AN ADVANCED THORAX-SHOULDER DESIGN FOR THE THOR DUMMY

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ABSTRACT

Thoracic injuries are one of the main causes of fatally and severely injured casualties in car crashes. Advances in restraint system technology and airbags may be needed to address this problem; however, the crash test dummies available today for studying these injuries have limitations that prevent them from being able to demonstrate the benefits of such innovations. THORAX-FP7 was a collaborative medium scale project under the European Seventh Framework. It focused on the mitigation and prevention of thoracic injuries through an improved understanding of the thoracic injury mechanisms and the implementation of this understanding in an updated design for the thorax-shoulder complex of the THOR dummy. The updated dummy should enable the design and evaluation of advanced restraint systems for a wide variety (gender, age and size) of car occupants.

The hardware development involved five steps: 1) Identification of the dominant thoracic injury types from field data, 2) Specification of biomechanical requirements, 3) Identification of injury parameters and necessary instrumentation, 4) Dummy hardware development and 5) Evaluation of the demonstrator dummy.

The activities resulted in the definition of new biofidelity and instrumentation requirements for an updated thorax-shoulder complex. Prototype versions were realised and implemented in three THOR dummies for biomechanical evaluation testing. This paper documents the hardware developments and biomechanical evaluation testing carried out.

INTRODUCTION

Data from the European Road Safety Observatory show that around 31,000 people were killed and more than 1.4 million injured in European road accidents in 2010 [1]. Although these figures continue the decline in road casualties observed since 20001, further efforts are needed to make European roads safer. In support of this the EU 7th Framework project THORAX (Thoracic injury assessment for improved vehicle safety) focused on reduction and prevention of thoracic trauma. As depicted in Figure 1, thoracic injuries are one of the leading causes of severe injuries and fatalities in car crashes.

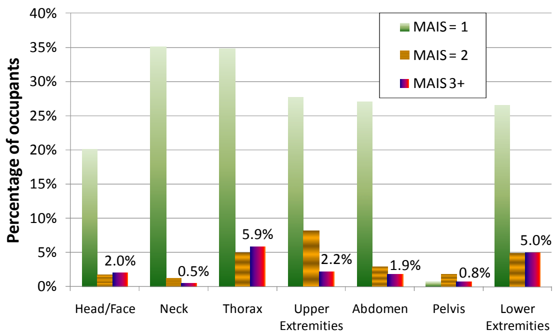

Figure 1 –MAIS injury level per body region (CCIS frontal impact sample n = 2,148 occupants) [2].

The THORAX consortium consisted of car manufacturers, suppliers, research groups and universities with wide experience in impact biomechanics. The main objectives of the project were:

- Identification of the two most relevant thoracic injury types for car occupants in view of societal relevance;
- Development of a mechanical demonstrator consisting of a new dummy thorax and shoulder design for the THOR NT dummy;
- Derivation of injury risk functions;
- Evaluation of the sensitivity of the demonstrator to modern vehicle safety systems.

This paper presents the demonstrator dummies developed including the biofidelity evaluations. The paper starts with a short summary of accident surveys and biomechanical studies which provided requirements for the dummy design.

BACKGROUND INFORMATION TO THE DESIGN

Outcome from accident surveys

Accident data were studied 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 reported in detail in [3], [4], [5] and [6]. The data analysis showed that at the AIS ≥ 2 severity level, thoracic fractures are the torso injuries that occur most frequently. These 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.

Biomechanical requirements definition

To ensure that a crash test dummy loads the vehicle and restraint system in a similar way to the human, biofidelity requirements are used to specify the dummy performance. In addition, these requirements are used to ensure that the response of the dummy to restraint system loading is relevant to be used in the prediction of injury risk in simulated crashes. Biofidelity requirements may be derived from human volunteer, PMHS (post-mortem human subject), or animal tests and the test conditions should be representative of real-world accidents.

As no full set of requirements and related biofidelity rating system was available for frontal impact dummies the THORAX project conducted an in-depth literature review to identify all available PMHS datasets relevant for frontal impacts. Criteria were developed for inclusion or exclusion of PMHS tests. When feasible, data were processed to account for differences in mass and age of the subjects. The test conditions for biomechanical evaluations included pendulum impactor, table top, static airbag and belt tests, quasi static volunteer shoulder tests and various sled tests. To ensure good performance under various loading conditions a much broader set of requirements was proposed when compared with those from the EEVC and NHTSA. The results of the literature review have been reported in [7]. The report includes a detailed description of each test configuration allowing for reproduction of the tests with the THOR dummy.

