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THORAX

Thoracic injury assessment for improved vehicle safety

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Executive summary

Road safety is a major societal issue. In 2009, more than 35,000 people died on the roads of the European Union, i.e. the equivalent of a medium town, and no fewer than 1,500,000 persons were injured[1]. The cost for society is huge, representing approximately 130 billion Euros in 2009. In view of this the European road safety policy orientations identify new technologies that have a high potential to improve road safety and should be promoted up to 2020. These new technologies identified as being able to improve road safety include advanced restraint systems. As a contribution to the improvement of road safety the THORAX project studied thoracic injuries. Injury mechanisms and the influence of occupant diversity factors like age and gender were investigated. The gained knowledge was implemented in numerical and experimental tools that enable the design and evaluation of advanced vehicle restraint systems which are capable of offering optimal protection for a wide variety of car occupants.

To develop the improved design and evaluation tools THORAX was structured in four work packages related to accident surveys, biomechanical studies, dummy development and dummy evaluations. Work-Package 1 analysed real world car crash data to provide detailed information on the type and severity of injuries in relation to impact type, restraint type, and occupant characteristics. The survey revealed rib fracture as the predominant thoracic injury and focus for the tool developments. Detailed case studies comparing real world accidents and consumer rating tests showed that female occupants generally are at higher risk in car crashes compared to males. In Work-Package 2 a set of biomechanical requirements for an enhanced shoulder thorax complex of a frontal impact dummy was defined. A suit of Post Mortem Human Subject (PMHS) data was collected and documented in detail for reproduction with the new tools. Missing data were identified and additional tests conducted to complete the dataset. In addition injury mechanisms and governing parameters were studied using Human Body Models. For this purpose PHMS tests conducted under well-defined conditions were simulated using human body models identifying excessive bending strain in the ribs as key factor for the initiation of rib fractures. Based on this finding two injury criteria were proposed. The first correlates dummy chest deflections at four locations to fractures observed in PMHS tests under various conditions in matched dummy – PMHS tests. The second uses local strain data measured around the dummy ribs. Based on the biomechanical requirements a demonstrator dummy with improved thorax and shoulder designs was developed in Work-Package 3. Three prototypes were built and installed on available THOR dummies. The demonstrators were subjected to extensive evaluation testing, reproducing the PMHS tests collected under Work-Package 2. Testing showed a superior biofidelity of the demonstrator compared to existing HIII and THOR dummies. The data was used also to generate preliminary injury risk curves related to the criteria proposed. As a final step, in Work-Package 4, the demonstrator dummy was subjected to extensive testing in a vehicle environment to assess its sensitivity to typical state of the art vehicle restraint systems. Full scale and sled tests were performed in which the demonstrators showed increased sensitivity to different loading severities, loading directions and restraint variations compared to the HIII. The injury risk prediction using the THORAX risk curves was in line with assumed real life observations. It was also shown that current restraint systems will need updates to conform to current rating levels in terms of injury risk. As such it is expected that the THOR injury risk evaluation using risk functions for young and elderly people as well as AIS2+ will result in further reduced injuries due to frontal injuries.

During the entire runtime of the project information was shared with key stakeholders in the field. Results and findings were forwarded to Euro NCAP and the GRSP Informal Group on

[1] EC Communication COM (2010) Towards a European road safety area: policy orientations on road safety 2011-2020

Frontal Impacts. Based on the THORAX findings both groups decided to include dummies representing females in their future crash test procedures. Also the GRSP Informal Group placed the THOR dummy on the agenda for their phase 2 update of the frontal impact directive for the 2020 timeframe. Information exchange with the National Highway Traffic Safety Administration resulted in the preliminary adoption of the new shoulder design and thorax updates from THORAX. This design will be evaluated in 2013 by NHTSA for decision making at the end of 2013.

Contents

1 Project context and main Objectives

1.1 Project Context

THORAX is a collaborative medium scale project under the Seventh Framework, theme 7 Transport. The project is coordinated by Humanetics Europe GmbH (HUMAN). Partners are Autoliv Research (Autoliv), Bundesanstalt für Straßenwesen (BASt), Chalmers University of Technology (Chalmers), Groupement d'Intérêt Economique de Recherches et Etudes PSA-RENAULT (Gie Re Pr), Partnership for Dummy Technology and Biomechanics (PDB), Continental Safety Engineering International GmbH (CSE), Uniresearch BV (UNI), Universidad Politécnica de Madrid (UPM), Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux (IFSTTAR), Transport Research Laboratory (TRL).

In 2010 about 31,000 people were killed and more than 1.4 million injured in European road accidents. Thoracic injuries are one of the main causes for fatalities and injuries in car crashes. For this reason the THORAX Project was focussed on reduction and prevention of injuries to this body region. The objective of the project was to develop required understanding in thoracic injury mechanisms. This new understanding was to be implemented into numerical and experimental tools that could 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 technology for different genders, ages and sizes, these tools had to be more sensitive to the in-vehicle occupant environment than existing tools.

For that purpose THORAX mobilised the European research community and car industry to study real world loading conditions and related injury mechanisms given the variation in occupant characteristics and system functionalities offered by modern restraint systems. The gained know-how was implemented in hardware and software demonstrators that were evaluated for their added potential on restraint optimisation. The developed tools are being forwarded to the automotive industry for usage in design of vehicle safety systems as well as to governments and stakeholder groups for adoption in assessment procedures of such systems.

1.2 Main Objectives

In more detail, the specific main objectives of the THORAX project were:

- Identification of the two most relevant thoracic injury types for car occupants in view of societal relevance, taking into account user diversities such as age, gender and size.
- Characterisation of the injury mechanisms and governing parameters for these two injury types
- Implementation of injury mechanism and related physical parameters in advanced HBM for use in supplementary virtual testing procedures that take into account a wider range of biometric and biomechanical criteria than those recorded with physical dummies.
- To produce a mechanical demonstrator consisting of a new dummy thorax and shoulder design (developed and implemented in a THOR NT frontal crash test dummy) capable of representing the identified injury mechanisms under real world loading conditions.
- To derive injury risk functions specific to the developed numerical and hardware demonstrators, differentiating between genders, age groups and sizes.
- Via evaluation by industry partners, demonstrate the sensitivity of the prototype demonstrator to modern vehicle safety systems and usability in safety system optimisation.

1.3 Objectives per work package

1.3.1 WP1 – Accident analysis

The accident surveys were conducted in close collaboration with the COVER Coordination and Support Action in which a portion of the activities were performed. The main objectives of the COVER and THORAX accident surveys were to:

- Based on real world (in-depth) accident data, define the relationship between thorax injuries and
  - Impact type
  - Restraint type and
  - Occupant characteristics (age, size, sex).
- Identify the two most relevant types of thoracic injuries
- Understand the difference between real world observations and crash test results to:
  - Define deficiencies in current dummy design, and
  - Provide input for dummy concept design development.
- Estimate the potential injury reduction benefit from introducing an improved thorax and shoulder complex for different occupant sizes and ages.

1.3.2 WP 2 – Biomechanics

- Define a set of biomechanical requirements for enhanced shoulder thorax complex of crash-test dummies.
- Study thorax design concepts; suggest designs capable of injury prediction in cars with modern restraints.
- Develop thorax injury risk criteria for human body models and for crash test dummies.
- Define a set of injury risk curves for different sizes and ages, based on tests executed with demonstrator dummies under WP3

1.3.3 WP 3 – Demonstrator development and validation

- Define requirements for and develop demonstrator dummies with improved thorax and shoulder devices based on biomechanical knowledge gained in WP2.
- Validate the demonstrator dummies against the set of biomechanical requirements defined in WP2.
- Deliver three of the validated demonstrator dummies to WP4 for assessment purposes.

1.3.4 WP 4 – Assessment of potential for restraint optimization

- To assess the demonstrator dummy in relevant load cases regarding its sensitivity against modern vehicle safety systems. Also robustness, durability and repeatability will be assessed.

2 Main Science & Technological results and Foreground

Thoracic injuries are one of the dominant causes of fatalities and severe injuries in car crashes today. Due to known limitations, the existing tools used for studying these injuries are not capable of supporting the latest potential implementation of advanced restraint systems and airbags. THORAX was a collaborative medium scale project under the Seventh Framework, Theme 7 Transport, which was focussed on the reduction and prevention of thoracic injuries through:

- Understanding the thoracic injury mechanisms
- Implementation of this understanding in numerical computer models and
- Implementation of an updated thorax design in a crash test dummy

The models and dummy are meant to enable the design and evaluation of advanced restraint systems for a wide variety (gender, age and size) of car occupants. The project started in February 2009 and ended in April 2013. Activities were distributed throughout four work packages, results of which are described in this chapter.

2.1 WP1 – Accident Analysis

2.1.1 Objectives

The accident surveys were conducted in close collaboration with the COVER Coordination and Support Action in which a portion of the activities were performed. Main objectives of the COVER and THORAX accident surveys were to:

1) Define the relationship between thorax injuries and (1) Impact type (2) restraint type and (3) occupant characteristics (age, size, sex) based on real world (in-depth) accident data.
2) Identify the two most relevant types of thoracic injuries
3) Understand the difference between real world observations and crash test results to:
    - Define deficiencies in current dummy design, and
    - Provide input for dummy concept design development.
4) Estimate the potential injury reduction benefit from introducing and improved thorax and shoulder complex for different occupant sizes and ages.

2.1.2 Accident analysis

In 2009 accident data were studied within the COVER project to identify the two most relevant thoracic injury types for car occupants and to provide detailed information on the type and severity of thoracic injuries in relation to impact type, restraint type, and occupant characteristics. The data were controlled for impact partner, impact severity, overlap and intrusion, and type of restraint system used. Results have been presented in Carroll *et al.* (2009a)[2], Carroll *et al.* (2010a)[3], Adolph *et al.* (2009)[4] and Chauvel *et al.* (2009)[5] all available from the COVER project website http://www.biomechanics-coordination.eu/. Because of their relevance for the THORAX project and in view of the close interaction between both projects an extensive summary of the results is provided below.

Body region: From the THORAX study, see for instance CCIS (Cooperative Crash Injury Study) analysis in Fig. 1, it became clear that the thorax has superseded other body regions in terms of the number of occupants receiving an injury, particularly at the severe MAIS (Maximum Abbreviated Injury Scale) ≥ 3 level.

Occupant position: From the combinations of injury groupings in the CCIS sample, it was evident that drivers had a particular risk of sustaining a thorax or a lower extremity injury. However, front seat passengers were at an even higher risk of sustaining a thorax injury and

[2] Carroll, J., Cuerden, R., Richards, D., Smith, S., Cookson, R., Hynd, D. (2009a). 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.

[3] Carroll, J., Adolph, T., Chauvel, C., Labrousse, M., Trosseille, X, Pastor, C., Eggers, A., Smith, S., Hynd, D. (2010a). Overview of serious thorax injuries in European frontal car crash accidents and implications for crash test dummy development. *IRCOBI 2010 proceedings.*

[4] Adolph, T., Eggers, A., Pastor, C. (2009). 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.*

[5] Chauvel, C., Labrousse, M. (2009). 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.*

at a higher risk of sustaining an injury to an upper extremity.

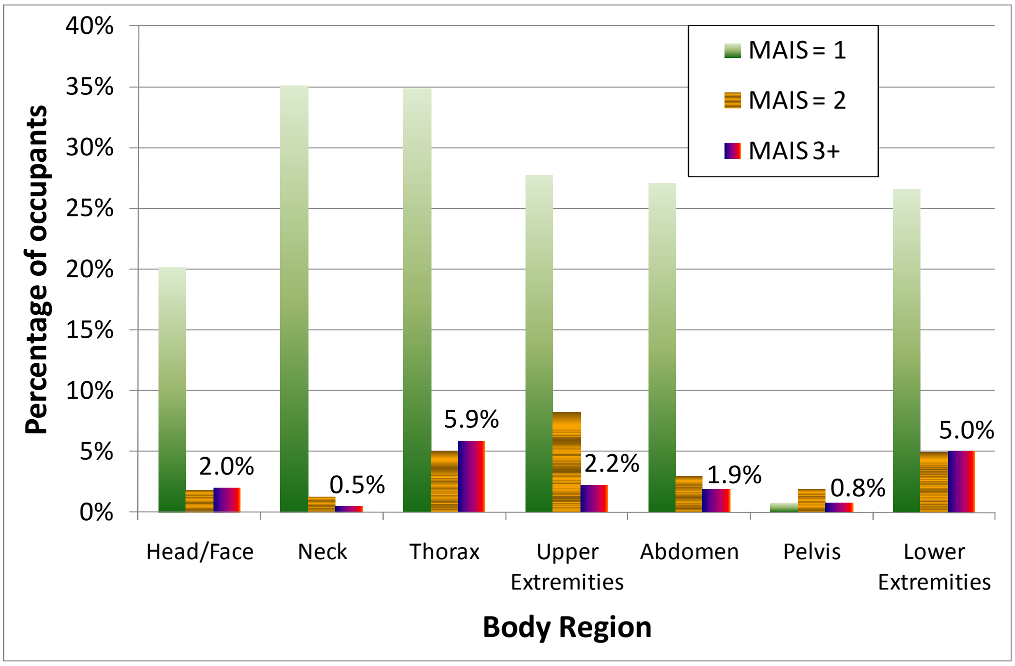


Fig. 1. Body regions injured and MAIS level for all occupants from the CCIS frontal impact sample (n = 2148 occ.)

<u>Crash types and speed:</u> The GIDAS (German In-Depth Accident Study) analysis indicated that AIS ≥ 3 torso injuries were more likely to occur in impacts with narrow objects (diameter less than 40 cm) than in collisions with other types of object. A trend from the GIE RE PR (Groupement d'Intérêt Economique de Recherches et Etudes PSA-Renault) torso injury data is that frontal impact accidents involving over two thirds of the vehicle front tended to produce proportionally more of the moderate to severe thorax injuries (AIS ≥ 2) than the other overlap categories. Despite differences in the data collection strategies this appears to be consistent with the findings from the UK CCIS sample. Regarding collision speed, an analysis of the distribution of front seat occupants in the GIE RE PR sample by Equivalent Energy Speed (EES) showed that most of the frontal impact accidents in this database occurred with an EES between 26 to 65 km/h.

<u>Occupant characteristics:</u> The GIDAS dataset was used to show that relatively more females had AIS 1 torso injuries and that males were overly represented in the group of uninjured. Both effects are significant. In addition the GIE RE PR data showed that the risk of receiving a torso injury was greater for older than for younger occupants. The older occupants (over 52 years of age) were 3.7 times more likely to receive an AIS ≥ 2 torso injury, and 2.8 times more likely to receive an AIS ≥ 3 torso injury than the younger occupants (12 to 52 years).

The GIDAS sample was able to show that occupants who were 150 to 180 cm tall were statistically more likely to have an AIS 1 torso injury than taller (180 to 220 cm) occupants. The analysis also showed that occupants weighing 40 to 60 kg were statistically more likely to have an AIS 1 torso injury. However, neither of these trends was significant at the more severe AIS 2 or ≥ 3 injury score levels. Additionally, the GIDAS sample showed that front seat passengers were statistically more likely to receive an AIS 1 torso injury than occupants in other seating positions. This finding was supported by CCIS sample analysis.

From the distribution of torso injuries of male and female occupants (including those occupants with no torso injury), it became clear that relatively more females had AIS1 torso injuries and that males were overly represented in the group of uninjured. Both of these effects were significant in the GIDAS sample.

Injury type: Data analysis showed that at the AIS ≥ 2 severity level, thoracic fractures occur most frequently of the various injury types recorded in the accident databases. These fractures occur to the ribs and sternum, and are observed often, particularly when AIS 1 rib fractures are counted. Lung injuries also occur frequently in frontal impact accidents (even though they are AIS ≥ 3) and are the most frequently observed injuries to an organ.

Restraint system dependency: The majority of front seat occupants in the sample of cars and car-derivatives, from 2000 onwards, had combined seat-belt and airbag restraint. Within the CCIS sample selected for this work, 1899 occupants had a front airbag fitted, which accounted for 97 percent of the drivers and 78 percent of front seat passengers. When considering seat-belt pre-tensioners, it was found that 1758 occupants (82 %) of the CCIS sample had a pre-tensioning device fitted at their seating position. However, based on the distribution of torso injuries amongst these occupants, it seems as though the presence of a pre-tensioner did not have a large influence on the risk of sustaining a torso injury. Most occupants (57 %) who received an AIS ≥ 3 torso injury were in a restraint system consisting of seat-belt, airbag, pretensioner(s), and a load limiting device.

The GIE RE PR database contains information about the force-limit used in different load limiting devices. Risks of AIS ≥ 2 and AIS ≥ 3 thoracic injuries as a function of the shoulder belt load limit for cars designed since 1990 and for all EESs (the number of cases with AIS ≥ 2 or AIS ≥ 3 divided by the total number of cases) are shown in Fig. 2. Efficiencies of the 6 kN and 4 kN or 5 kN load limitations for EES > 45 km/h (with regard to a baseline of 100 passengers without a load limiter) were calculated and appear to be 21% and 49% respectively for 6 kN and 4 kN or 5 kN. A further analysis showed that the use of 4 or 5 kN limiters and the increase of car mass decreased the risk of thoracic injuries.

Also the availability of force-limit data allowed a global comparison between crash investigation outcomes and Euro NCAP tests in terms of shoulder belt force limitation efficiency. Fig. 3 shows estimated thorax injury risks for '4 to 5 kN load limiters' and 'without load limiters' as obtained from cases with impact conditions close to those from Euro NCAP frontal impacts. Fig. 4 provides mean chest deflections from Euro NCAP tests. In the tests the chest deflection for the drivers remains almost constant for any levels of load limiter (except for the case without a load limiter) while for the passenger chest deflections increase with load limit levels. Also passenger chest deflections are lower compared to the driver. Effects of other available parameters like mass of the car were checked and found not to be significant. When comparing risks calculated from the Euro NCAP tests and values from the crash investigations (45 year old occupant, 58 km/h, 40 % of overlap, car mass of 1323 kg) results appear to be coherent for the drivers but markedly different for the passengers. While the passengers had a higher risk of torso injury than the drivers in accidents, chest deflections are lower in the Euro NCAP tests. This indicates that the risk of thoracic injuries is underestimated for the passengers in Euro NCAP tests.

