechanics, *Chalmers University of Technology*, Goteborg, Sweden, 2008.
[47] Schneider L, Robbins D, Pflug M, Snyder R, Development of Anthropometrically based Design Specifications for an Advanced Adult Anthropomorphic Dummy Family, Volume 2, *University of Michigan Transportation Research Institute,* 1983.
[48] Untaroiu C, Lim JY, Shin J, Crandall J, Malone DP, Tannous RE, Evaluation of a Finite Element Model of the THOR-NT Dummy in Frontal Crash Environment, *Proceedings of 21st International Conference on Experimental Safety Vehicles (ESV)*, Stuttgart, Germany, 2009, Paper Number 09-0272.
[49] Davidsson J, Mendoza M, Vanama M, Dummy concept studies - Chest deformation in the FE-THOR-NT as a function of rib stiffness and shoulder designs, *THORAX project GA No. 218516*, Included in Deliverable D3.3 - Dummy Validation Report, 2012.
[50] Song E, Troisseille X, Mendoza-Vazquez M, Davidsson J, Vezin P, Definition of injury mechanism and related physical parameters based on datasets from PMHS tests and advanced HBM simulation, *THORAX project GA No. 218516*, Deliverable D2.4, Version 1 (M12), 2010.

[51] Kent R, Bass C, Wood W, Salzar R, Melvin J, The Role of Muscle Tensing on the Force-Deflection Response of the Thorax and a Reassessment of Frontal Impact Thoracic Biofidelity Corridors, *Proceedings of the IRCOBI Conference*, Graz, Austria, pp. 95-107, 2004.
[52] Kent R, Bass C, Woods W, Salzar R, Lee S, Melvin J, The Role of Muscle Tensing on the Force-deflection Response of the Thorax and a Reassessment of Frontal Impact Thoracic Biofidelity Corridors, *Journal of Automobile Engineering, Proceedings of the Institution of Mechanical Engineers*, Vol. 220, pp. 853-868, 2006.
[53] Shaw G, Lessley D, Crandall J, Kent R, Elimination of thoracic muscle tensing effects for frontal crash dummies, *Society of Automotive Engineers World Congress April 11*, Paper 05B-81, 2005.

## IX. Appendix

TABLE AI

SHOULDER BIOFIDELITY REQUIREMENTS SELECTED BY THORAX AND COMPARISON WITH REQUIREMENTS FROM OTHER GROUPS

| Type | EEVC [12] | NHTSA [13] | ACEA/ISO [14] | THORAX [11] |
|---|---|---|---|---|
| Sled | Vezin [15]<br>Two restraints and two speeds | None defined | None defined | Törnvall [16]<br>3-pt seat belt, 27 kph<br>Shaw [17]<br>3-pt. seat belt, 40 kph |
| Table-top | | | | Cesari [26], [29]-[31]<br>Belt loading – relative regional compression, PMHS and volunteer |
| Quasi-static volunteer | None defined | None defined | None defined | THORAX Project – to be published |

TABLE AII

THORACIC SPINE BIOFIDELITY REQUIREMENTS SELECTED BY THORAX AND COMPARISON WITH OTHER GROUPS

| Type | EEVC [12] | NHTSA [13] | ACEA/ISO [14] | THORAX [11] |
|---|---|---|---|---|
| Sled | Vezin [15]<br>Two restraints and two speeds | None defined<br>*Tentative proposal* | None defined | Shaw [17]<br>3-pt. seat belt, 40 kph |

TABLE AIII

THORACIC STIFFNESS/DEFORMATION BIOFIDELITY REQUIREMENTS SELECTED BY THORAX AND COMPARISON WITH OTHER GROUPS

| Type | EEVC [12] | NHTSA [13] | ACEA/ISO [14] | THORAX [11] |
|---|---|---|---|---|
| Impactor | Kroell [18]<br>Frontal rigid impactor; 23.4 kg, 4.3 and 6.7 m/s<br>Yoganandan [19]<br>Oblique padded impactor; 23.4 kg, 4.3 m/s | Frontal rigid impactor: 4.3 m/s<br>Yoganandan [19]<br>Oblique padded impactor; 23.4 kg, 4.3 m/s | Lebarbé [14]<br>Frontal rigid impactor; 23.4 kg, 4.3 and 6.7 m/s | Lebarbé [14]<br>Frontal rigid impactor; 23.4 kg, 4.3 m/s<br>Yoganandan [19]<br>Oblique padded impactor; 23.4 kg, 4.3 m/s |
| Sled | Vezin [15]<br>See Table **Error! Reference source not found.** – N.B. more tests required | None defined | Proposed - Shaw [17]<br>3-pt. seat belt, 40 kph | Bolton [20]<br>Lap belt and airbag, two speeds<br>Forman [21] (not incl. Shaw [22]<br>Various restraints<br>Rouhana [24]<br>Mostly four-point belt restraint<br>Shaw [17]<br>3-pt. seat belt, 40 kph |
| Table-top | None defined | Proposed:<br>Schneider [25]<br>Quasi-static thorax regional coupling | None defined | Kent [27]<br>Relative thorax compression in different loading conditions<br>Shaw [28]<br>Relative regional thorax compression |

| | | |
|---|---|---|
| | Proposed:<br>Cesari [26] | Cesari [26], [29]-[31]<br>Belt loading – relative regional compression, PMHS and volunteer |