Injury criteria and dummy instrumentation

A study into injury criteria and risk curves that are independent of experimental parameters such as the apportionment of seatbelt and airbag loading was performed using a validated Human Body Model [8], [9]. The model was submitted to a wide range of loading types: impactor, static airbag, belt only restraint, airbag only restraint and combined belt and airbag restraint. For each loading type different severities were applied to generate different levels of rib fracture: from the absence of fractures to numerous fractured ribs. From these studies rib bending was identified as being the main loading resulting in fracture as opposed to torsion. Two injury criteria representing this pattern were formulated. The first one, called the Combined Deflection (Dc) criterion, uses chest displacements at four locations to compute overall and differential deflections resulting in bending strains. The second criterion, called Number of Fractured Ribs (NFR), uses locally measured strains at individual ribs to identify those ribs for which the bending strains at any location has exceeded a critical value. The Dc criterion requires displacement to be measured at four locations in the chest while the NFR requires local strains to be measured at individual ribs.

SHOULDER / THORAX DESIGN

Based on the findings of the accident surveys and the outcome of the biomechanical work a demonstrator dummy was designed. Extensive design and prototyping efforts were made to realise three demonstrator prototypes for evaluation testing and restraint sensitivity testing [10]. The main focus was on the updates to the SD2 shoulder, rib response tuning to corridors and the implementation of instrumentation to capture information for newly proposed injury criteria.

Shoulder and arm design

Various updates were made to the THOR SD2 shoulder which was originally developed by Törnvall [11]. The sterno-clavicular joint was redesigned to meet anthropometry requirements for the 50th percentile male described in [12]. The original SD2 design did not meet the anthropometric target position of ±20 mm lateral from mid saggital plane (it was ±44 mm).

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

The THOR dummy had Hybrid III arms which did not match the anthropometry requirements in [12]. Moreover the arms were not well integrated in the SD2 shoulder design. To correct these discrepancies, a new upper arm was developed which is compatible with the shoulder design and meets the anthropometric targets. The new design includes load measurement capabilities at the middle of the humerus using a WorldSID 50th loadcell.

Finally, clavicle load cells were implemented in the updated shoulder design. Two-channel load cells can be installed at both ends of the clavicles to measure force in the forward and vertical directions.

The updated shoulder-arm design is shown in Figure 2 through Figure 4. It is being referred to as the SD3 shoulder.

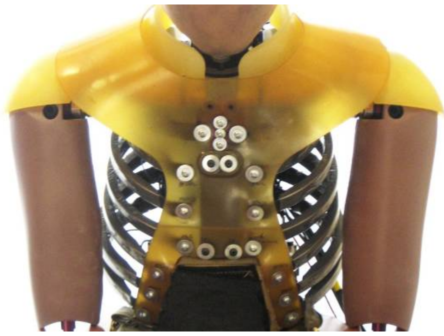

Figure 2 – SD3 shoulder and arms installed on demonstrator dummy.

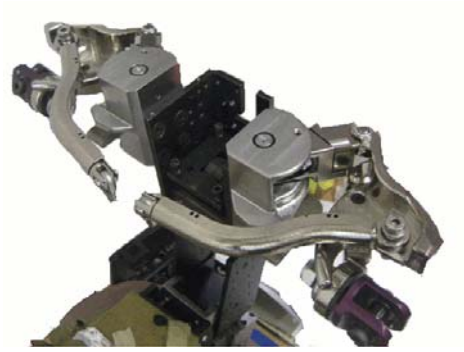

Figure 3 – The pivot mechanism.

Figure 4 – Updated arm design (flesh not shown).