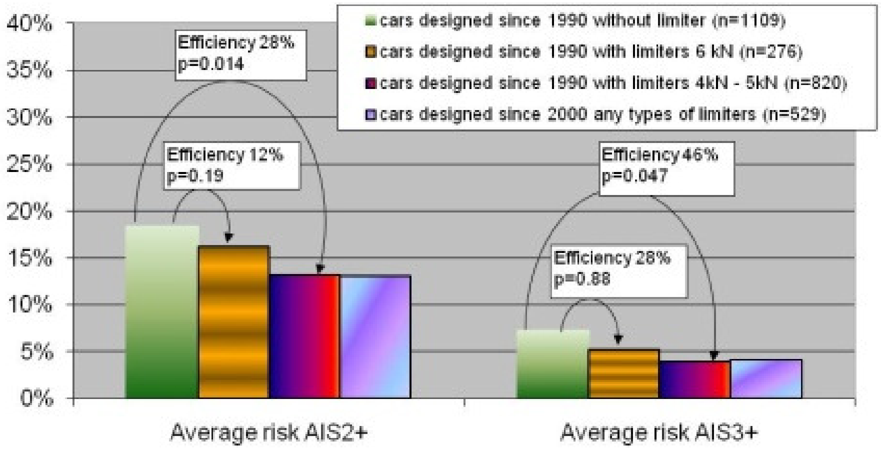


Fig. 2. Evolution of average thoracic injury risk for belted front occupants in frontal impacts at all EES

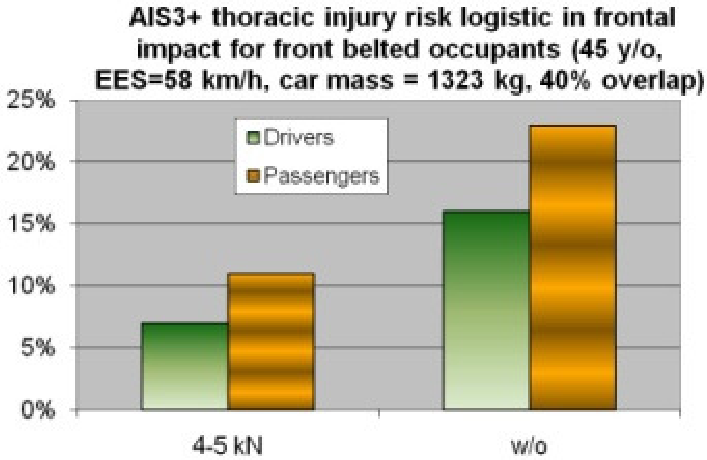


Fig. 3. Thoracic injury risks from accident studies

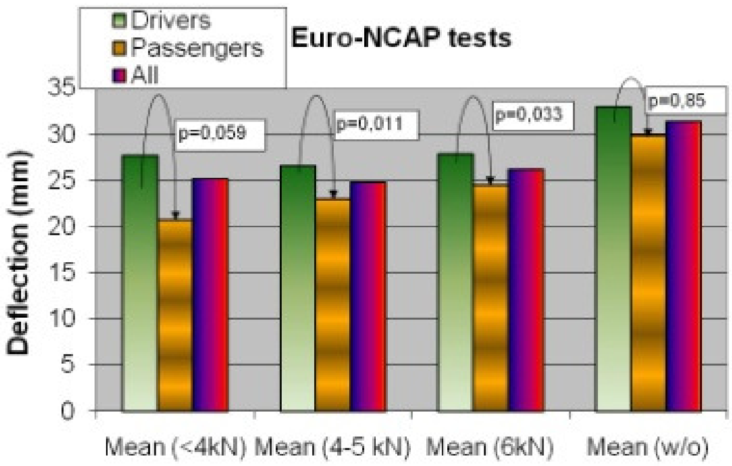


Fig. 4. Mean deflections NCAP tests for different load limitations

In addition to the analysis of in-depth studies as summarized above, detailed case-by-case analysis was used in the THORAX project to review accidents with impact conditions close to the Euro NCAP frontal impact crash test (Euro NCAP, 2009). These were analysed and compared with the test outcome (Carroll *et. al.* (2009b)[6]). This comparison included 20 cases from the CCIS and 14 from the GIDAS. The number of cases was limited by the requirement for them to have impact conditions similar to those of a Euro NCAP test. A comparison was made between the thoracic injury outcome predicted from the test and observed in the real-world accident. Due to the small number of cases available, which met the study specification, it appeared to be difficult to make conclusive statements based on the case-by-case analysis. However, the study confirmed findings of the in-depth study presented above. For instance, it seems that the groups of occupants currently at greatest risk of receiving a thorax injury in accident configurations similar to the Euro NCAP frontal impact test are elderly people and women. Neither of these groups is represented specifically by the dummy used in European regulatory frontal impact crash tests or the Euro NCAP frontal impact test. The full report on the case by case analysis by Carroll *et al.* (2009b) is available from the THORAX website.

2.1.3 Estimate of injury reduction potential for different occupant sizes and ages, and total benefit expected to arise from the project

Taking into account the new research regarding different occupant characteristics, accident configurations, and restraint systems, the objective for THORAX Task 1.2 was to estimate the potential benefit arising from the THORAX Project. This objective was met through consideration of the thorax-related safety interventions that may be put in place as a result of the THORAX Project and the injury reductions that those measures may bring about. Below a summary of the benefit estimation is provided. The full report is available as THORAX D1.2 (Carroll et. al. 2010)[7].

Accident data from the UK (CCIS) provided information on 320 occupants who were Killed or Seriously Injured and who sustained a torso injury of at least AIS 2 (or an AIS 1 rib fracture). This information was used to estimate the potential benefit expected if outputs from the THORAX Project were used in future frontal impact testing. Occupants and their injuries were categorised by the impact conditions of their accident, their seating position, and their size, age and sex. These categories were then used to define target groups which could be influenced by potential safety interventions. The distributions of occupants and their injuries amongst the restraint system and crash categories were compared with data from France (GIE RE PR) to establish where sample specific features were evident.

Costs were assigned to specific occupant and torso injuries using two methods, either a willingness to pay, or societal costs as reported by Miller *et al.* (2001). The benefits estimated were then associated with mitigation of torso injuries and therefore a reduction in the overall seriousness of the accident for each particular occupant influenced by the intervention. Taking into account the THORAX Project activities and the likely use of the resulting dummy, four basic safety intervention options were considered. These were:

1) A more sensitive dummy thorax that is capable of supporting a drive towards advanced restraint systems offering improved protection for the torso
2) A new injury risk function to represent ages of the occupant population having a lower tolerance to torso loading

[6] Carroll, J., Smith, S., Adolph, T., Eggers, A. (2009b). A comparison between crash test results and real-world accident outcomes in terms of injury mechanisms and occupant characteristics. *THORAX project GA No. 218516, Deliverable D1.1*

[7] Carroll, J., Cuerden, R., Richards, D., Smith, S., Cookson, R., Hynd, D. (2009a). Estimate of injury reduction potential for different occupant sizes and ages, and total benefit expected to arise from the project. *THORAX project GA No. 218516, Deliverable D1.2.*

3) An additional size of dummy available for representing a different size of occupant as well as the mid-sized male (either smaller or larger than the mid-size)
4) Extending the scope of frontal impact testing to include another configuration:
   - Introduction of a full-width test
   - Introduction of a small-overlap test
   - Introduction of another test procedure to safe-guard against injuries caused in low-speed impacts (of a speed lower than that represented by the current procedures)

It was found that a more sensitive dummy thorax that is capable of supporting a drive towards advanced restraint systems could offer protection for the torso providing a potential benefit of up to £ 33 million (€ 41 million) based on a willingness to pay. Alternatively, using the societal costs of injuries from Miller *et al.* (2001)[8] the potential benefit was as large as £ 76 million (€ 94 million).

A new injury risk function to represent ages of the occupant population having a lower tolerance to torso loading could also be beneficial if protection is improved for older occupants. Depending on the overlap with improvements brought about through the use of a new dummy torso, this could lead to an estimated benefit of as much as £ 30 million (€ 37 million) (willingness to pay, for the EU-27 countries).

The influence of using a dummy that represents occupants who are either smaller or larger than the mid-sized male was difficult to determine because of small sample sizes and a lack of reporting of stature and mass information. Indications are that the use of a larger than average size dummy could lead to the greatest benefit, of up to £ 154 million (€ 190 million) (willingness to pay). The benefits for small occupants were not as large, which may reflect the comparative exposure of larger and smaller occupants in frontal impact accidents.

Of the three options investigated with respect to adding a new test procedure, one which helps to provide safety for accidents that occur at speeds lower than the current offset frontal impact tests appears to offer the greatest maximum estimate of benefit. This benefit could be as much as £ 247 million (€ 305 million) on a willingness to pay basis. However, the French data suggested low speed impacts were less important in the causation of torso injuries (of at least moderate severity) than the CCIS data from Great Britain.

A full-width test was estimated to offer benefit in the range from £ 0 to £ 105 million (€ 130 million). This could be enhanced by setting the test speed to account for accidents which occur at a lower severity than the current offset procedures, with the use of the new dummy hardware, and a torso injury criterion which protects older occupants. This could extend the benefit to beyond £ 300 million (€ 370 million), each year for the EU-27 countries, based on the CCIS data.

Introducing a low-speed test to protect older occupants provided a large target group of torso injuries, whether offset impacts are included or full-width impacts. On the basis of the combined intervention options considered within this report, torso protection for older occupants in impacts of severities below those of the existing frontal impact test procedures seemed to be a priority in terms of potential benefit.

[8] Miller, T., Romano, E., Zaloshnja, E., and Spicer, R. (2001). Harm 2000: Crash cost and consequence data for the new millennium. *45th annual proceedings of the Association for the Advancement of Automotive medicine (AAAM), 24-26 September 2001, San Antonio, Texas, U.S.A.* Illinois, U.S.A.: AAAM.

2.2 WP 2 – Biomechanics

2.2.1 Objectives

Within WP2, four mayor activities were performed:

- Definition of the biomechanical requirements for enhanced shoulder thorax complex in frontal crash test dummies
- Development of design concepts for an improved dummy thorax / shoulder complex to be developed in WP3
- Definition of injury mechanism and criteria based on analysis of new and past PMHS tests and advanced HBM simulations
- Thoracic injury risk curves for the developed dummy and scaling techniques to enable the use of these curves to predict injury risk for different ages, genders and sizes.

2.2.2 Biofidelity requirements

Existing frontal impact dummy thorax biofidelity requirements were reviewed with respect to the loading environment observed in modern cars during a typical frontal impact. It was found that existing biofidelity requirements were biased towards higher loading velocities than is now recommended and unrepresentative loading conditions. Therefore, a review of the available data sets that could be considered for defining thorax biofidelity requirements for an advanced frontal impact dummy was undertaken. In addition a set of objective criteria by which the relevance of candidate data sets could be assessed was developed.

From this review, a set of sled, impactor and table-top tests have been recommended to compose the biofidelity requirements to be used in Task 3.3 (Table 1). Several data sets have been recommended for defining biofidelity requirements, while several others have been recommended for use in defining ‘engineering guidelines’. Typically the latter have been defined either where the original data was sampled from only a small number of subjects, and where relative (not absolute) requirements are defined – for example the relative stiffness of the upper, middle and lower part of the thorax, not the absolute stiffness of each of these regions. In addition data was recommended for injury risk curve construction in Task 2.6. Some of the recommended data sets have been documented in detail and were appended the D2.1 report.

A review has been undertaken of the normalisation techniques that have been used in the biomechanics literature in an attempt to make volunteer and PMHS test data more representative of a particular car occupant group. The limitations of various techniques for different types of test and different types of data have been explored. From this, recommendations have been made for appropriate normalisation techniques for some types of data, such as local force-compression responses in impactor tests. However, it was also found that the normalisation methods reviewed did not provide a consistent result when used with data from more complex loading environments, such as whole-body kinematic sled test

Table 1: THORAX biofidelity requirements

Body region	Type	Absolute / Relative	THORAX
Shoulder	Sled	Absolute	Törnvall (2008) • 3-pt belt, three impact directions, 26.5 kph
			Shaw (2009) • 3-pt seat-belt, 40 kph
	Quasi-static	Absolute	Davidsson (2010) • THORAX tests
	Table-top	Relative	Cesari and Bouquet (1990 and 1994), Riordain (1991), Belt loading – relative regional compression; PMHS
Thoracic spine	Sled	Absolute	Shaw (2009) • 3-pt seat-belt, 40 kph
Thorax	Impactor	Absolute	Lebarbé (2010) • Based on Kroell (1971), INRETS, and CEESAR • Frontal rigid impactor: 23.4 kg; 4.3 m/s
			Yoganandan (1997) • Oblique padded impactor: 23.4 kg; 4.3 m/s
	Sled	Absolute	Bolton (2006) • Lap belt & airbag, two speeds
			Forman (2006) (not inc. Shaw 2000) • Chest bands with various restraints
			Rouhana (2003) • Mostly four-point belt restraint
			Shaw (2009) • 3-pt seat-belt, 40 kph
	Table-top	Relative	Kent (2004) • Relative chest compression in different loading conditions
			Shaw (2007) • Relative regional compression
			Cesari and Bouquet (1990 and 1994), Riordain (1991), • Belt loading – relative regional compression; PMHS

data. In this case, it was recommended that no normalisation is performed; it therefore particularly important that the test subjects were representative of the occupant group – in this case 50th percentile male – for which biofidelity requirements are being developed. Further work will also be required to understand how this data should be scaled to represent significantly different occupant sizes, such as a 5th percentile female.

Where an appropriate normalisation method has been identified, normalised biofidelity requirements have been defined, either by adopting requirements from the literature, from current parallel work by an ACEA/ISO expert group, or developed within the project. In addition, for sled tests biofidelity requirements have been defined using non-normalized data.

The full report on biofidelity requirements is available as THORAX D2.1.[9]

2.2.3 Volunteer tests

The shoulder complex, including the shoulder girdle and the clavicle, is rarely exposed to injuries in life-threatening frontal and oblique frontal collisions but it does influence the belt interaction and as such the thorax compression and head kinematics. Therefore, volunteer tests were carried out to establish response requirements for the shoulder complex in terms of range-of-motion and stiffness.

[9] Hynd, D., Carroll, J., Davidsson, J., Vezin, P. (2010). Biofidelity requirements for the THORAX project", THORAX project GA No. 218516, Report D2.1.

Six male volunteers of average size were seated in a rigid seat that simulated a car driver's posture whilst in a special designed test rig (Fig. 5). Static loads to the shoulders were applied through the arms (50, 100, 150 and 200 N/shoulder) while torso movement was blocked by diagonal belts. These were routed close to the neck to avoid excessive clavicle bone interaction. A test series included four load series repeated there times with each volunteer: shoulders pulled straight forward, forward-upward, upward and rearward.

Film analysis was used to measure head, shoulder, and spine responses to shoulder loads. Average resultant volunteers' acromion relative to T1 range-of-motion is shown in Fig. 5 (18 tests for each series). Volunteers provided measurements with reasonable repeatability.

On limitation with the study approach was that the applied loads were lower than those commonly seen in frontal crashes. However, the shoulder is highly mobile and its response to loads is largely dependent on muscle characteristics and as such studies using volunteers may be complimentary to tests with PMHSs. The volunteer tests are reported in THORAX D2.2.[10]

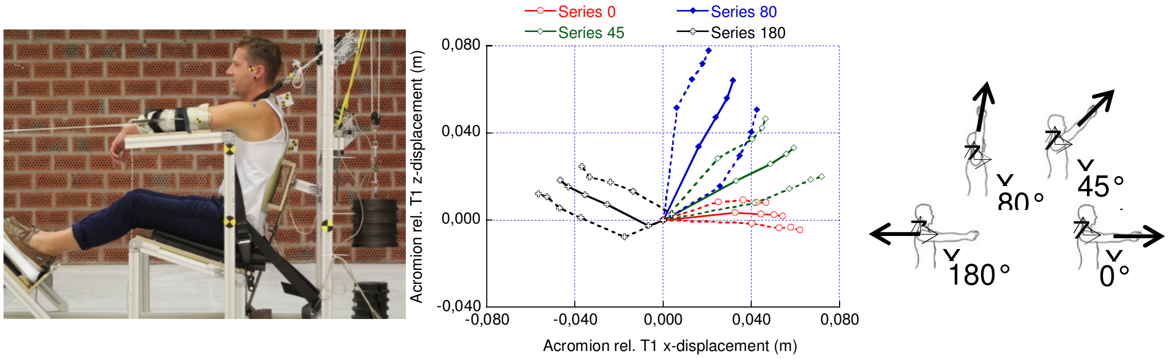


Fig. 5.Biofidelity requirements for the shoulder based on new volunteer tests

2.2.4 Injury mechanisms

The THORAX Task 2.3, Injury mechanism, was designed to achieve the following objectives:

- Characterization of injury mechanisms of the most relevant thoracic injury types as defined in WP1;
- Definition of assessment criteria for use in an improved THOR frontal crash test dummy as well as in Human Body Models. An injury criterion is considered as relevant if it is restraint-independent, capable to discriminate between different loading conditions.

To achieve these objectives, PMHS test were carried out with the purpose to study skeletal thoracic injury mechanisms (see Section 2.2.6), Human Body Models (Fig. 6) were used extensively to identify the most relevant global injury criteria and to study thoracic stiffness and the contributions of the various elements in the thorax to this stiffness.

[10] Erwan, L. and Davidsson, J. (2013). DATA FOR EVALUATION OF CRASH TEST DUMMIES AND HUMAN BODY MODELS: New and past Post Mortem Human Subject Data from Groupement d'Intérêt Economique de Recherches et Etudes PSA-RENAULT; and Volunteer shoulder range-of-motion and stiffnessBiofidelity requirements for the THORAX project, THORAX project GA No. 218516, Report D2.2.

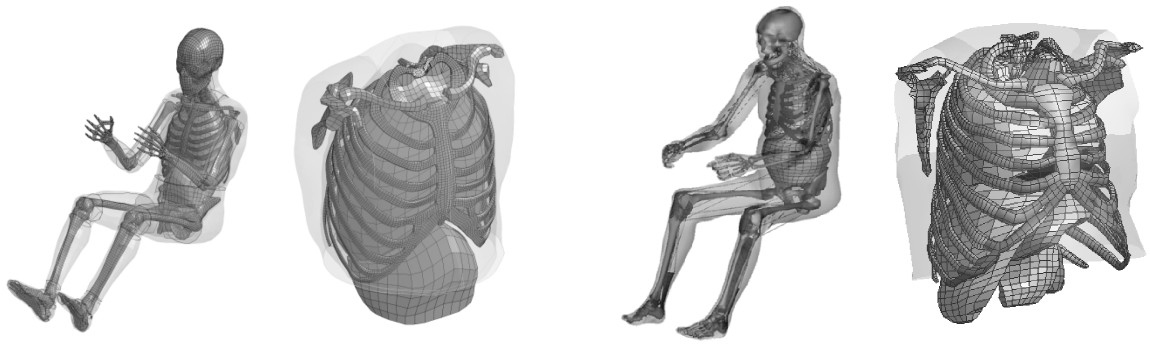


Fig. 6. Thorax part of the THOR (left) and HUMOS (right). Some parts have been hidden to facilitate visualization.

For the studies into assessment criteria, a human body model, the HUMOS2LAB, was extensively validated with respect to four types of biomechanical data: 1) global force and deflection-based corridors, 2) rib strain profile, 3) spatial repartition of rib fractures and 4) ribcage damage evolution versus loading severity, under different loading types and regarding different impact directions. Thereafter a series of simulations were performed and a "virtual" PMHS tests database was established. Five loading types were covered by this database. For each simulation, rib fracture outcome was established and different metric of ribcage deflection were recorded. Finally the data were extensively analysed to suggest skeletal thorax assessment criteria.

The main results include:

- Excessive strain, provoked mainly by bending, was identified as mechanism of rib fractures.
- It was demonstrated that maximum peak strain of ribs does not predict number of fractured ribs correctly.
- It was suggested to directly use the NFR (Numbers of Fractured Ribs) as a global injury criterion.
- A scheme to use the NFR on a mechanical dummy, where ribs always remain in elastic state, was proposed.
- A more usual metric, named as Combined Deflection and noted as Dc, was also proposed. This metric is a global deflection-based predictor for serious injury (more than six fractured ribs). Injury curve and risk curve constructed with this criterion do not vary significantly from one loading type to another (Fig. 7). It has potential to candidate as a restrain-independent injury predictor.
- Both the above mentioned criteria have been reported to the THORAX team and have been considered in the demonstrator THOR dummy. For the Combined Deflection criterion multiple point chest deflection measurement devices (3D-ITRRAC) were developed. For the evaluation of the NFR criterion the chest cage of the demonstrator was instrumented with a suitable numbers of strain gages.

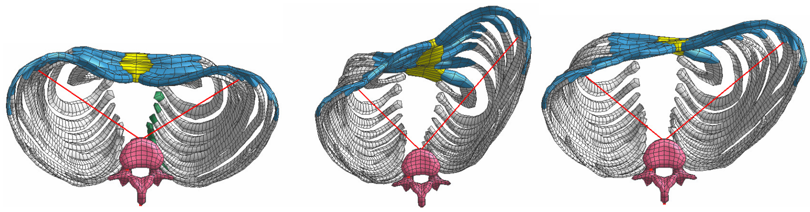


Fig. 7. Examples of ribcage deformation shape under different loading types based on the HUMOS2LAB simulations. From left to right: airbag only, 6kN load limiter only, 4kN load limiter + airbag

For studies into the thoracic stiffness another HBM was used; the Total HUman Model for Safety (THUMS) version 3.0. This model was modified by including a finely meshed ribcage, and thoracic flesh and appropriate material properties for these organs. Thereafter the modified THUMS was tuned against three different PHMS data sets:

- The pendulum impact test as in Neathery (1974)[11] using the corridors as defined in GESAC (2005)[12].
- The four different Table Top tests configurations, hub, belt, double diagonal and distributed, as in Kent et al (2003)[13].
- The three different states, including intact, denuded and eviscerated, of the PMHS torsos in table top tests as in Kent et al (2005)[14],[15].

The modified THUMS kinematic response was validated in the Gold Standard configuration (Shaw et al 2009)[16].

A parametric study was carried out using the Table Top and Gold Standard sled conditions to clarify the contribution of the thoracic organs and tissue properties on the overall thoracic response, and to support the ATD design. The parameter changes include changes of material stiffness, here denoted weak states, and design changes that made its torso resemble that of an anthropometric test device. Examples of these weak states are weaker costal cartilage, ribs and intercostal muscles whereas examples of ATD-like designs are remove the internal organs, horizontal clavicle and divided sternum. The parameters measured were total stiffness change, coupling between the upper and lower chest regions and coupling between the right and left chest regions and particularly the calculated combined deflection criterion (DC).

[11] Neathery, R. (1974). Analysis of chest impact response data and scaled performance recommendations. Stapp Car Crash Conference, Ann Arbor, Michigan, USA, pp.459-493.

[12] GESAC (2005). Biomechanical response requirements of the THOR NHTSA advanced frontal dummy (Revision 2005.1), GESAC-05-03.

[13] Kent, R., Sherwood C., Lessley D., Overby B. ,Matsuoka F. (2003). Age Related Changes in the Effective Stiffness of the Human Thorax Using Four Loading Conditions. International Research Council on the Biomechanics of Impact, Lisbon, Portugal, pp. 249-264.

[14] Kent, R., Murakami D. ,Kobayashi S. (2005). Frontal thoracic response to dynamic loading: the role of superficial tissues, viscera and the ribcage. International Research Council on the Biomechanics of Impact Prague, Czech Republic, pp. 355-365.

[15] Mendoza, M., Brolin, K., Davidsson, J. and Wismans, J. (2012). Human rib response to different restraint systems in frontal impacts: a study using a Human Body Model, Accepted for inclusion in International Journal of Crashworthiness.

[16] Shaw, G., Parent, D., Purtsezov, S., Lessley, D., Crandall, J., Kent, R., Guillemot, H., Ridella, S. A., Takhounts, E., Martin, P. (2009). Impact response of restrained PMHS in frontal sled tests: skeletal deformation patterns under seat belt loading, Stapp Car Crash J, 53: 1-48.

Main results of the studies included:

- Related to the studies into combined deflection criterion it can be concluded that:
  - THUMS showed an inverse relationship between coupling and chest stiffness. This implies that for THUMS, an increase in chest stiffness is followed by a decrease in both the C and differential deflection (dD).
  - The whole kinematic response of THUMS was not substantially affected by the weak states. Weak intercostal muscles and weak ribs were the states with largest dD. The smallest dD values were found when the cartilage was made shorter and ribcage was made stiffer in combination with removal of the internal organs.
  - For THUMS in the sled tests condition, the C and dD peak values varied in amplitude and timings. Since the DC value is reported as one single value, corresponding to its maximum, and the DC is calculated as the sum of C and dD, it is important to consider their timing.
- Related to the thoracic stiffness studies and introduction of ATD design changes using the THUMS model it can be concluded that:
  - The kinematic response of THUMS was changed the most when ATD-like changes were introduced. The results suggest that small changes on THOR ribcage stiffness will not affect its kinematic response, but changes on its clavicle and thoracic mass distribution will probably do.
  - Different tests on THOR indicate that it has a stiffer response than PMHS. The parametric study has shown that the weak ribs state decreased the effective stiffness. Hence, a reduction in the THOR chest stiffness could be achieved by a substantial decrease in the thickness or height of the ribs in the THOR.
  - The jacket in the THOR is intended to represent the intercostal muscles and fat tissue. From the simulations with the THUMS we found that there is a risk that the THOR jacket will influence the chest response differently for different load cases. For hub loads, the jacket would be engaging a small surface and therefore underestimating its contribution on the chest response as compared to distributed load for which the jacket would be engaging a large rib cage surface.
  - The state with the anteriorly displaced clavicle shielded the belted upper chest.
  - Different states experienced a change on the displacement pattern in the coronal plane. This pattern change could modify the deflection results. For example, a larger caudal rib rotation may be interpreted as a larger rib compression. It is therefore suggested that the biofidelity requirements include 3D displacements of the anterior end of the rib relative the spine and not only the compression relative to the spine.
- Related to the thoracic stiffness studies using the HUMOS2LAB model it can be concluded that:
  - Organ simplification does not fundamentally change the thoracic behaviour. The main features of rib strain profile remain the same, and the global stiffness decrease of the thorax may be compensated in a mechanical dummy by using stiffer rib materials. These conclusions suggest that it may not be necessary to represent organs and rib-spine joints in a mechanical dummy.

The work on injury mechanisms, injury criteria and studies into the thoracic stiffness using Human Body Models are presented in THORAX D2.4[17] and in Brolin et al 2012[18].

[17] Song, E., Mendoza-Vazquez, M., Lecuyer, E., Trosseille, X., Davidsson, J. (2012). Definition of injury mechanism and related physical parameters based on datasets from PMHS tests and advanced HBM simulation. THORAX project GA No. 218516, Report D2.4.

[18] Brolin, K., Mendoza-Vazquez, M., Song, E., Lecuyer, E. and Davidsson, J. (2012) Design Implications for Improving an Anthropomorphic Test Device based on Human Body Simulations, Proc. Int. IRCOBI Conf. on the Biomechanics of Impact, Dublin, Ireland, IRC-12-88.

2.2.5 Dummy Concept studies

In the dummy concept studies the principle thorax design to be developed was defined. An extensive literature review was carried out with the aim to identify important design changes to the THOR-NT. This included studies into the response of this dummy, and earlier versions, compared to PMHS tests and user-friendliness. Focus was on the thorax hardware; total chest and individual rib stiffness, shoulder complex design, clavicle geometry and instrumentation of the dummy that enabled multiple-point measurements of ribcage deformations. Examples of such designs are shown in Fig. 12. The work resulted in a specification report[19] for Task 3.2. Examples of changes that were specified were reduced rib stiffness, modification and adoption of a new shoulder, and numerous strain gauges mounted to every second rib, for rib bending measurements, and four IR-tracc sensor that allowed for chest compression measurements at four positions.

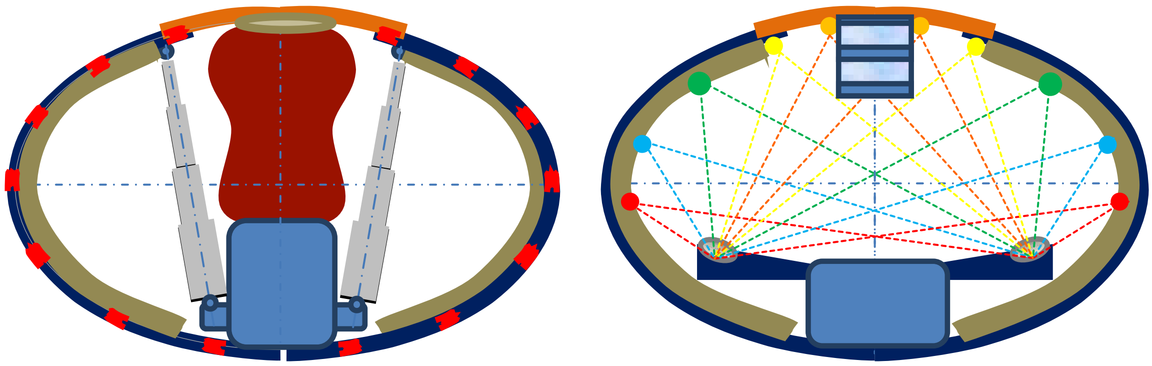


Fig. 8. Rib strain and IR-tracc concept (left) and multi-point sensing concept (right)

The finite element FE-dummy model of the THOR was made available late; hence a limited evaluation was carried out and minor updates to this model were introduced. Parameter studies were carried out; the effects of rib stiffness and clavicle position on thorax response and head excursion in simulated car crashes were studied. In addition, a FE-model of a shoulder developed for the THOR NT dummy, named SD2 (see 2.3.3), was developed and used to study the influence of the shoulder design on thorax response in simulated frontal car crashes. Although the FE- THOR NT model was poorly validated, the studies confirmed that a large proportion of the diagonal belt loads were transferred via the clavicle bone and, as a consequence, large rib stiffness reductions provided minor upper chest deformation increases. Further, the THOR NT exhibited regional stiffness dissimilar those of PMHSs; the study suggested that a significant stiffness reduction of the upper most ribs would provide a more human like response. The work using the FE-THOR is appended D2.5[20].

2.2.6 PMHS Testing

Despite access to most of the world's data involving testing of PMHS, it is recognized that additional PMHS tests will be required in order to understand the mechanisms that are responsible for thorax injuries and for injury risk curve construction. Therefore, PMHS were tested to complete the dynamic biofidelic kinematic and response requirements as defined in Task 2.1 and to improve the understanding of injury mechanisms studied in Task 2.3. For the requirements, three PMHS tests were conducted at LAB within the THOMO project and

[19] Been, B. (2010). Dummy Concept Specifications. THORAX project GA No. 218516, Report D2.
[20] Been, B. (2010). Dummy Concept Specifications. THORAX project GA No. 218516, Report D2.5.

analysed further within this project to support the needs identified in Task 2.1. The results from these test and analysis are reported in D2.2[21].

Studies into injury mechanisms were conducted at IFSTTAR. The activities included test protocol development, definition of test program, testing, analysis and reporting. Specific attention was paid to the effect of ageing on thoracic response when subjected to non-injuries and injuries loads. Experiments on 6 ribcages of PMHS were conducted and the 3D deformation of the structure was determined when exposed to dynamic antero-posterior loading. As the main objective was to characterize the real motion of the ribs relative to the spine and explain the rib fracture mechanisms, which could be different from isolate ribs, the entire rib cage was used in these tests and the spine was attached to a rigid base (Fig. 9).

Tests on both denuded and eviscerated thoraxes and intact torsos were conducted to further understand the viscoelastic effects of inner organs and effect of muscle and soft tissues covering the ribcage. The study demonstrated that:

- For the upper ribs, the deformation was mainly in the sagittal plane with a downward flexion and an antero-posterior deflection of the rib, whereas the deformation was mainly in the transverse plane with an antero-posterior and transverse deformation in the rib plane for the lower ribs.
- Variability was found among the different rib cages but the result variations were not correlated significantly with geometrical parameters. However, a trend was found between the initial rib slope and the amount of rib deformation.
- The orientation and, at a less degree, the position of the ribs in relation to the vertebrae are not fixed during the loading and depends on the costal level.
- The initial rib orientation influences the rib deformations and rotations at various degrees force are applied. Consequently, the variations of the rib slope are an important factor in the biomechanics of the thorax, and can partially explain the greater injury risk of older people.

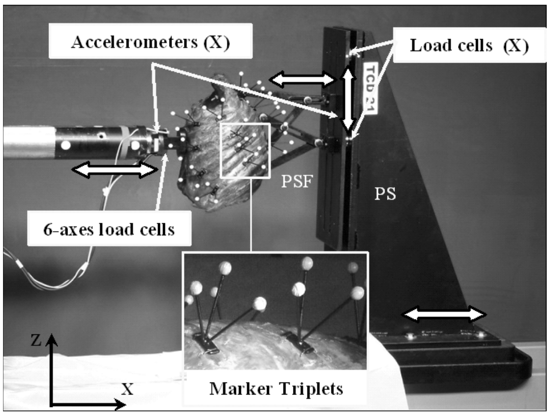


Fig. 9. Positioning of rib cage on test fixture. The lines with double arrows show the translation of the fixture to adapt the mechanical system to the rib cage morphology. The lines with single arrow show the location of the sensors.

2.2.7 Development of injury risk curves and scaling techniques

Injury risk curves for usage with the THORAX demonstrator were developed under Task 2.6. For this frontal and oblique impact tests conducted with PMHS and reported in the literature were reviewed for possible inclusion in the development of risk curves. Paired tests of relevant PMHS configurations were performed under Task 3.3 and results forwarded to Task 2.6 for scaling the results and injury risk curve development. In addition, real world accident

[21] Erwan, L. and Davidsson, J. (2013). Data for evaluation of crash test dummies and human body models. THORAX project GA No. 218516, Report D2.2.

events were recreated with the dummy in the laboratory and injury risk curves were constructed.

In total 153 tests were reproduced and considered; out of these 59 test were found to be suitable for further analysis. Twenty-six of these were frontal or oblique impactor tests, nine were airbag or inertia load tests and 24 were sled tests (Fig. 10).

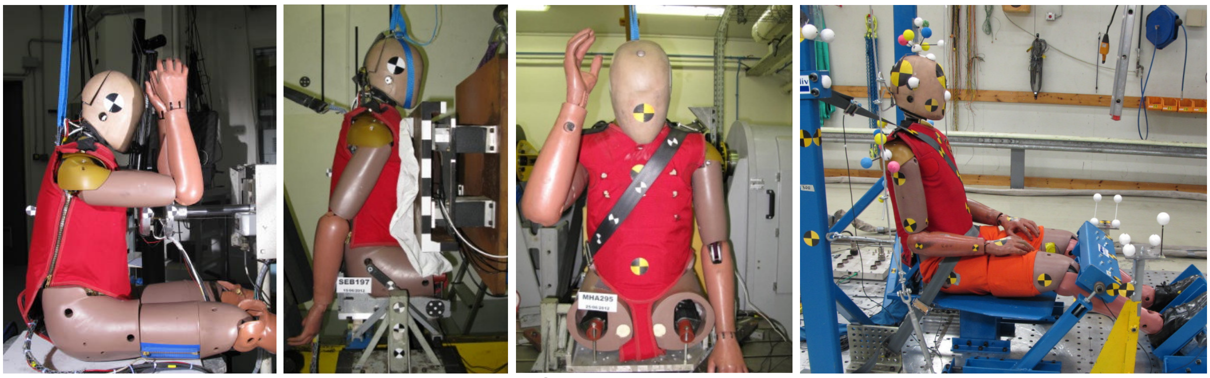


Fig. 10. Examples of reconstructions of PMHS tests used fir injury risk construction. From left to right; impactor test, airbag test, inertia test and sled test.

The WP1 provided that thorax injury-risk curves should be constructed for multiple thorax injury levels, especially focus on lower risks of rib fractures and lower levels of injury severity. The PMHS data allowed for the development of risk curves for rib fractures at an injury level of AIS2+ and AIS3+.

An injury risk curve relates injury criteria values to the risk of injury. Prior to the curve construction the injury criteria to be used were adjusted for the THORAX demonstrator. First, a regression analysis was carried out to investigate which combination of chest deformations, the new THORAX demonstrator is fitted with sensors that measure chest compression in x, y, z at four positions, would be most useful for a *fundamental measure*. The analysis found that maximum peak x-axis measurement from any of the four measurement points (*Dmax)* was the most useful fundamental measure. Second, the Combined Deflection criterion, which was developed for a mathematical model of the Human Body in Task 2.3, is a measure of chest compression in combination with right-left differential chest deflection. This criterion was modified to be suitable for use with the THORAX demonstrator and to take both the upper and lower chest deformations into account. The new criterion is referred to as *DcTHOR.* Third, a criterion denoted NFR, which stands for Number of Fractured Ribs, was developed in Task 2.3 and is a single measurement based on strain in the ribs. The main advantage would be that local strains would be intrinsically closer to the rib fracture mechanism than rib end deflections. A strain based NFR criterion was also developed for the THORAX demonstrator; a total of twelve of the ribs of the demonstrators were fitted strain gauges along the ribs and a protocol to derive a single value metric from the strain peak values was developed. Fig. 11 illustrates the approach adopted. The key point is to determine a strain threshold that provide the NFR(dummy) that matches the NFR(PMHS). Once the strain threshold is determined, the NFR can be measured easily and becomes an injury criterion just as sternal deflection. A complete description on NFR calculations can be found in report D.2.3.[22]

[22] Davidsson, J., Carroll, J. A., Hynd, D., Lecuyer, E., Song, E., Eggers, A., Sunnevang, C., Praxl, N., Lemmen, P., Been, B. and Martinez, L. (2013) Set of injury risk curves for different sizes and ages. THORAX project GA No. 218516, Report D2.3.

The demonstrator data was scaled to account for the difference in anthropometry between the dummy and the individual PMHSs included in the dataset used for risk curve construction. A scaling methodology, using a mass spring model, was adopted for impactor tests but none could be found or developed for sled tests.

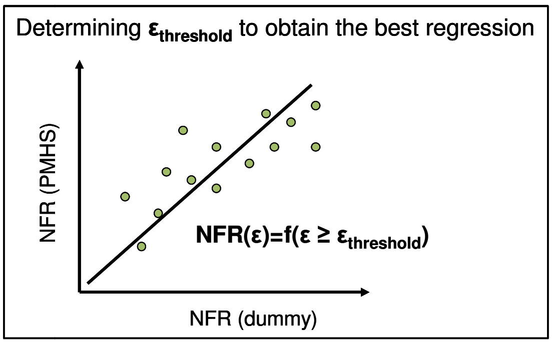


Fig. 11. Scheme of a possible approach to apply the NFR as an injury criterion to dummies.

Risk curves were developed using survival analysis for two injury severity levels, for an occupant age of 45 and 65 years, using age as a covariant in the analysis, and for three criteria; *Dmax*, *DcTHOR*, and *NFR.* Curves were constructed using non-normalized data and data normalized for a dummy that represents a mid-size adult male. In Fig. 12 three risk curves are presented to illustrate the main results of Task 2.6

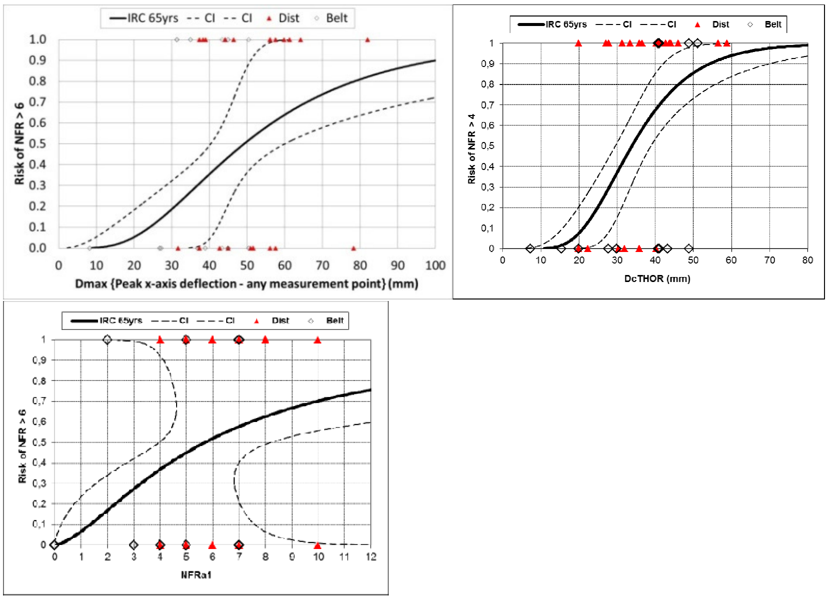


Fig. 12. Thoracic skeletal injury risk curve NFR7+ (AIS3+) as a function *Dmax, DcTHOR* and *NFR* adjusted to a 65 year old person for the THORAX demonstrator. Non-normalized data.