Rib cage response tuning

To optimise the thorax response the sensitivity to rib stiffness and damping behaviour were investigated in pendulum impactor tests [9], [10]. The rib stiffness was gradually reduced first by damping thickness reduction, then by stepwise cutting the height of the metal. On this basis an optimal response with respect to the NHTSA (Kroell) biofidelity corridors was pursued as starting point for further biofidelity evaluations. Based on the outcome 3 rib sets were produced with 1.6 mm rib metal and 9 mm damping material gauge. An additional 6 mm foam pad was added inside the front jacket to increase damping and, to a small amount, the external deflections. In a first evaluation the demonstrator dummies were subjected to frontal and oblique pendulum impactor tests (see Figure 5). Figure 6 shows responses from frontal pendulum impact tests for three dummies plotted against corridors based on Kroell [13]. The peak pendulum force is exceeded by less than half the corridor width and the peak compression is close to the mean. Some variability between the dummies is observed due to differences in the configuration of the demonstrator dummies as described below. Figure 7 shows the performance for oblique lower rib impact tests (15° about a vertical axis) and the NHTSA certification requirements for peak force and peak compression [14]. One dummy is inside the requirement while the other slightly exceededs the peak compression. This was considered close enough to the corridor to proceed with biofidelity evaluation.

Instrumentation

In conjunction with the injury criteria proposed, four 3D IR-Traccs in the thorax were adopted from the THOR mod-kit [15]. The IR-Traccs provide the required input to be used in calculating the Dc criterion. As input to the NFR criterion two of the demonstrator dummies were equipped with a total of 72 strain gauges on the ribs (see Figure 8). The gauges are implemented such that the influence on the chest dynamic response is negligible. From the second rib down, all six lower ribs have six strain gauges on both sides equally spaced in ratio to the length of the ribs.

THORAX demonstrators

Three demonstrators were built based on THOR donor dummies provided by THORAX partners IFSTTAR, Autoliv and TRL. All three included tuned rib sets, modified jackets and SD3 shoulders. The Autoliv and TRL dummies also included the Pelvis-Femur-Knee Mod Kit described in [15].

Figure 5 – Dummy in frontal and oblique pendulum impact test set-up (Jacket removed for photo).

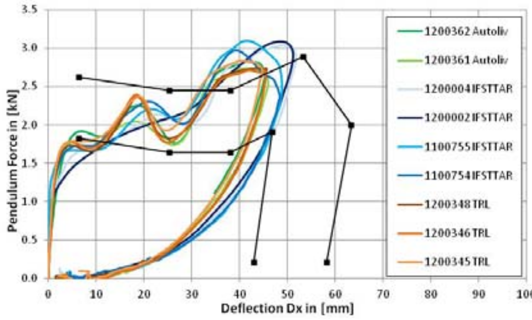

Figure 6 – Response for three THORAX demo dummies in frontal 4.3 m/s pendulum impact tests.

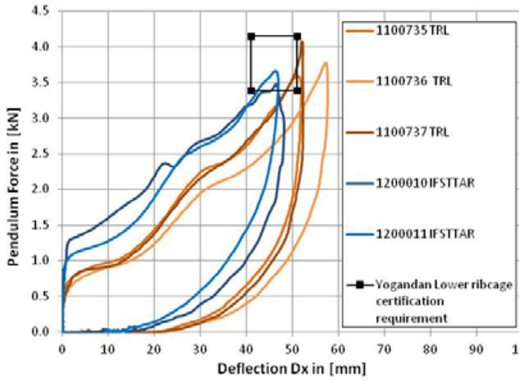

Figure 7 – Results for two THORAX demo dummies in oblique pendulum impact tests.

Figure 8 – Example of rib with gauges.

BIOMECHANICAL EVALUATION

In 2009, ISO/TC22/SC12 Working Group 5 started an effort defining frontal impact biofidelity targets in a world-wide expert group. The ISO Task Force led by ACEA and CEESAR contributed a literature review and also defined selection criteria to find biofidelity test configurations. In the end, the work focused on three test configurations and biofidelity targets were proposed by ACEA-TFD and CEESAR and released by Lebarbé and Petit [16], [17]. Their current proposal for biofidelity targets is being reviewed by ISO WG5, with a draft Technical Report under revision. Acknowledging this effort and previous evaluation proposals by EEVC and NHTSA, the THORAX project sought further test conditions under which an advanced dummy thorax could be evaluated. In view of this the THORAX project considered a wide set of test conditions for the biomechanical evaluation of the demonstrator dummies [7]:

- Pendulum impactor (Lebarbé [17], Yoganandan [14]).
- Table top (Cesari & Bouquet [18], Kent [19]).
- Quasi static volunteer shoulder tests.
- Sled tests (Forman [20], Bolton [21], Shaw [22]).

In most cases matching tests with a Hybrid III and / or baseline THOR dummy were included. Where previous tests had been performed with one of those dummies, this was used to give confidence to the accuracy of the testing set-up. It also allowed analysis of the relative dummy performance.

Thorax pendulum tests

Pendulum impactor tests replicating the Kroell frontal sternum and Yoganandan oblique lower rib tests, were evaluated against corridors defined by Lebarbé [17] and, for the oblique impacts, by the THORAX project itself based on Yoganandan pendulum tests.
The requirements for the frontal sternum impacts were developed as part of the ACEA-TFD support of ISO Working Group 5. They define an external (surface of the chest) deflection measurement. As this can not be measured with the IR-Traccs inside the thorax the pendulum penetration was recorded with High Speed Video analysis. 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 (see Figure 5). For the Yoganandan tests the pendulum was lined with 19 mm Rubatex foam, as specified.
Results for the upper thorax impact tests are given in Figure 9. The peak penetration in these tests was between 67 and 72 mm. The response is in fairly good correlation with corridors defined by Lebarbé [17]. 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. In THORAX [7] the orginal Yoganandan [14] data was reanalysed 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 deflection seen in the original tests,

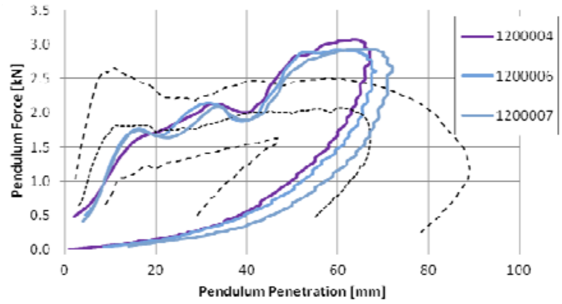

Figure 9 – Results Pendulum Force versus Pendulum Penetration. Corridors from Lebarbe [17].

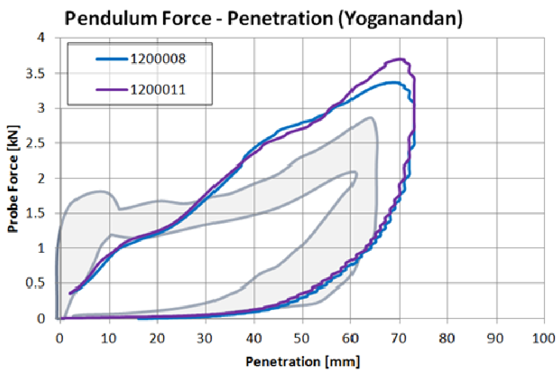

Figure 10 - Pendulum force – penetration for oblique impact tests on lower thorax. Normalised PMHS responses grey shaded [7].

and corridors are narrow at peak deflection. Figure 10 shows resulting corridors and the 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 [18] and previous authors. For this purpose a replica of the table-top rig as described in [18] 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

Figure 11 – Image of table top set-up with THOR-NT

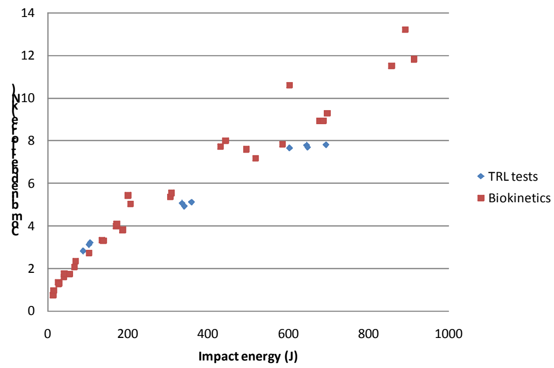

Figure 12 – Comparison of belt force for original set-up (red dots) and replica (blue dots) using Hybrid III [23].

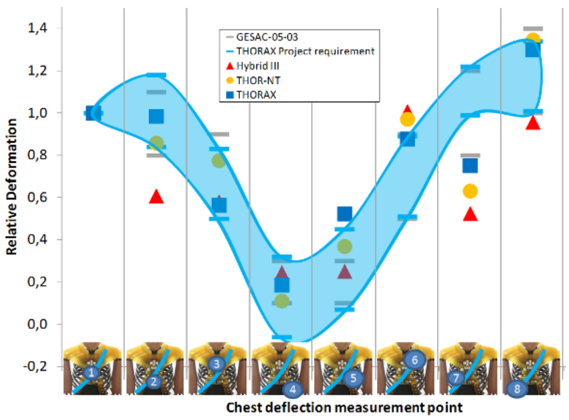

Figure 13 – Relative deflections for Hybrid III, THOR NT and THORAX demonstrator with SD3 in comparison to corridor from PMHS data.