In addition an extended data set was developed and used to study the effect on the risk curve shape and confidence limits if a larger dataset was used. The latter did not provide better risk curves, most likely due to inclusion of tests that were not suitable for risk curve development. These curves are presented in D2.3 but presented here.

In conclusion injury risk functions were developed for the THORAX demonstrator. The two displacement based criteria, (*Dmax*) and differential deflection criterion (*DcTHOR*), were found to have a good injury risk quality index. The *DcTHOR* was found consistent with an established field data observation: a 4 kN shoulder belt force limiter associated with an airbag offers better protection than a 6 kN shoulder belt. For the *NFR* based on strain, the quality index for the risk curves were not as good compared to the displacement based criteria. Never the less, the strain based criterion appears to be a potential injury criterion candidate as by nature it is less sensitive to restraint conditions.

Finally, techniques to scale the obtained injury risk functions to different sizes and gender have been developed. A model with high degree of flexibility that allow for the scaling to different chest sizes and compensate for change in material properties, such as when the population to study is younger or older than the average person, was adopted. The results have been validated using PMHS data and the model provided reasonable results. It was identified that the model is an improvement compared to past scaling models but additional validation data required before the scaling method is used to a greater scale.

The set of injury risk curves and the scaling techniques suggested for scaling the risk curves to different sizes and ages are presented in D2.3.[23]

2.3 WP 3 – Demonstrator development and validation

2.3.1 Objectives

Based on the findings of the accident surveys and the outcome of the biomechanical work, a demonstrator dummy consisting of a new thorax / shoulder design was designed in WP3. Three prototypes of the demonstrator were build and installed on THOR dummies available at partners for extensive evaluation testing against the biomechanical requirements defined in WP2. Key points of attention during the development were the rib response tuning to impact biofidelity corridors and updating an existing shoulder design called SD2 in relation to durability and functionality and implementation of instrumentation to capture newly proposed injury parameters.

2.3.2 Rib cage design

Because of the complex structure of the upper body of the THOR NT preference was given to experimental investigations to fine tune rib stiffness rather than using a Finite Element model (Fig. 13). For the initial design realisation pendulum impactor tests representing the low-speed NHTSA[24] and ISO (also referred to as Lebarbé)[25] requirements for the thorax were performed. Both are partially based on the same biomechanical background data, but Lebarbé included results from newer data sets. Also, Lebarbé's corridor is based on a newly developed mathematical methodology[25], 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' to construct an envelope of straight lines around the responses. Apart from the above mentioned differences Lebarbé'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

[23] Davidsson, J., Carroll, J. A., Hynd, D., Lecuyer, E., Song, E., Eggers, A., Sunnevang, C., Praxl, N., Lemmen, P., Been, B. and Martinez, L. (2013) Set of injury risk curves for different sizes and ages. THORAX project GA No. 218516, Report D2.3.

[24] 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.

[25] Lebarbé, M. (2010). "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.

1/2” (12.7mm) and was subtracted from pendulum penetration to give a representation of the internal skeletal deformation, which then allows direct comparison to the output of the chest compression measurement system inside the dummy. Fig. 13 shows a comparison of the NHTSA and Lebarbé corridors. Although peak forces are around the similar level, clearly Lebarbé corridors allow for larger deflection, but the corridors are not in contradiction.

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 the 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. 14). Test data indicated that the peak deflection increases at a much higher rate than peak force reduction with gradual stiffness reduction.

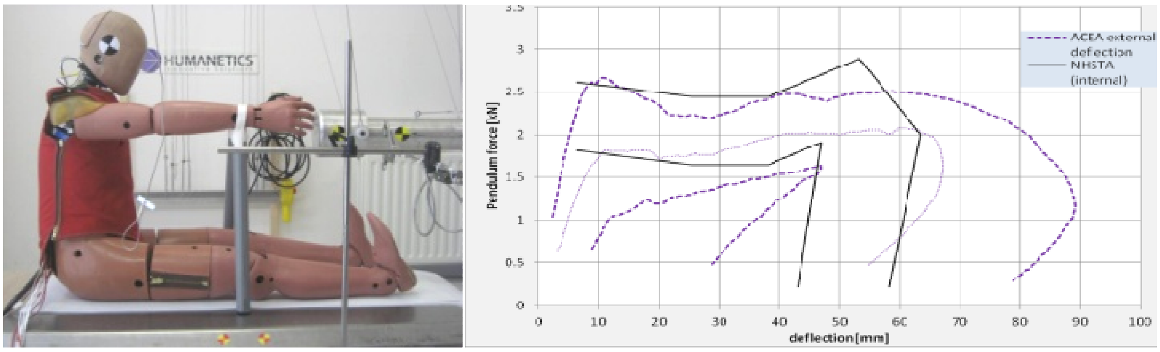


Fig. 13. Set-up frontal impactor test and comparison of NHTSA and Lebarbé corridors for 4.3m/s 23.4kg pendulum test

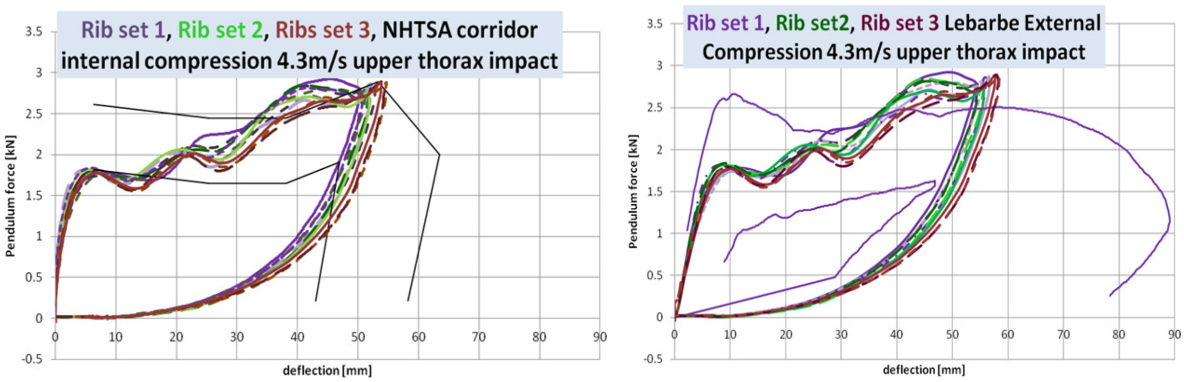


Fig. 14. Test results compared to NHTSA (top) and Lebarbé (bottom) corridors

Further peak force reduction may have been possible but this was 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. Note that for the comparison against the Lebarbé 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.

2.3.3 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 (2008)[26]. The sterno-clavicular joint was redesigned to meet anthropometry requirements for the 50th percentile male described by Schneider et. al.[27]. See Fig. 15 - Fig. 17. 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. Apart from this correction, the original SD2 linkages and joint positions were adopted in the updated design.

Of particular importance is the update of the shoulder cover (Fig. 16). 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 flexible neopreneSD2 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. Instead, the updated SD shoulder employs a solid elastomer moulding, which is closer to the original NT part in geometry and firmness. As the THOR-NT jacket incorporates features to achieve the desired chest response, the original THOR jacket is used with the updated SD shoulder, however slightly modified to allow for the larger range of shoulder motion. The SD2 applied a standard Hybrid III arm, which was not well adapted to the shoulder and was short compared to anthropometry specifications. This was addressed by implementing a dedicated SD3 arm (Fig. 17). The SD3 arm design includes a six channel load cell at mid shaft, meets anthropometric requirements and the same assembly can be used on left and right side, to reduce component count.

In addition, weak spots previously identified in tests at the University of Virginia (UVa) were addressed and updates realised. The changes include going back to a spherical joint for the clavicle (Fig. 15), introduction of adjustable joint friction to obtain a more reproducible dummy seating position (Fig. 16), geometric simplification of components for ease of manufacturing (Fig. 16), etc.. The humerus joint, originally a universal joint, was replaced by a metric version of the Hybrid III style joint, to address lack of joint friction and durability problems (Fig. 16). Finally a clavicle load cell has been implemented that allows measurement of vertical and interior-posterior loads in both ends of the clavicles (Fig. 15). During the project some further small improvements were implemented to address findings of the demonstrator evaluation. The updated shoulder design is being referred to as the SD3 shoulder and is currently being implemented for production.

2.3.4 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 the required input to be used in calculating 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 NFR (Number of Fractured Ribs) criterion two of the demonstrator dummies are equipped with a total of 72 strain gages on the ribs (Fig. 18). 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. 18). 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.

[26] 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.

[27] 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.

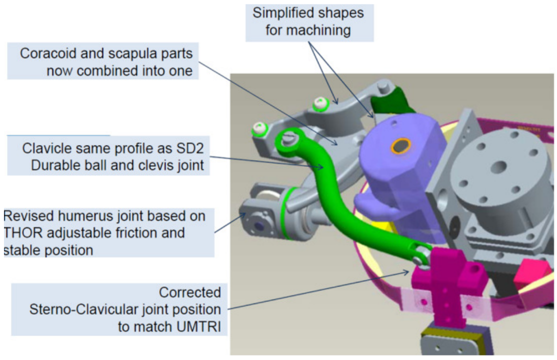


Fig. 15. Shoulder updates

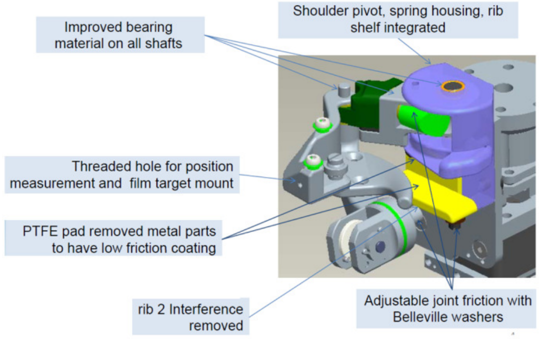


Fig. 16. Details pivot region

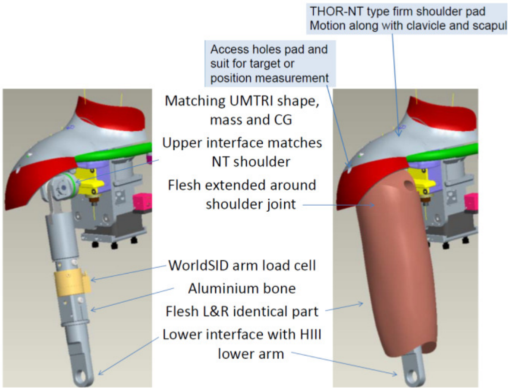


Fig. 17. Shoulder cover and arm

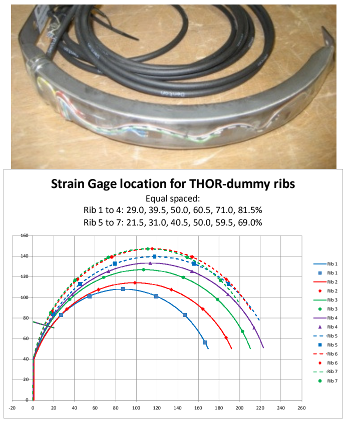


Fig. 18. Example of rib with gages and gage positions

2.3.5 Pelvis-femur-knee

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

2.3.6 Biomechanical performance evaluations

The THORAX demonstrator dummies were evaluated against a set of biomechanical requirements defined in WP2 (see Table 1)

Thorax pendulum tests

Pendulum impactor tests replicating the Kroell frontal sternum and Yoganandan oblique lower rib tests, were evaluated against corridors defined by NHSTA and Lebarbé and for the oblique impacts, by NHSTA and by the THORAX project itself based on Yoganandan pendulum tests (Fig. 19). A standard 23.4 kg and 152 mm diameter pendulum was used at an impact speed of 4.3 m/s. The dummy was positioned according the PMHS test positions. The NHTSA corridors are based on human post mortem skeletal deflection and are suitable to compare the output of the dummy chest displacement instrumentation after alignment of the measurement co-ordinate system with the pendulum axis.

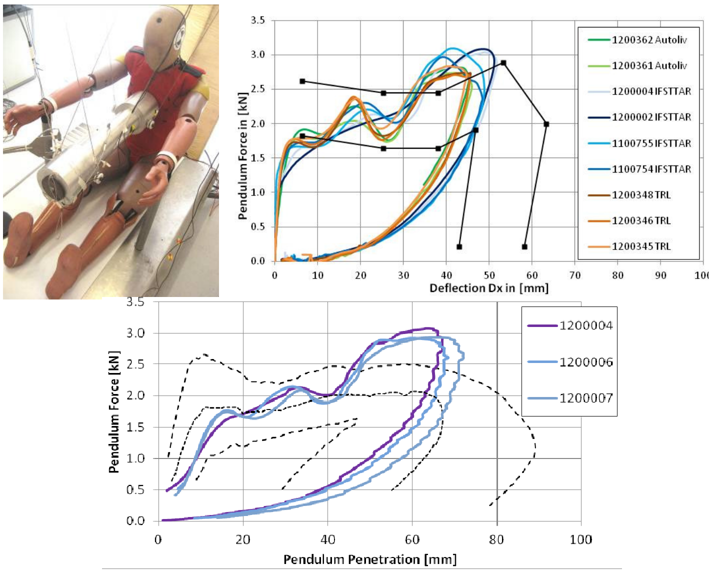


Fig. 19 Response for three THORAX demo dummies in frontal 4.3 m/s pendulum impact tests, NHTSA corridor internal upper chest compression (left) and Lebarbe corridors pendulum penetration (right).

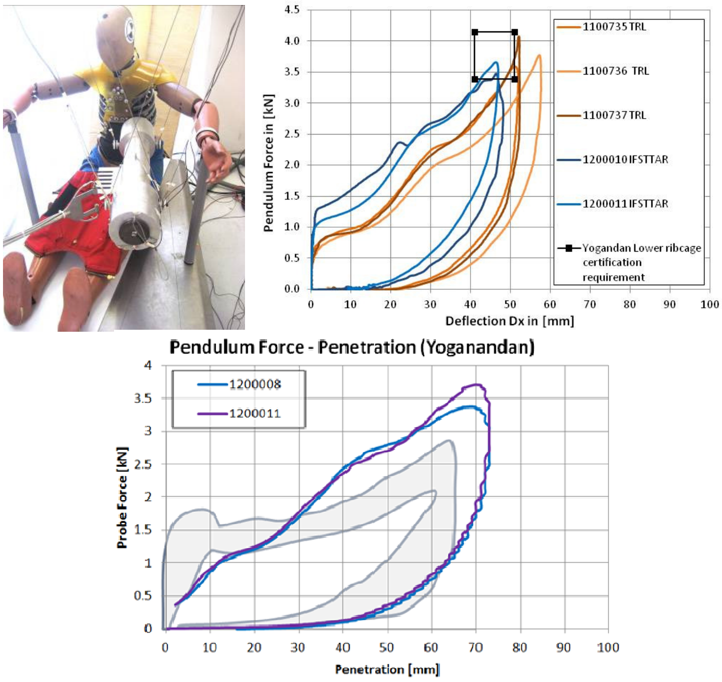


Fig. 20 Results for two THORAX demo dummies in oblique pendulum impact tests, NHTSA corridor internal lower chest compression (left) and THORAX pendulum penetration (right). Normalised PMHS responses grey shaded.

The Lebarbé et.al. requirements for the frontal sternum impacts were developed as part of the ACEA-TFD support of ISO Working Group 5. These corridors define an external (surface of the chest) deflection measurement or pendulum penetration. As this cannot be measured with the IR-Traccs inside the thorax the pendulum penetration was recorded with High Speed Video analysis. Fig. 19 clearly shows the difference in internal deflection and pendulum penetrations.

The sternum peak pendulum penetration in these tests was between 67 and 72 mm, while internal deflection was around 50mm (only IFSTTAR results can be compared). The response is in fairly good correlation with corridors defined by Lebarbé. The peak penetration corresponds well with the average found in PMHS tests. The peak pendulum force exceeds the target by around half the corridor width. The unloading phase is entirely within the corridor.
For the Yoganandan tests the pendulum mass and velocity were the same, but the pendulum was lined with 19 mm Rubatex foam, as specified. In THORAX the original Yoganandan lower oblique data was re-analysed and Moorhouse normalisation applied, which was found to reduce scatter more than other methods. An artefact of this method is that the corridors do not represent the variation of peak penetration seen in corresponding demonstrator dummy responses. Due to inaccuracy of the time zero of pendulum contact with the dummy, the penetration derived from high speed video analysis was possibly overestimated upto 17mm. The peak forces of the dummy exceed the PMHS responses. Considering that dummy peak penetrations were almost certainly overestimated, the penetration response was close to the requirement.

Cesari & Bouquet table top tests
As part of the evaluation the THORAX demonstrator was subjected to table-top conditions reported by Cesari and Bouquet and previous authors. For this purpose a replica of the table-top rig as described in was built. The new demonstrator dummy and the baseline THOR-NT were assessed on this rig with additional Hybrid III tests required to prove that the set-up was comparable with the original Cesari and Bouquet experimental work. In the original tests an impactor of mass 22.4 or 76.1 kg loaded the belt. Impact velocities ranged from 3 to 9 m/s. The two ends of the seat belt passed through the table over low friction supports and were attached to a horizontal spreader bar. The movement of the bar was activated by a dynamic impactor. The force at each end of the belt was measured with a load cell before connection to the rod. The chest deflection was measured at eight different locations spread over the different ribs.
The behaviour of the new equipment was compared with the original behaviour via a comparison of test results with the Hybrid III dummy (see Fig. 22). Slight differences were noted in the belt forces and external deflection measurements at the higher severity loading conditions. These differences were regarded as being acceptable for the intended purpose of comparing relative displacement measurements and hence regional stiffness and coupling.
A limitation of the set-up was in the accuracy with which the external measurement points were positioned around the thorax of the subject. The locations had to be manipulated in order to align them with realistic hard points throughout the thorax. Whilst efforts were taken to minimise those errors, it is considered that small variations in the positions of the external deflection measurement points could have an influence on the biofidelity results.

Results comparing the three different dummies in relation to corridors from the PMHS data are depicted in Fig. 23. Results for both the THORAX demonstrator as well as the THOR-NT were found to be close to the response corridor. Results for both dummies are quite similar indicating no negative effect of the modifications to the chest and shoulder complex on the regional stiffness distribution as evaluated in this test condition.

Fig. 21 Image of table top set-up with THOR-NT

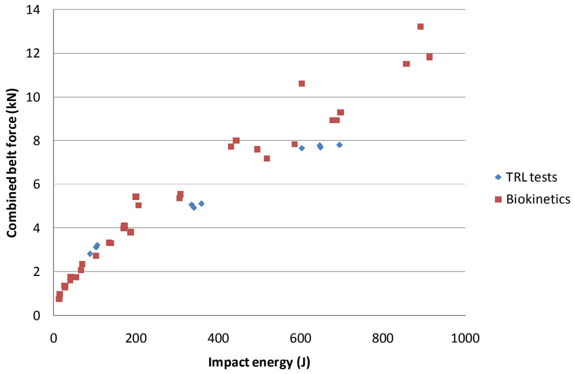


Fig. 22 Comparison of belt force for original set-up (red dots) and replica (blue dots) using Hybrid III.