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 Figure 12). 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 Figure 13. 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.

Kent *et al.* table top tests

In addition to the Cesari and Bouquet tests the THORAX demonstrator was subjected to table-top conditions described in [19]. 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 conditons 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 positoned 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

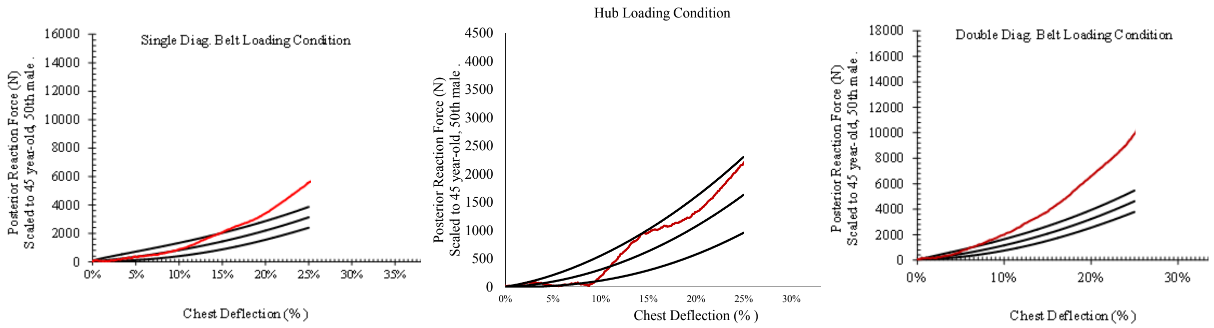

Figure 14 – Force deflection data for the THORAX demonstrator compare with the characteristic average and corridors of the PMHS for hub (left), single (middle) and double (right) diagonal belt. PMHS corridors are scaled to a 45 year-old, 50th percentile male.

chest deflection at a rate similar to the rate applied on the PMHS chest. 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 Figure 14). 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.

Quasi static volunteer shoulder tests

In the Thorax project a test rig for evaluation of the human shoulder stiffness was developed (see Figure 15). 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

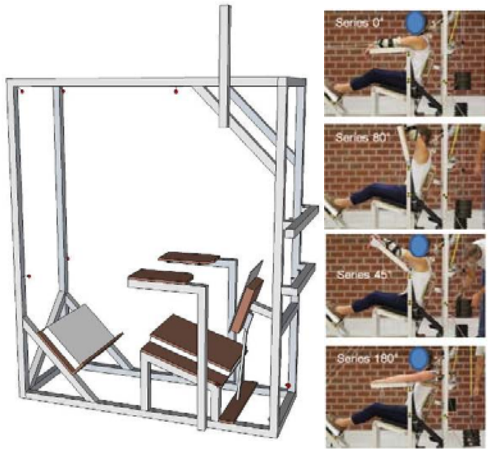

Figure 15 – Test rig used for shoulder stiffness tests

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 [24]. 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 [11] 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 (Figure 16). 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 (Figure 16). For this loading condition the THORAX demonstrator exhibited 22 mm rearward motion whereas the average volunteer exhibited 47 mm.

Forman and Bolton sled tests

To replicate PMHS sled test configurations reported by Forman *et al.* [20] and Bolton *et al.* [21] a sled rig was developed (see Figure 17). The rig consists of a stiffened Ford Taurus buck equipped with airbags,

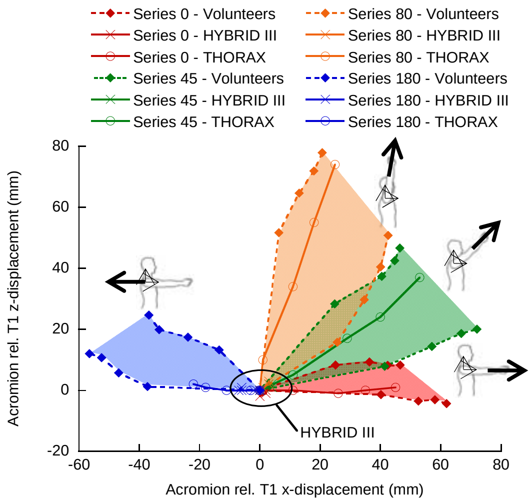

Figure 16 – THORAX project shoulder response corridors, Hybrid III and THORAX displacements in four loading directions.