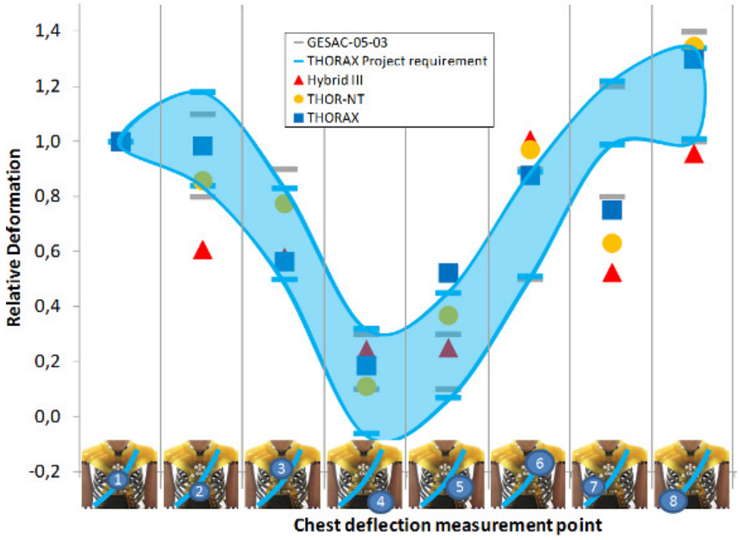


Fig. 23 Relative deflections for Hybrid III, THOR NT and THORAX demonstrator with SD3 in comparison to corridor from PMHS data.

Kent *et al.* table top tests

In addition to the Cesari and Bouquet tests the THORAX demonstrator was subjected to table-top conditions described by Kent et. al. [28]. In their research, Kent et al. studied the effect of four different loading conditions on the biomechanical response of the human thorax using PMHS. For the purpose of the evaluation of the demonstrator, three of four loading conditions applied by Kent et al. were reproduced. These loadings conditions were: hub, single diagonal belt and double diagonal belt. The hub had the same geometry as the one used in Kent et al. The belt for the single and double diagonal belt loading conditions was positioned on the dummy chest similarly to the cadaver tests. The breadth of the belt used was a little smaller than the original belt (4.6 cm instead of 5 cm). The test rig was not reproduced identical to the original set-up but the positions and orientations of the loading devices as well as the loading conditions were identical to the PMHS tests. A universal tensile test machine was used to generate chest deflection at a rate similar to the rate applied on the PMHS chest.

[28] 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, pp 495-519, 2004.

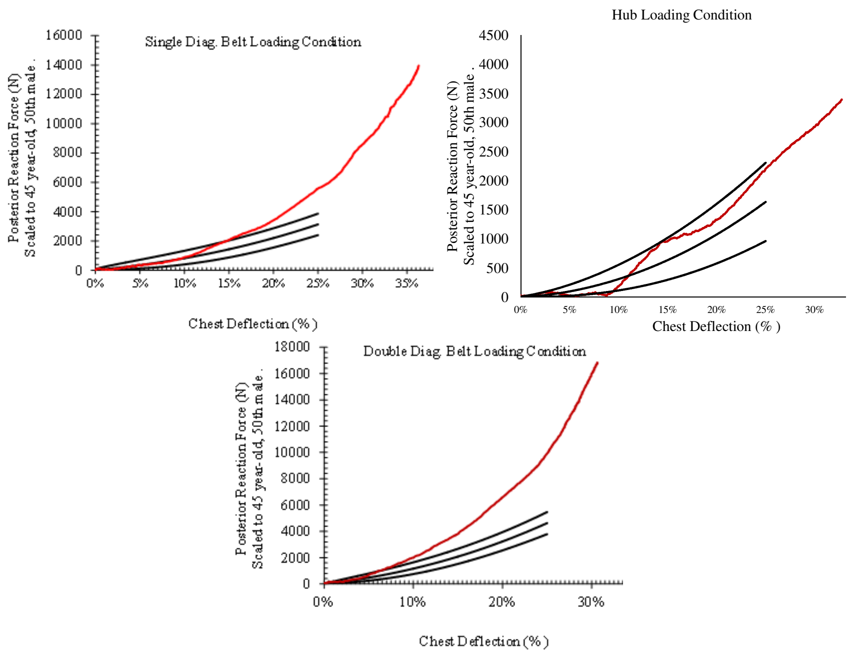


Fig. 24 Force deflection data for the THORAX demonstrator compare with the characteristic average and corridors of the PMHS for hub (left), single (middle) and double (right) diagonal belt. PMHS corridors are scaled to a 45 year-old, 50th percentile male.

This chest deflection is supposed to mimic the deflection of a restrained PMHS in 48 km/h frontal sled tests. This corresponds to a linear displacement with a constant velocity of 1 m/s. In order to replicate the PMHS protocol accurately, the pre-test 10-cycle preconditioning regime described in the Kent paper was also applied to precondition the thorax of the demonstrator. The dummy was positioned in the same way as the PMHS with its back lying on the table.

Applied and reaction force were recorded with the same sampling frequency as in the PMHS tests. In addition to the dummy instrumentation, the chest deflection at mid-sternum was also measured with a linear transducer (LVDT) to facilitate the comparison with the PMHS corridor established by Kent et al. [19]. Kent et al. performed non-injurious tests with the different loading condtions on each cadaver and a final injurious test with one of the four loading conditions for each PMHS. For the THORAX demonstrator, successive tests were performed by increasing the chest deflection from 10% up to 30%. The 30% of chest deflection corresponds roughly to the injurious tests performed on the PMHS. This allowed to check the repeatability of the demonstrator response and to avoid damage to the dummy by checking the rib conditions after each test and before increasing the deflection.

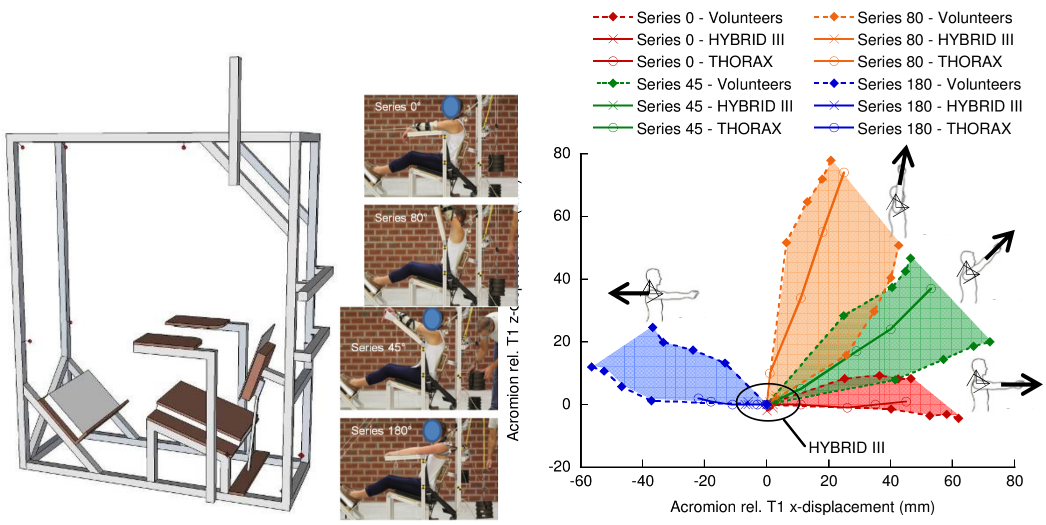
The responses of the demonstrator were compared with the PMHS corridors (see Fig. 24). The demonstrator response is within the corridor for the hub loading condition. Nevertheless, for low chest deflection (<10%) the reaction force was low compared to cadavers. The reaction force increased rapidly between 10 and 15% and then the demonstrator followed the cadaver response with a value slightly higher than the average characteristics of the PMHS. For the single diagonal belt loading, the demonstrator behaviour fitted very well with the corridor up to 10% of chest deflection. Then, the stiffness of the dummy chest increased and became higher than the upper corridor above 15% of deflection. The THORAX demonstrator appears too stiff compared with the PMHS corridor with the double diagonal belt loading condition. It should be noted that permanent deformation of the lower ribs of the demonstrator were observed for this series, which is to be expected considering the peak load of 18 kN applied.

Shoulder

In the Thorax project a test rig for evaluation of the human shoulder stiffness was developed (see Fig. 25). Belted volunteers were seated and their shoulder bone motions measured when loaded forward (0°), forward-upward (45°), upward (90°) and rearward (180°). The forward and upward loads to the shoulders were applied through the arms by means of arm brackets fastened to the elbows Rearward loads were applied by means of a padded strap wrapped around the shoulder complex. To block torso movement the volunteers were restrained by two shoulder belts, routed close to the neck, that were pre-tensioned to 100 N each. The arms or shoulders were statically loaded with 50 N increments to a maximum of 200 N/side. Each volunteer was exposed to three tests for each loading direction. The position of the shoulder complex was recorded by three digital cameras. The left acromion process relative to T1 displacements were used to calculate shoulder motion in 3D. Belt loads and seat back loads were recorded to facilitate a comparison between dummy interactions during testing as compared to those of the volunteers.

Tests were done with six volunteers and reproduced using the THORAX demonstrator dummies as well as a standard Hybrid III. Evaluation of the dummy performance in this loading condition is regarded as complimentary to PMHS sled tests like, for instance, the Gold Standard sled tests[29]. Average T1 change in position for each loading condition was below 32 mm forward-rearward and 14 mm upward-downward when maximum load was applied (both for volunteers and dummies). This means that the shoulder motion was more successfully isolated from other motions in this study than in similar previous studies[30] and therefore more suitable for evaluation of crash test dummy shoulders.

The THORAX demonstrator produced similar shoulder motions as the volunteers did when the loads were applied forward, oblique and upward (Fig. 25). For series 0° the shoulder relative to T1 forward motion was 54 mm for the average volunteer, 45 mm for the THORAX demonstrator and 2 mm for the Hybrid III when maximum load was applied. For series 45° the resultant maximum shoulder relative to T1 motion was 68 mm for the average volunteer, 64 mm for the THORAX demonstrator and 2 mm for the Hybrid III. Both the THORAX demonstrator and the Hybrid III exhibited less than half the rearward shoulder motion of the volunteers in the 180° tests (Fig. 25). For this loading condition the THORAX demonstrator exhibited 22 mm rearward motion whereas the average volunteer exhibited 47 mm.



29 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.

30 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.

Fig. 25 Test rig used for shoulder stiffness tests (left) and HIII and THORAX demonstrator results against corridors in four loading directions.(Right)

Forman and Bolton sled tests

To replicate PMHS sled test configurations reported by Forman et al.[31] and Bolton et al.[32] a sled rig was developed (see Fig. 26). The rig consists of a stiffened Ford Taurus buck equipped with airbags, safety belts, dashboard, seat, etc. Four front passenger sled test configurations were replicated using the Autoliv THORAX demonstrator dummy:

- No shoulder belt (2pt belt) + airbag.
- Only 3-point belt load, no airbag. 5 kN Shoulder belt load.
- 3-point belt (force limiter) + airbag. 5 kN Shoulder belt load.
- 3-point belt (no force limiter) + AB. 8 kN Shoulder belt load.

High speed filming with motion capture was applied to obtain dummy kinematics data. Dummy reponses were compared against global kinematics, thoracic spine accelerations and thoracic deformations obtained from the PMHS tests.

To derive the acceleration corridors, the original raw PMHS data from the tests performed by UVa have been used. PMHS corridors were derived for T1, T8 and T12/L1 resultant accelerations. An attempt was made to apply normalisation to the standard 50th percentile size. However, the different temporal scaling factors between subjects appeared to generate different values resulting in a bi-modal mean response, which was not representative of any of the PMHS and cannot reasonably be reproduced by the dummy. Therefore normalisation was not applied for the corridors used in the performance comparisons. The acceleration versus time responses were obtained as the mean response with a corridor set at ± one standard deviation.

For T1 acceleration corridors, the positions of the accelerometers in the PMHS and in the dummy are different. To derive the T1 corridors, the PMHS response with three accelerations and three rotational velocities have been used to obtain the acceleration corridors for the position of the dummy T1 accelerometer. Therefore the T1 corridors presented in this paper are dummy specific corridors.

Fig. 26 General view of the sled rig.

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

[32] 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. Shaw G., Crandall J. and Butcher J., “Biofidelity evaluation of the THOR advanced frontal crash test dummy”, Proceedings of the IRCOBI Conference, Montpellier, France, pp 11-29, 2000.

Furthermore, the kinematics behaviour is analysed (trajectories of different targets on the head, T1 or hip) in order to perform a general comparison of the demonstrator dummy with respect to the PMHS.

The results from the two tests with the demonstrator dummy in each test configuration, together with the response corridors, are shown in Fig. 27 to Fig. 29. It is observed that:

- The general behaviour of the THOR kinematics is good. The lower part of the dummy underwent a greater excursion than the mean of the PMHSs. It is possible that the main factor was the knee to dashboard distance which, together with the forward displacement of the pelvis from condition to condition, was variable in the PMHS. The T1 and head excursions are well reproduced.
- The resultant spine accelerations (T1, T8 and T12) gave good results. Dummy accelerations are greater than the PMHS, but the morphology and timing was well reproduced. The T8 and T12 dummy accelerations are influenced by the direct contact of the knees against the dashboard.
- The THOR dummy had less chest compression than the PMHS, especially for the more severe configurations. The dummy thoracic deformation was able to discriminate the configurations in terms of their severity. In the three-point belt loading, the PMHS had large uncoupled deflections (the upper compression was 4 to 6 times greater that the lower compression); however, the prototype dummy could not reproduce this. With the three-point belt, the lower left thoracic location had high deflection and the lower right location had very little deflection (even considering the local chest depth at that level) reproducing the behaviour of the PMHS.

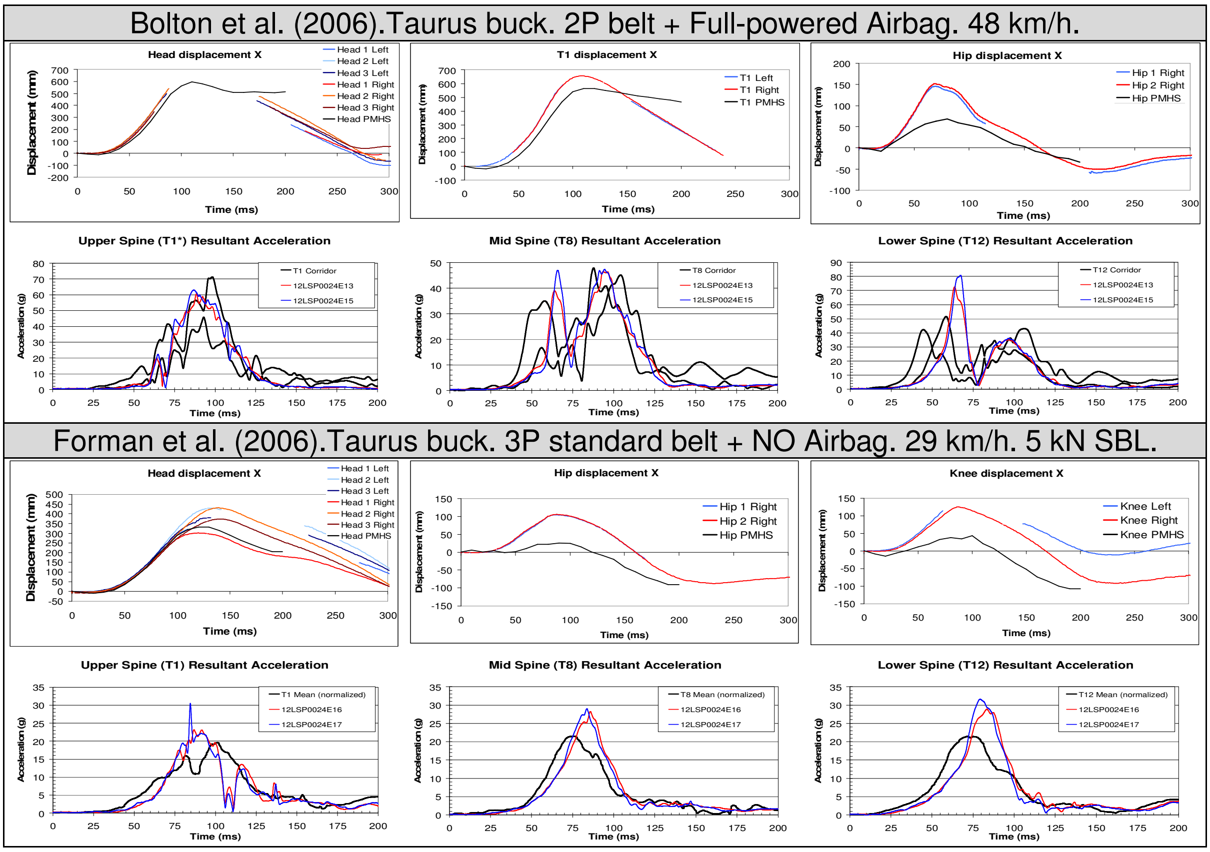


Fig. 27 Head, T1 and hip x-displacements; upper spine, mid spine and lower spine resultant accelerations for tests with 2 point belt and airbag (top rows) by Bolton et al.32 and tests with 3 point belt without airbag (bottom rows) by Forman et al. et al. 31.

2P belt + Full-powered Airbag

	THOR Right	PMHS Sternum	THOR Left
Upper	-12.2%	-11.0%	-11.1%
Lower	-4.1% (5.9%)	-	-4.1% (6.3%)

3P belt pretensor & FL + depowered Airbag

	THOR Right	PMHS Right	PMHS Sternum	PMHS Left	THOR Left
Upper	-10.4%	-25.9%	-27.6%	-24.8%	-17.0%
Lower	-4.4% (4.3%)	6.2%	-6.9%	-11.5%	-16.3% (1.7%)

3P standard belt + NO Airbag

	THOR Right	PMHS Sternum	THOR Left
Upper	-6.7%	16%	-14.3%
Lower	-5.2% (2.4%)	7%	-13.0% (1.4%)

3P standard belt + depowered Airbag

	THOR Right	PMHS Right	PMHS Sternum	PMHS Left	THOR Left
Upper	-16.7%	-33.5%	-34.1%	-38.0%	-18.5%
Lower	-6.6% (3.4%)	7.1%	-5.9%	-13.4%	-20.7% (2.7%)

Fig. 28 Comparison of chest x-deflections (as a percentage of the chest depth at measurement location) tests for all four load conditions considered by Forman et al. 31 and Bolton et al. 32.

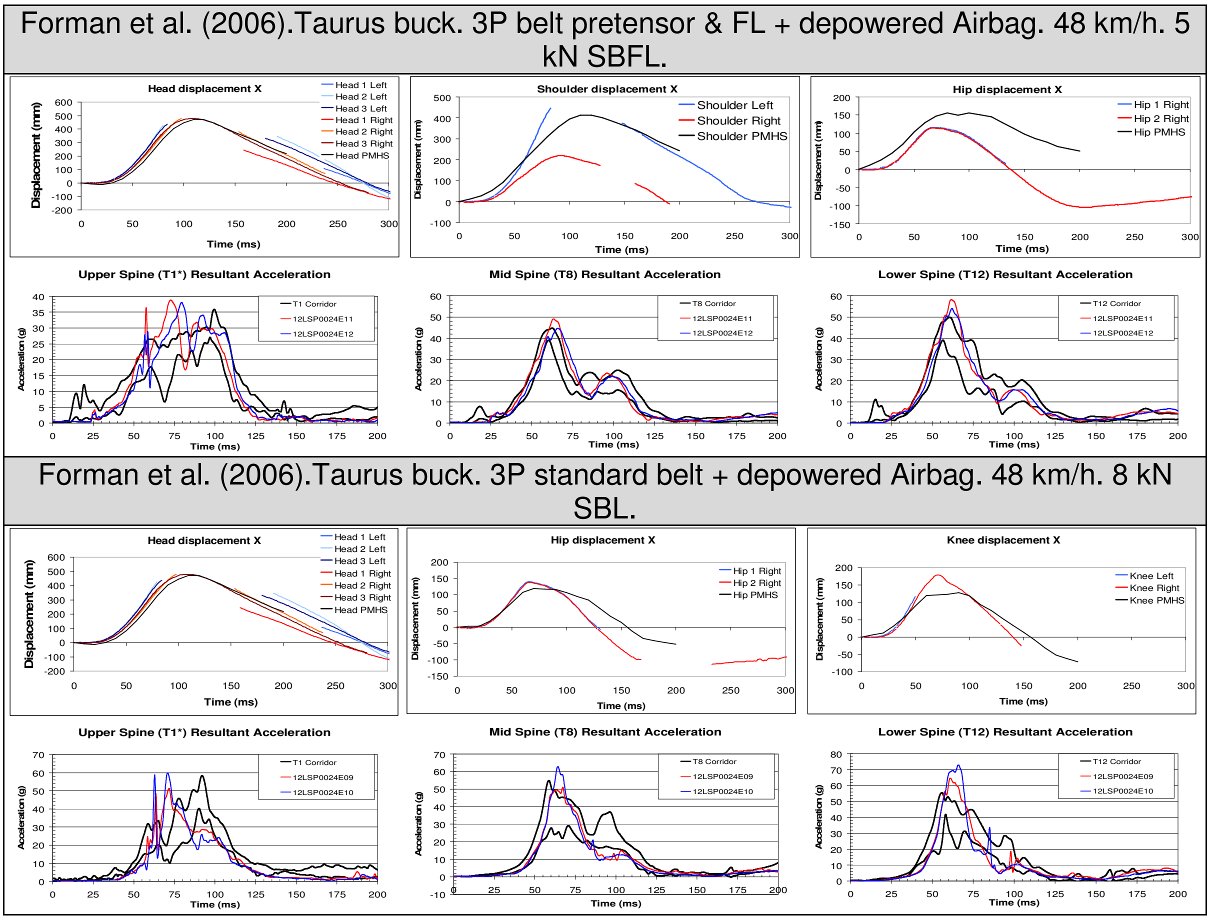


Fig. 29 Head, T1 and hip x-displacements; upper spine, mid spine and lower spine resultant accelerations for tests with 3-point force limiting belt (5 kN) and airbag (top rows) and tests with 3-point force limiting belt (8 kN) with airbag by Forman et al. 31.

Gold Standard Shaw et al. sled tests

In a sled test series, commonly referred to as the 'Gold Standard', by Shaw et al. [33] and [34], eight PMHSs were positioned on a rigid planar seat with their torso and head supported

[33] Shaw G., et al. "Frontal Impact PMHS Sled Tests for FE Torso Model Development", Proceeding of the 2009 International IRCOBI Conference on the Biomechanics of Impact, September 7-10, York, UK, pp. 341-356.

by a matrix of wires. The subjects were restrained by a three-point shoulder and lap belt, using separate adjustable-length sections joined near the subject's left hip, tensioned to approximately 5 N and 50 N, respectively, prior to each test. In addition, a rigid knee bolster, adjusted to be in contact with the knees, and a footrest with ankle straps restrained the lower extremities. The sled and the PMHS were subjected to a peak acceleration of 140 m/s2 that resulted in a velocity change of 40 kph. Instrumentation was comprehensive and enabled the extraction of acromion, spine, and head displacements and chest compressions using video analysis [33], [34] and [35].

The new THORAX demonstrator and Hybrid III dummy were subjected to Gold Standard sled tests using a replica of the original test rig. Dummy rib cage deformations were measured using internal sensors and recalculated to the coordinate system used in the the Gold Standard series; anterior chest displacements in a T8 vertebra coordinate system. T8 location and coordinate system attitudes were transferred to dummy drawings from drawings of seated humans.

THORAX demonstrator upper chest deformations were larger than those of the THOR NT but still lower than the response target (Fig. 30). In the tests with the demonstrator dummy slightly larger belt downward sliding was observed compared to the original PMHS tests. This off-loaded the left chest and may, to some degree, explain the smaller upper left chest deformations. For the belted shoulder, the clavicle of the PMHS moved somewhat rearward and exposed the chest to belt loads. This was not fully reproduced by the demonstrator; the clavicle shielded the upper right chest to a higher degree in the demonstrator. In addition, the demonstrator exhibited slightly larger thorax rotation around its vertical axes and this could explain why the demonstrator exhibited relatively large lower left chest compressions as compared to those observed in the upper chest. Another reason for larger lower left chest deformations were differences in pelvis motions; the demonstrators moved on average 35 mm forward while the PMHSs only moved on average 25 mm.

The results indicate that the dummy chest may be slightly stiffer than that of the average PMHS in this loading condition. Hybrid III chest deformations were uniform but also small; upper right and lower left chest deformations were smaller than the biofidelity targets (Fig. 30). In addition to chest stiffness, two other factors highly influenced the chest response of the Hybrid III; the Hybrid III thorax spine is rigid and as a result the thorax did not flex as did the demonstrator and the PMHS (Fig. 31); the Hybrid III exhibited smaller head forward displacements than those specified in the project requirements (Fig. 31). These differences may not seem to be important in this sled condition but influences restraint interactions in modern cars. Neither the THORAX demonstrator nor the Hybrid III exhibited lower right chest bulge out as did the average PMHS. The THORAX demonstrator appears to be repeatable based on these three tests.

Shaw G. et al. "Impact response of restrained PMHS in frontal sled tests: skeletal deformation patterns under seat belt loading" 53rd STAPP Car Crash Conference, Savannah, Georgia, USA, 2-4 November, 2009.

[34] Shaw G. et al. "Impact response of restrained PMHS in frontal sled tests: skeletal deformation patterns under seat belt loading" 53rd STAPP Car Crash Conference, Savannah, Georgia, USA, 2-4 November, 2009.

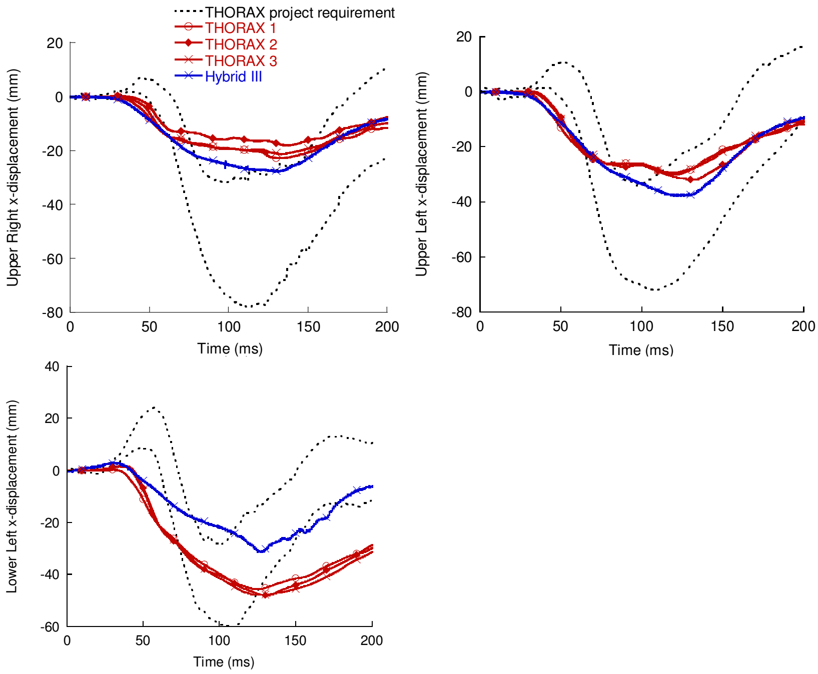


Fig. 30 Chest deformations relative T8 for THORAX demonstrator with SD3, Hybrid III compared with biofidelity target provided by Lebarbé and Petit [35].

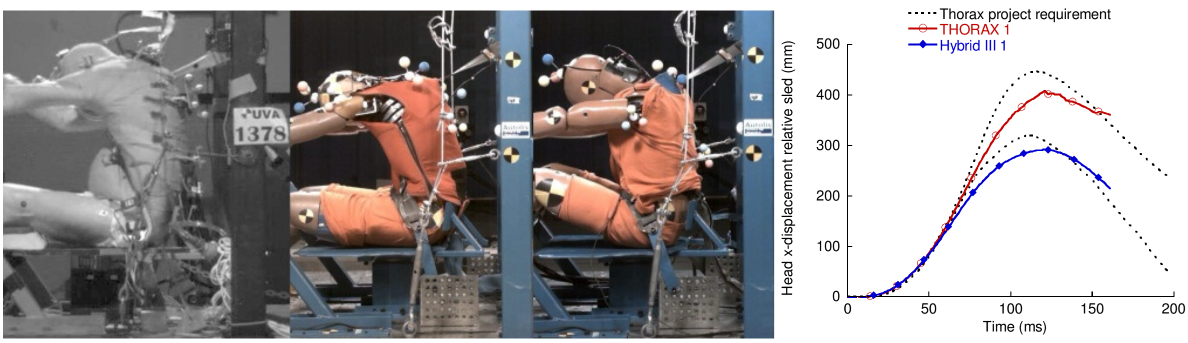


Fig. 31 Stills from high speed video of tests in Gold standard conditions with PMHS, THORAX and Hybrid III (left) and resulting Head displacement relative sled for THORAX demonstrator and Hybrid III compared with biofidelity target provided by Ash et al. [2012] (right).

Summary of biofidelity evaluations

Three demonstrator dummies were prepared for evaluation against a broad list of biomechanical requirements and test conditions. This included hub impactor tests, table-top tests and sled tests under various restraint conditions. Although in some individual tests differences between dummy response and corridors / requirements from PMHS tests were observed, the THORAX demonstrator generally shows reasonable to good correlation over a broad range of conditions.

The upper rib - clavicle complex seems stiffer though than those of the PMHSs in various conditions. As currently no specific biomechanical data for this region is available it is recommended to collect such data in future studies for further improvement of the dummy.

[35] Lebarbé M. Petit, P., "New Biofidelity Targets for the Thorax of a 50th Percentile Adult Male in Frontal Impact", Proceedings of IRCOBI Conference, Dublin, Ireland, 2012.

2.4 WP 4 – Assessment of potential for restraint optimization

2.4.1 Objectives

THORAX WP4 assessed the demonstrator in relevant load cases regarding its sensitivity against settings of modern vehicle safety systems. In this test program also other items of the dummy were evaluated like robustness, durability and repeatability. For this purpose an extensive test program with full scale sled testing was conducted considering different impact conditions, as well as different restraint configurations. The sled tests were performed at partners BASt and Autoliv Development AB.

At BASt the test setup was generic but with an existing production seat cushion to have a representative kinematic performance in the pelvis area. In the test matrix performed by BASt large variation in restraint configurations were investigated as well as belt routing, shoulder position and distance between thorax and steering wheel. See Fig. 32.

Fig. 32 Generic sled set-up used in the sled test at BAST

At Autoliv the large test series was performed in a complete body-in-white (BiW) representing a mid-size family car with a 5 star Euro NCAP rating. Sled tests were performed at two severities; USNCAP and Euro NCAP. The USNCAP configuration represents full-frontal load case at 56 km/h, and the EUCAP the offset deformable barrier at 64 km/h. In the Euro NCAP setup the BiW was rotated 6° counter clockwise to represent the lateral motion observed in a full vehicle test. Two oblique configurations were also added using the Euro NCAP pulse, in which the BiW was rotated counter clockwise 15° and 25° respectively. For the two pulses and four impact directions restraint variations were evaluated.


Fig. 33 Test Setup Autoliv

As a complement to the BiW test series a separate oblique test series was performed using a generic setup in order to evaluate contact between the thorax and side structure.

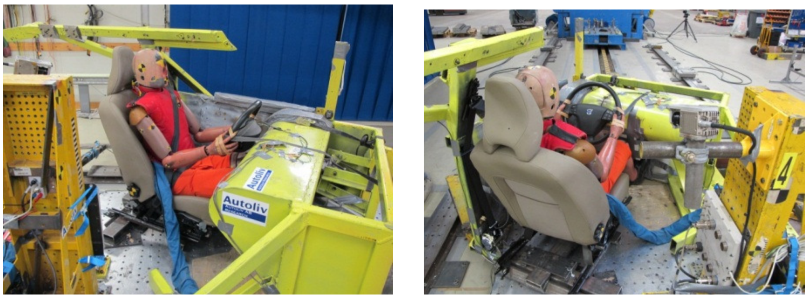


Fig. 34 Sled setup for 25° oblique with pre-deformed lateral intrusion

The dummy output and injury measurements with applied AIS3+ injury risk functions (IRC) were compared to the measurements of the currently used Hybrid III 50th percentile male (HIII). For the THOR three injury criteria were evaluated: the maximum deflection (Dmax), combined deflection (Dc) and strain. For HIII the rodpot deflection was used as well as the DEQ(lin).

For the BiW tests the THOR deflections followed the same trend as the HIII deflection in most cases. It should be noted though that the absolute deflection number is generally higher for THOR and the absolute number can due to the different measurement systems not be directly compared. For the larger restraint variations, such as test without airbag and the low speed Euro NCAP pulse, the deflections differed compared to the HIII in what is believed to be a more biofidelic response. In all test configurations the four measurement points as well as the complement with strain profiles did provide more detailed information of the thorax loading in comparison to the HIII.

.

Table 2 Overview of chest response comparison between THOR and HIII

Overview of chest deflection response for THOR vs. HIII	EuroNCAP ODB BIW 6°	USNCAP FF BIW 0°	IIHS SO Oblique BIW 15°	IIHS SO Oblique BIW 25°	25mph ODB BIW 6°
Driver					
Reference system	1	1	1	3	
Influence of airbag shape (differential thorax loading)	1	1	1		
Influence on thorax response from two levels of LL	1	1			
Influence on thorax response from CLT (optimal point)	3	3	3		
Influence on thorax response from 6kN LL no DAB	3				
Influence on thorax response from 4kN LL and DAB	1				
Influence of steering column no def.	2				
Passenger					
HIII vs THOR in standard EU restraint system	1	1	1		
HIII vs THOR in standard US restraint system	1	1	1		
THOR ADS repeatability, EUNCAP	2				
THOR ADS repeatability, USNCAP		2			
Influnce of thorso angle 20°	1				
Influnce of 4 point belt**			2		
Influnce of BIW in 25°				1	
Influnce of lower speed 40kph					3
1= same					
2= small difference					
3=large difference					

Although similar trends were found between the THOR and HIII, the kinematic behaviour was found to be very different, and the THOR chest and head motion was also assumed to be more biofidelic. In the most oblique test scenario (25°) the THOR head and thorax came close to the vehicle interior.

Fig. 35 BiW sled test at Euro NCAP pulse in 25° Oblique. To the left THOR is the driver and HIII the passenger. To the right THOR is the passenger and HIII the driver.

In the tests using a pre-deformed side interior, contact between the THOR thorax and door side was found. This contact was not possible to achieve using the HIII. The interaction with the door panel was detected by the strain gauges but not with the IR-TRACC measurement.

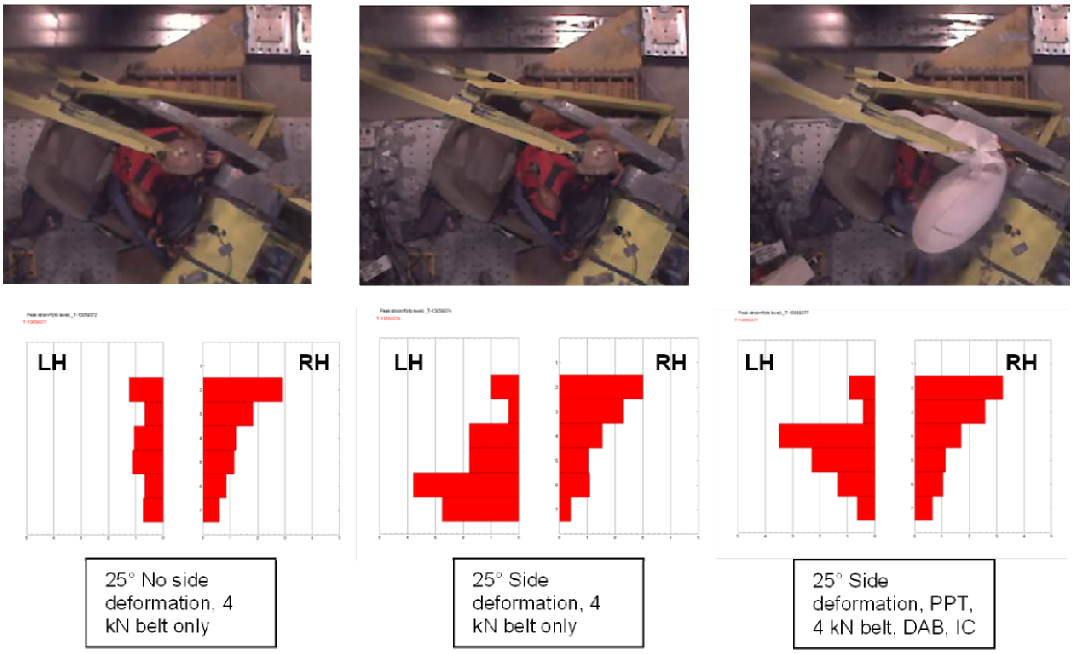


Fig. 36 Strain profiles from three THOR tests in 25° Oblique with a reference tests to the left and pre-deformed side structure to the mid and right.

Comparing the injury risk levels between THOR and HIII for all tests showed that in general the THOR predicted a higher risk of AIS3+ injury to the thorax. This was consistent for all three injury criteria. Also, the injury risk on the passenger side was higher than for the driver (in the comparable tests). As an attempt to relate the test results to real-life the AIS3+ injury risk measured by the THOR and HIII was compared for test configurations which should result in lower real life injury risk according to real life studies.

For a driver it was assumed that in the Euro NCAP pulse a configuration of 6kN belt only is more harmful than 4kN+airbag and that reducing the load limiter further to 3kN+airbag would be even less harmful. For the HIII the injury risk measured by the rodpot show a slight increase in risk going from belt only to belt+bag, and then a decrease as the belt force decrease. Using DEQ(lin) there is a decrease as predicted for all three tests. For THOR the injury risk reduction was enhanced and Dc, Dmax and strain show great reduction going from belt only to bag+belt and then further reduction when belt force was decreased.

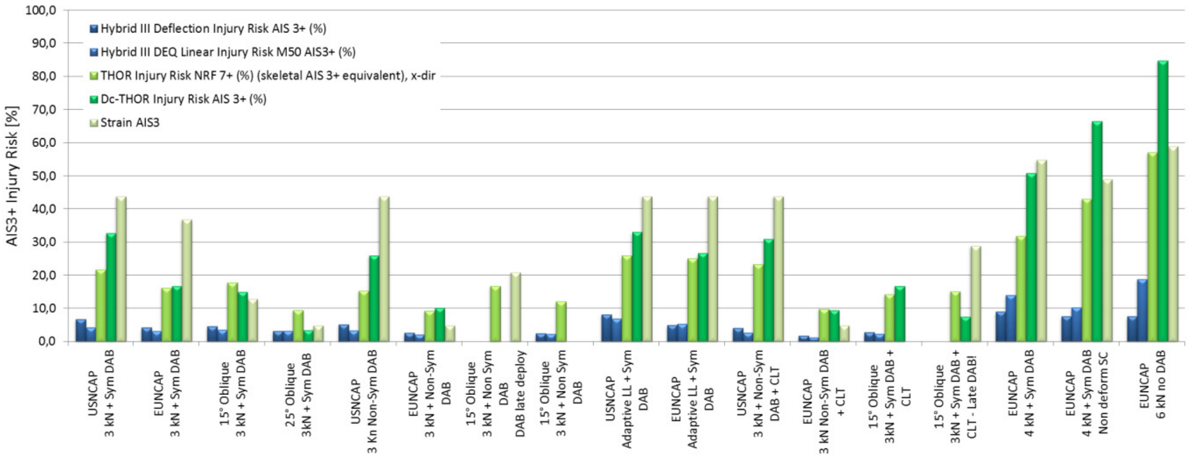


Fig. 37 Injury risk comparison (AIS3+) for all driver tests

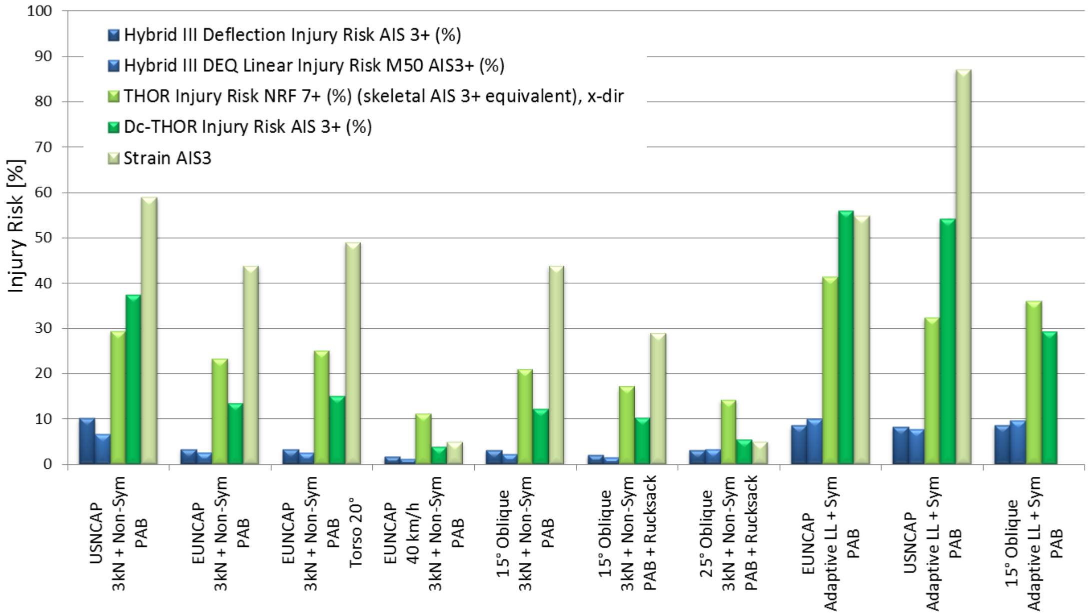


Fig. 38 Injury risk comparison (AIS3+) for all passenger tests

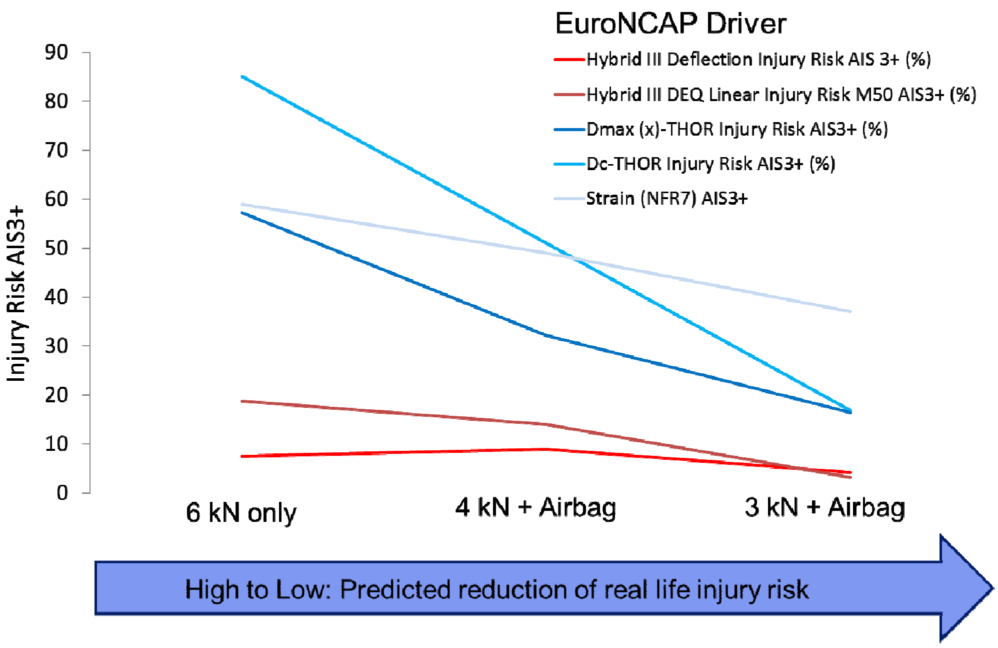


Fig. 39 Comparison driver injury risk to real-life predicted risk reduction for various restraints

For the passenger different impact severities (but same, standard, restraint) were selected for comparison, see Fig. 40. It was assumed that the full-frontal rigid barrier in USNCAP is more severe than the Euro NCAP ODB, and then as a third step that the low speed Euro NCAP is even less severe for a human occupant. For HIII there was a small decrease in injury risk when changing the pulse from USNACAP to Euro NCAP. The injury risk was however at the same level when reducing the impact speed. The trend was similar for the injury risk measured by rodpot and DEQ(lin). For THOR all criteria showed a significant reduction of the AIS3+ injury risk for all three pulses. Dc and strain an even more pronounced decrease than Dmax, but most importantly, all three criteria did also show further injury risk reduction for the low impact speed.

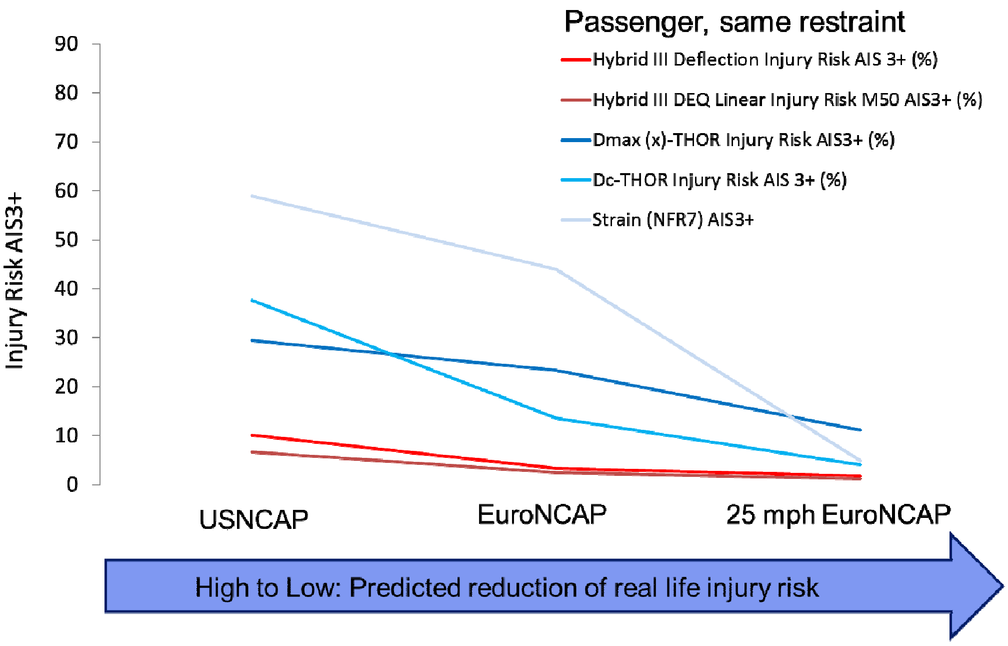


Fig. 40 Comparison passenger injury risk to real-life predicted risk reduction for various crash pulses

Limited repeatability assessment of the THORAX updates was undertaken, with three repeat tests using the Euro NCAP ODB pulse and three using the US NCAP FWRB pulse, with 3 kN load limiter and non-symmetric passenger airbag in both cases. In the US NCAP condition the peak lower left and lower right IR-Tracc measurements were very repeatable. However the upper left measurement had a range of 6 mm (17% of the largest value) and the upper right measurement had a range of 6 mm (13% of the largest value). In the Euro NCAP test condition all four IR-Tracc measurements showed variation, with a range of 4 mm (upper left and lower right) to 8 mm (21%, lower left). No difference in the test setup, pulse, spine excursion, or chest acceleration response was noticed. The spread in deflection is believed to be due to slight differences in belt position or due to the measurement system. It is recommended to perform a larger set of repeated tests and also to develop certification procedure to ensure measurement repeatability.

The dummy usability was in terms of physical tests good. Some modifications are needed for the positioning procedure to ensure the correct shoulder position as well as neck/head position. For the dummy output it is requested that a validated script should be presented since the post-processing is quiet challenging. A post-processing procedure also for the Dc and strain based criterion is also requested.

During the test series’ some critical design issues were found. For the IR-Taccs the potentiometers failed in several tests. For the z-pot it was found that the dimod on-board data acquisition boxes collecting the strain gauge data were mounted so that the pot could contacted and damaged by the dimod box during a test. The boxes were moved further down on the spine and the new placement is currently being evaluated. In some tests the potentiometer shaft was shifted out of the calibrated position. This resulted in some strange deflection results. In a few tests some strain gauges were damaged, but overall the gauges were very consistent. The illiac wing was broken which was determined to be a manufacturing issue. The pelvis flesh was also damaged due to sharp edges.

2.5 WP 6 – Dissemination

An overview of the main dissemination activities is provided in section 3.2.

3 Impact

3.1 Potential Impact

Around 31,000 people were killed and more than 1.4 million injured in European road accidents in 2010 (European Commission, 2010). Although data from the European Road Safety Observatory show that the number of road fatalities continues to decline, 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 expansion of the EU with countries that historically lacked effective safety standards.

While efforts are needed on all levels of road safety, the THORAX project is focussed on reduction and prevention of thoracic trauma. As depicted in Fig. 41 thoracic injuries are one of the leading causes of severe injuries and fatalities in car crashes. The general objectives of THORAX was 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 needed to be much more sensitive to the in-vehicle occupant environment than the tools already being used.

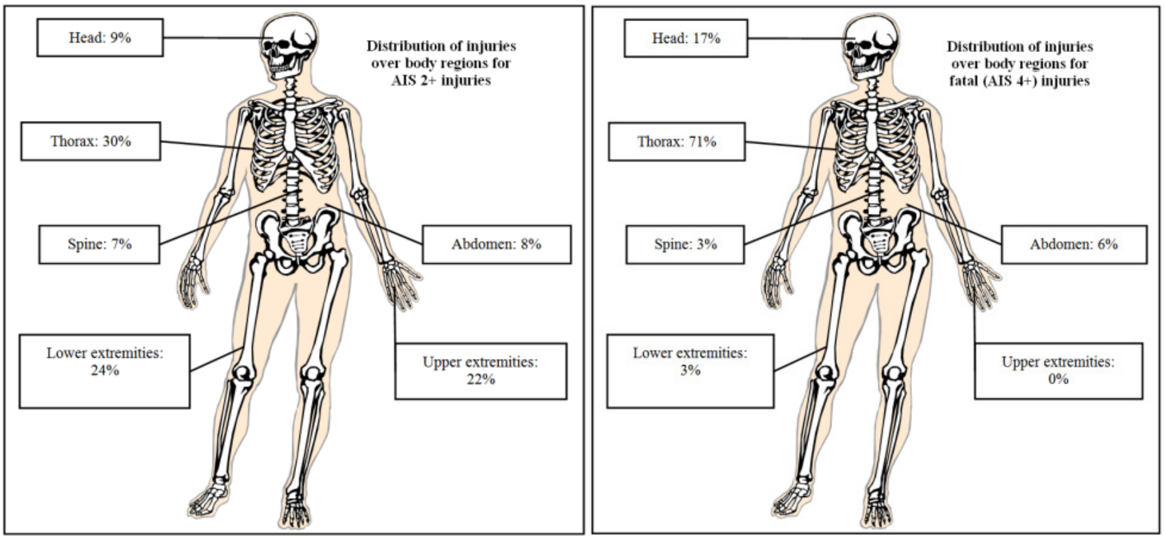


Fig. 41. (a) Distribution of AIS 2+ and (b) AIS 4+ injuries over body regions to car occupants sitting in front seats in frontal impacts for cars manufactured between 1996 and 2004 (Cuerden et al., 2006).

3.1.1 Societal impact of ASSESS - improving road safety

Expected impacts as defined in the THORAX Description of Work and confirmed in the benefit estimates conducted under WP1:

- Accelerated coverage of smart restraint systems that offer optimal protection in frontal collisions based on occupant characteristics like age, gender and size into the EU vehicle fleet to a level of 75% of all new vehicles in 2020.
- Improved survivability of frontal collisions by 20% and a reduction of the risk of severe injuries by 25% by 2020, reported and monitored through the European Road Safety Observatory

Although the THORAX participants are convinced that significant reductions in fatalities and injuries will be achieved by implementing the project findings and results in future regulatory and rating procedures for vehicle safety, the benefit of the THORAX results will not become visible in short term. This is because of the pre-competitive nature of the activities and the fact that actual implementation of results and findings into regulations normally have a long lead time. As such forecasting of the contribution of THORAX to the casualty and injury reduction is a rather difficult and imprecise process. In the Advanced Passive Safety Network (APSN) "Secondary Safety Research Action Plan", it is estimated that the development of new test methods and tools for passive safety systems reduce the fatalities and seriously injured in most common road accidents by 15-20 % in 2020 in addition to the existing general trend (total about 25%). Although this number results from contributions of several crash modes (front, side, read and rollover) ultimately a higher percentage is expected for the THORAX project based on the fact that the developed know-how and demonstrator tools will also serve as basis for integrated vehicle safety systems.

For introduction of findings into regulatory and consumer testing procedures THORAX communicated results into the GRSP informal group on Frontal Impacts and Euro NCAP. The GRSP group foresees inclusion of the THOR dummy in a second phase of their activities to be implemented in the 2020 timeframe[36]. An important aspect in this process is the harmonisation of the experimental and numerical tools between the different regions world-wide. Harmonisation of the experimental tool is being realised via close cooperation with NHTSA and stakeholder groups in Japan. This is facilitated through the Technical Advisory Group meetings organized in THORAX. As an outcome of this it can already be indicated that the thorax design proposed by the project has been adopted by NHTSA and is currently undergoing extensive evaluation testing for final decision making by the end of 2013. In view of the developments in GRSP and NHTSA it is to be expected that the forecasts made on coverage of smart restraints and improved survivability in frontal impacts for new vehicles in 2020 seem very realistic.

Harmonisation of the human body models is being arranged via the world wide human body modelling consortium. Developments and findings from the THORAX project are being implemented in the updated thorax model developed in THOMO which is part of this consortium.

Parallel to the updates of tools and regulations, findings and results are being implemented in new products developed by suppliers and OEM's involved in the project. For this purpose the project includes an extensive testing program evaluating the performance of the tools developed against typical current and advanced restraint systems.

3.1.2 Strategic and economic impact of ASSESS

A direct measurable cost of road accidents is in the order of EUR 45 billion. Indirect costs (including physical and psychological damage suffered by the victims and their families) are three to four times higher. The annual figure is put at EUR 160 billion, equivalent to 2% of the EU's GNP[37]. The sums spent on improving road safety fail to reflect the severity of the situation outlined above. Efforts to prevent road accidents are still inadequate, corresponding to less than 5% of the total costs of those accidents, i.e. EUR 8 billion.

Based on the realization of new frontal impact test procedures by 2020 as well as the introduction of dummies representing females in frontal impact procedures and consumer testing rating procedures (Euro NCAP) in the 2014 – 2016 timeframe the results and findings

[36] Castaing et. al., "Proposal for new terms of reference for the mandate to the informal group on frontal collision", submitted by the chair of the informal group on frontal collisions to the fiftieth GRSP session, 6-9 December 2011, Geneva (Item 14 of the provisional agenda).

[37] Retrieved from EU-website on Transport: www.europa.eu.int/comm/transport

of the THORAX project will significantly contribute to improving road traffic safety and herewith contribute to the reduction of the societal cost of road accidents.

Another important economic (and employment) impact is the preservation of the competitiveness of Europe's automotive industry. The automotive sector spends over €20 billion per year on research and technological development (RTD), making it the largest private investor in RTD in Europe. It directly provides 1.9 million direct jobs and a further 10 million indirect jobs in Europe. It has an annual turnover of €489 billion and represents 3% of the European Union's GDP. By being directly involved in developing and implementing the protocols European suppliers and OEM's could prepare in an adequate manner for the future challenges set in the new protocols. This includes experience in specification and testing of the new safety systems.

3.1.3 Contributions to standards and regulations

Vehicle safety is a concern extending far beyond individual countries. With the support of the Member States the European Commission sounds out the prospects for new practical measures on vehicle safety and prevention of road accidents and seeks uniform interpretation and application of the international regulations throughout the Community. The consortium has made valuable contributions by providing required knowledge on chest injuries and development required assessment tools (experimental or numerical) for use in frontal impact protection rules. The GRSP Informal Group on Frontal Impacts is redefining the European Frontal Directive on frontal impacts (96/79/EC) that became effective in October 1998. Based on findings of the THORAX project, dummies representing females are being introduced in a first phase of updates. These phase 1 updates are planned for the 2014-2016 timeframe. Following this the GRSP group will continue its activities in a second phase consideration amongst others the THOR dummy for introduction in the 2020 timeframe.

Also NHTSA is considering the introduction of the THOR dummy in test procedures. As a first step decision making on the THOR configuration (including risk curves) is expected at the end of 2013. This decision will consider adoption of the SD3 shoulder developed in THORAX.

3.2 Main dissemination activities

The following sections provide an overview of the main dissemination achievements during the project and plans after THORAX is finished. Note that the project website is presented in Chapter 4 of this report.

3.2.1 Project public reports

Dissemination of projects results by making deliverables publicly available is regarded as one of the most important means to publish results. For that reason almost all technical deliverable reports are either marked as public or a public version for download from the website is generated. Table 3 gives an overview of the public documents.

Table 3 THORAX reports available from www.thorax-project.eu

No.	Deliverable title	Nature	Diss. level	Del. date
1.1	Report on the differences between crash test results and real-world accident outcomes in terms of injury mechanisms and occupant characteristics. Recommendations for WP2 and WP3 for prioritising	R	PU	M9

	improvement of the test tool or improving injury risk functions for the different occupant groups identified as most at risk.			
1.2	Estimate of injury reduction potential for different occupant sizes and ages, and total benefit expected to arise from the project.	R	PU	M14
2.1	Definition of biomechanical requirements for enhanced shoulder thorax complex for different sizes and ages	R	PP	M12, M30
2.2	Recommended test procedures for the evaluation of these test devices	R	PP	M32
2.3	Set of injury risk curves for different sizes and ages	R	PP	M38
2.4	Definition of injury mechanism and related physical parameters based on datasets from PMHS tests and advanced HBM simulation	R	PP	M12, M30
2.5	Dummy concept specifications	R	PP	M12
3.1	Design specification for demonstrator development (public domain report)	R	PU	M14
3.2	Dummy certification document (report)	R	PU	M36
3.3	Dummy validation report (public domain report)	R	PU	M38
3.4	Validated demonstrator dummy with improved upper torso complex (three hardware dummies).	D	PP	M38
4.1	Report on the defined load cases and performance criteria, test Matrix	R	PU	M38
4.2	Report with first preliminary dummy test experience	R	PU	M41
4.3	Report on test performance of dummy prototypes	R	PU	M51

3.2.2 Project flyers and newsletters

To bring the THORAX project results under the attention of the automotive community flyers and newsletter were prepared during the runtime of the project. These were distributed via the COVER Coordination and Support Action together with information from other projects in the field of biomechanics for crash safety. A first flyer publication was developed in M6 containing a brief overview of the project main goals, the technical approach, the expected achievements, a list of project participants and interrelations with the other projects under the COVER CSA. Next to this main results and findings were published on an annual basis via the COVER Newsletters. All flyers and newsletters were distributed via a dissemination database assembled during the first year in the COVER CSA, the THORAX and COVER websites as well as partner websites.

Fig. 42 Examples info in THORAX flyer / Newsletters: pages from the 2nd COVER newsletter published December 2011. Note that the COVER newsletter also include info from other projects in the field of Biomechanics like THOMO, EPOCh and CASPER.

Technical Advisory Group meetings

The THORAX project organises annual advisory group meetings to inform and collect advice from external stakeholders. Representatives from EEVC, NHTSA (US Department for Transport), University of Virginia, Japanese Automotive Manufacturing Association (JAMA), Japanese Automotive Research Institute (JARI), Department for Transport (UK) are involved. The meetings were mostly organised in conjunction with the IRCOBI conference to facilitate participants to join the meeting. During the meeting project results were forwarded to key stakeholders involved in rulemaking and consumer testing. Discussions focussed on harmonisation of dummy designs in the different regions. The TAG meetings in principle were the only means for this as no groups on the THOR dummy existed under GRSP or other bodies. Key success is the adoption of the SD3 shoulder by NHTSA for further evaluation in 2013. Also extensive exchanges were organised on the risk curve developments, dummy position procedure and other items.

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Fig. 43 Impression of THORAX Technical Advisory Group meeting September 2011 – Dublin. Attendees from US, Japan and EU project partners

3.2.3 Public workshops

In cooperation with COVER WP2 activities two public workshops were organised. Both were linked to the IRCOBI conference to facilitate participation by a wide audience. During the workshops results of THORAX and THOMO were presented.

The first workshop was held in conjunction with the 2010 IRCOBI conference. It was joined by more than 50 participants from industry, governments, research groups and academia world-wide. The agenda included short introductions to COVER, THORAX and THOMO followed by detailed technical presentations on the PMHS testing, development of injury mechanisms including studies on the influence of the chest geometry (user diversity factor), human body modelling activities (also input from other projects outside THORAX and THOMO).

The final workshop from THORAX / THOMO on thoracic injuries was organised as a special session of the 2012 IRCOBI conference. The session was held at the Friday 14th of September and chaired by Mr Stephen Ridella, Director - Office of Vehicle Crashworthiness Research from NHTSA. In his position Mr. Ridella is responsible for the Biomechnaics research activities by NHTSA. The workshop was joined by about 80 participants from industry, governments and research groups world-wide. Results of THORAX and THOMO were presented in the form of reviewed papers in the IRCOBI proceedings as well as presentations during the workshop. In addition to the input from both the EU FP7 projects information from projects in the US was provided by speakers from that region.

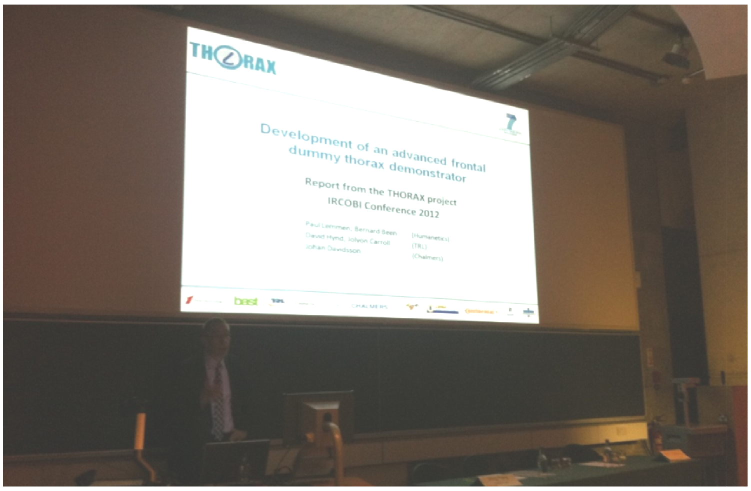

Fig. 44 Impression of THORAX Final Workshop (Dublin-2012)

3.2.4 Participation and/or Organisation of Events

GRSP Informal Group on Frontal Impacts and Euro NCAP

The GRSP Informal Group on Frontal Impacts is redefining the European Frontal Directive on frontal impacts (96/79/EC) that became effective in October 1998. Various THORAX partners are participating in the meeting, forwarding results and findings. Presentation of accident surveys from THORAX and COVER in the April 2010 meeting showed the relevance of user diversity in frontal crash tests. Based on this information the Informal Group is now proposing the introduction of a female dummy in front seats of future test procedures. The THOR dummy introduction is on the list for a second phase[36].

The same is true for Euro NCAP which is in the process of defining new protocols for the 2015 timeframe. Euro NCAP meanwhile has decided to introduce the HIII 5^{th} percentile dummy representing small females in frontal crash tests for these future protocols.

COVER Coordination and Support Action

COVER (Coordination of Vehicle and Road Safety Initiatives) is a Cooperation Support Action under the 7th framework which was meant to bring together a number of initiatives dealing with biomechanics in car crashes. See Fig. 45. The involved projects included CASPER (Medium Scale Project dealing with child safety), EPOCh (Medium Scale project dealing with the development of a Q10 / Q12 dummy) and THOMO (Medium scale project dealing with the development of human body models). These projects covered a broad range of research topics in the field of biomechanics addressing the development of numerical and experimental tools for the design and evaluation of vehicle safety systems. As depicted in Fig. 45 various age groups are considered. Under the implementation of COVER joined dissemination activities were organised and cooperation between the different projects arranged. This included for instance the joined accident surveys for THORAX and THOMO into priorities of rib injuries. Also joined THORAX and THOMO workshops were organised as described above.

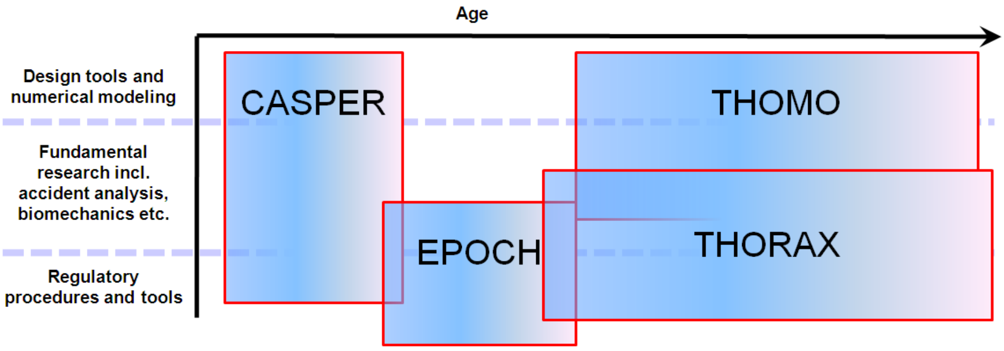

Fig. 45 FP7 Biomechanics projects in COVER

Part of the COVER dissemination activities included the collection of main research findings on thoracic injuries from THORAX and THOMO into an overview report[38]. This COVER deliverable report gives a full status overview of biomechanical know-how on thoracic injuries, tools and methods developed in the projects. The information is largely coming from (reviewed) papers presented at key conferences like IRCOBI. The report became available April 2013.

NHTSA and other Workshops

In addition to the Technical Advisory Group meetings various workshops between technical experts in the US, Japan and Europe were organised to discuss progress and results on THOR dummy developments. Examples include:

1) NHTSA Workshop on Biomechanics 2010 on Thoracic Injuries. The NHTSA Biomechanical Workshop is an annual event preceding the STAPP conference. It is attended by about 100 representatives mainly from industry and governments from the different regions. In 2010 the workshop was related to thoracic injuries and THOR dummy developments. During this workshop the THORAX status and plans were presented. In total four presentations from the THORAX project were provided.
2) THOR Dummy seating procedure. In October 2012 a seating workshop was organized at BMW. This workshop should give the reference for positioning the dummy in the THORAX WP4 testing. The workshop was joined via WebEx by members form JAMA / JARI (both Japan) and VRTC/ NHTSA / UVa (all US) providing input and experience

[38] Lemmen, P., Trosseille, X., Baudrit, P., Carroll, J.. Report on Thoracic Injuries. *COVER project GA No. 218740, Deliverable D24.*

on the seating of the THOR dummy previously gained in projects / activities in Japan and the US. The exercise resulted in a seating procedure as included in THORAX D4.2. The procedure will be forwarded to the SAE group in the US for adoption.

3) NHTSA workshop on THOR dummy developments 2012. During the 2012 STAPP conference NHTSA organised a THOR dummy workshop presenting the developments ongoing world-wide. As for the 2010 Biomechanical workshop a full update and forecast of the THORAX activities was presented to an audience of about 40 participants (largely from the US car industry).

4) In addition to the final workshop organised under COVER and the STAPP event it was decided to have a special event forwarding the final THORAX results to OEM's and suppliers. On April 25, following the final General Assembly meeting, a workshop open to the public was organised at BASt in Bergisch Gladbach. An audience of about 80 persons was informed on the results for the Injury Risk Curves (WP2), the biofidelity evaluations of the demonstrator (WP3) and the application of the demonstrator and the risk curves in sled tests (WP4).

ISO frontal dummy corridors

During the entire projects THORAX partners contributed to the ISO discussions on development of frontal dummy corridors. This ISO group was coordinated by CEESAR which is closely linked to the THORAX partner Gie Re Pr. Proposed corridors for impactor tests were used as design target for the thorax – shoulder demonstrator.

3.2.5 Conference and Journal Papers

During the runtime of the project papers were presented at key conferences in the field of vehicle safety like IRCOBI, SAE Government Industry Meetings, and TRA conference. Amongst others the following conference and journal papers were published:

[1] Carroll, J., Adolph, T., Chauvel, C., Labrousse, M., Trosseille, X, Pastor, C., Eggers, A., Smith, S., Hynd, D.. Overview of serious thorax injuries in European frontal car crash accidents and implications for crash test dummy development. *IRCOBI 2010 proceedings*.

[2] Lemmen, P., Been, B., Carroll, J., Hynd, D., Davidsson, J., Lecuyer, E., Song, E.. Development of an advanced frontal dummy thorax demonstrator. *IRCOBI 2012 proceedings*.

[3] Brolin, K., Mendoza-Vazquez, M., Song, E., Lecuyer, E., Davidsson, J.. Design implications for improving an anthropomorphic test device based on human body simulations. *IRCOBI 2012 proceedings*.

[4] Lemmen, P., Been, B., Carroll, J., Hynd, D., Davidsson, J., Lecuyer, E., Song, E.. Thoracic injury assessment for improved vehicle safety. *Transport Research Arena 2012 proceedings.*

[5] Lemmen, P., Been, B., Carroll, J., Hynd, D., Davidsson, J., Lecuyer, E., Song, E.. Development of an advanced thorax / shoulder complex for the THOR dummy. *SIAT 2013 proceedings (SAE International publication)*.

[6] Lemmen, P., Hynd, D., Carroll, J., Davidsson, J.. Thoracic Injury Assessment for Improved Vehicle Safety, *SAE Government Industry Proceedings 2012.*

[7] Lemmen, P., et. al. An Advanced Thorax-Shoulder design for the THOR dummy. *ESV paper 13-0171.*

3.2.6 Planned dissemination plan for the period after the project's runtime (2012-2016)

An overview of intended dissemination activities by project partners for 2013 – 2016 is provided below.

2013 – 2016 Present results of research activities as follow-up at international conferences, e.g. ESV 2013 and through the project's website:
Results on the dummy performance, it's sensitivity to restraint systems and injury risk curves are planned to be presented at leading conferences in the field of vehicle safety. Abstracts and papers were submitted for the 2013 ESV conference.

2012 – 2016 Demonstration activities at end-user level to gain acceptance of the new technology. Partially this is performed in the THORAX project itself (WP4). After the project the demonstrator dummies will remain available for use by the EU industry and research group to generate input for GRSP IG on Frontal Impacts

2013 – 2014 Continued presentation of the research activities to relevant stakeholder groups in Europe other regions of the world. This includes presentations to the GRSP Informal Group on Frontal Impacts as well as to Euro NCAP and NHTSA.

2013 - 2017 Implementation of the research themes developed within THORAX in undergraduate and post-graduate classes to prepare the next generation of engineers and R&D personnel. Partners here are Chalmers, IFSTTAR, UPM and UVA.

3.3 Exploitation of results

The main future area of exploitation of this pre-competitive research project is the development of safer vehicles[39]. This concerns passive and integrated vehicle safety systems. This product innovation will take place at the automotive companies and suppliers, being the end-users of the project results. Although this product development itself is not a part of this research programme, but the knowledge and tools developed in THORAX project are essential to improve vehicle safety and design new systems: Improving passive safety requires a clear understanding on human behaviour, the typical injuries sustained under (frontal) impact loadings and their causation. To be able to judge the effectiveness of a design or restraint system, tools (=human body model and crash test dummies) are needed that shows realistic, humanlike responses and that provide engineers with accurate information on the direction (how and how much) these systems should be improved. A computer model (=human body model) is a crucial tool to help understand cause and effect in terms of injuries and the influence of various design parameters in this process. The injury risk curves provide the manufacturers with a direct relationship between dummy responses and the protection offered.

Hence, the research organisations in this project like TRL, BASt, INSIA and INRETS will use the knowledge and tools achieved in this project in supporting industrial companies in designing safer vehicles (technology transfer) and advising governments, while the industrial partners like Autoliv, CSE, PDB and Gie Re Pr bring in their day-to-day experience and assess the value of the developed tools for their needs. The resulting crash dummy components from this project will be exploited by Humanetics. The computer models of the human body in this project will be exploited by Chalmers, Gie Re Pr, and INRETS and the developing participants.

[39] Lemmen, P. (2013). Final version of the exploitation plan in conformity with Commission's guidelines. *THORAX project GA No. 218516, Deliverable D4.5.*

An approximate estimate of an exploitation of results is follows[39]:

- 2008 – 2013: Realisation of numerical and experimental tools for usage in the design and evaluation of frontal restraint systems, steps as designed in the project plan
- 2012 – 2014: Suppliers and OEM partners review the results and findings of THORAX and related projects world-wide, to integrate the resulting product requirements into the new product plans for the premium segments
- 2012 – 2014: Completion of harmonised frontal impact dummies based on latest biomechanical insight, through close cooperation with NHTSA. It is expected that the average male is considered first and subsequently the small female
- 2014 – 2019: Implementation of harmonised frontal impact dummy in EU and US frontal impact directives. This will be realised via THORAX participants that support national governments in developing procedures
- 2010 – 2014: Implement know-how in harmonised human body models, considering relevant biometrics (age, gender and size)
- 2012 on: Suppliers and OEM's develop restraint products and advanced vehicle safety systems based on new design and assessment tools for mass production launch

4 Website and contact details

4.1 Website

The project public website has been set up for the general public and can be found at the web address: www.thorax-project.eu The website provides general information on the project objectives and the work to be performed as well as details of the project partners, and contact details for the project coordinator. It includes a password protected section with access restricted to partners only. The website will be accessible for 4 years after the project is closed. Public deliverable reports and other open project documentation will be available via the website to the public during this period. Confidential reports will remain available to partners via the restricted part.

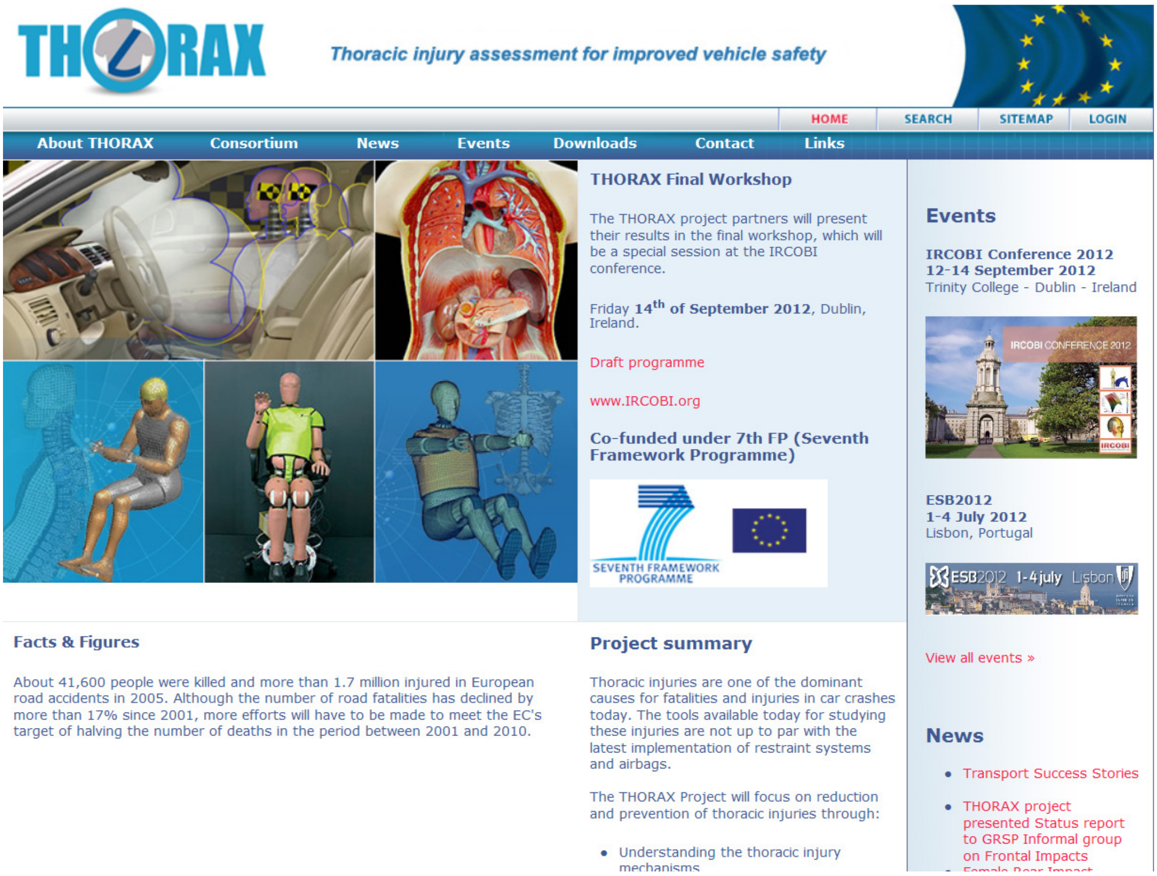

Fig. 46 Screenshot of THORAX project website accessible under www.thorax-project.eu

4.2 Contact persons

Technical coordinator:
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Linnewever 12
2292 JH Wateringen
The Netherlands
Mr Paul Lemmen
e-mail: plemmen@humanetics.eu
Tel: +31 6 227 56 277

5 List of project participants

Partner no.	Participant organisation name	Short name	Country
1 Co.	First Technology Safety Systems[1)]	FTSS	NL
1 Co.	Humanetics Europe GmbH	HUMAN	DE
2	Autoliv Research	Autoliv	SE
3	Bundesanstalt für Straßenwesen	BASt	DE
4	Chalmers university of technology	Chalmers	SE
5	Groupement d'Intérêt Economique de Recherches et Etudes PSA-RENAULT	GIE RE PR	FR
7	Partnership for Dummy Technology and Biomechanics	PDB	DE
8	Continental Safety Engineering International GmbH	CSE	DE
10	Uniresearch BV	UNI	NL
11	Universidad Politécnica de Madrid	UPM	ES
13	French institute of science and technology for transport, development and networks	IFSTTAR	FR
14	Transport Research Lab.	TRL	UK

[1)] In Jan 2011 FTSS Europe BV was declared bankrupt. EU FP7 research activities were transferred to Humanetics Europe GmbH as described in Amendment II of the THORAX project.