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 [25]. 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

Figure 17 – General view of the sled rig.

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.

Furthermore, the kinematics behavior 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 Figure 18 to Figure 20. 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.

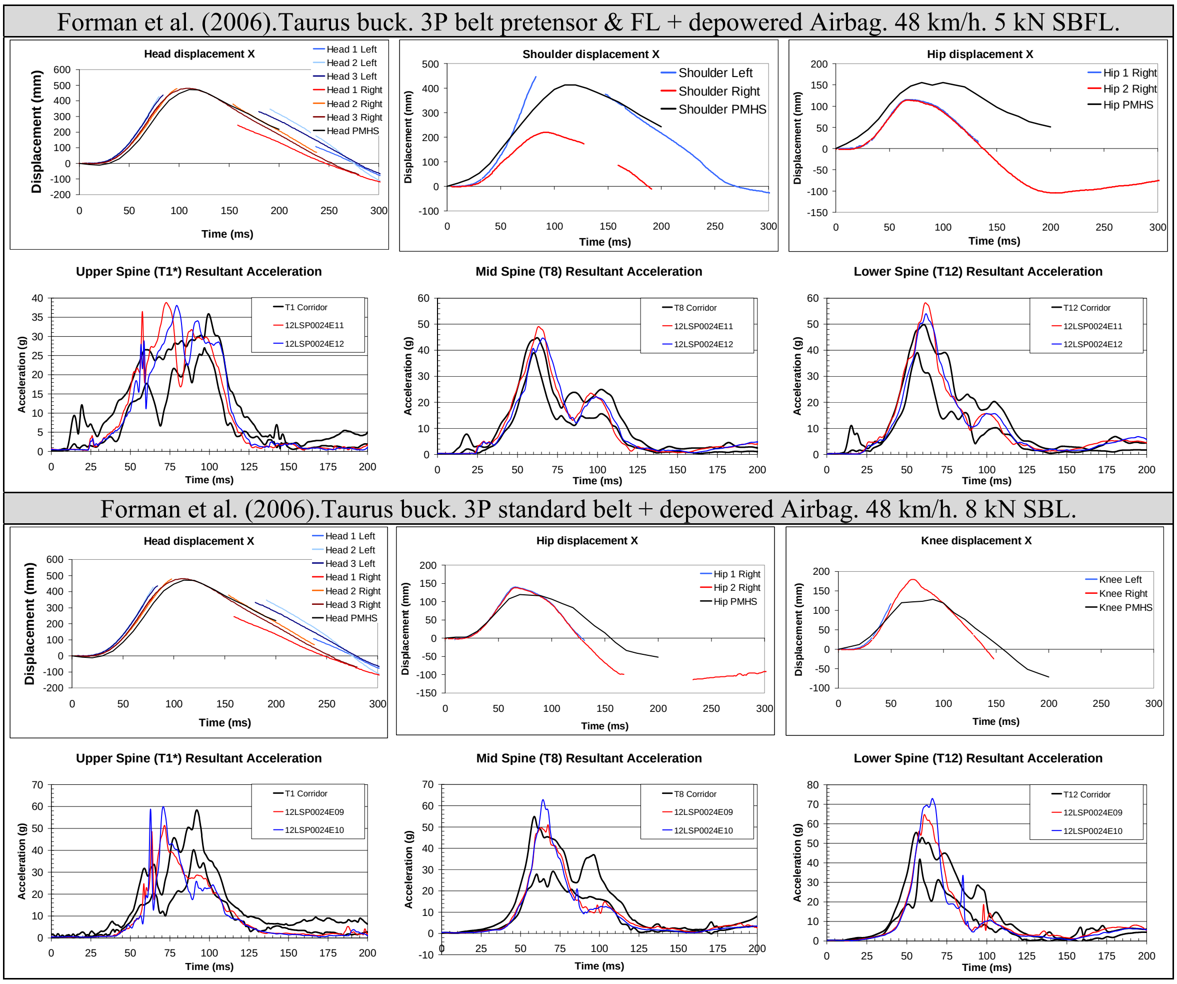

Figure 18 – Head, T1 and hip x-displacements; upper spine, mid spine and lower spine resultant accelerations for tests with 2 point belt and full powered airbag (top rows) by Bolton et al. [21] *and tests with 3 point belt without airbag (bottom rows) by Forman et al. et al.* [20].

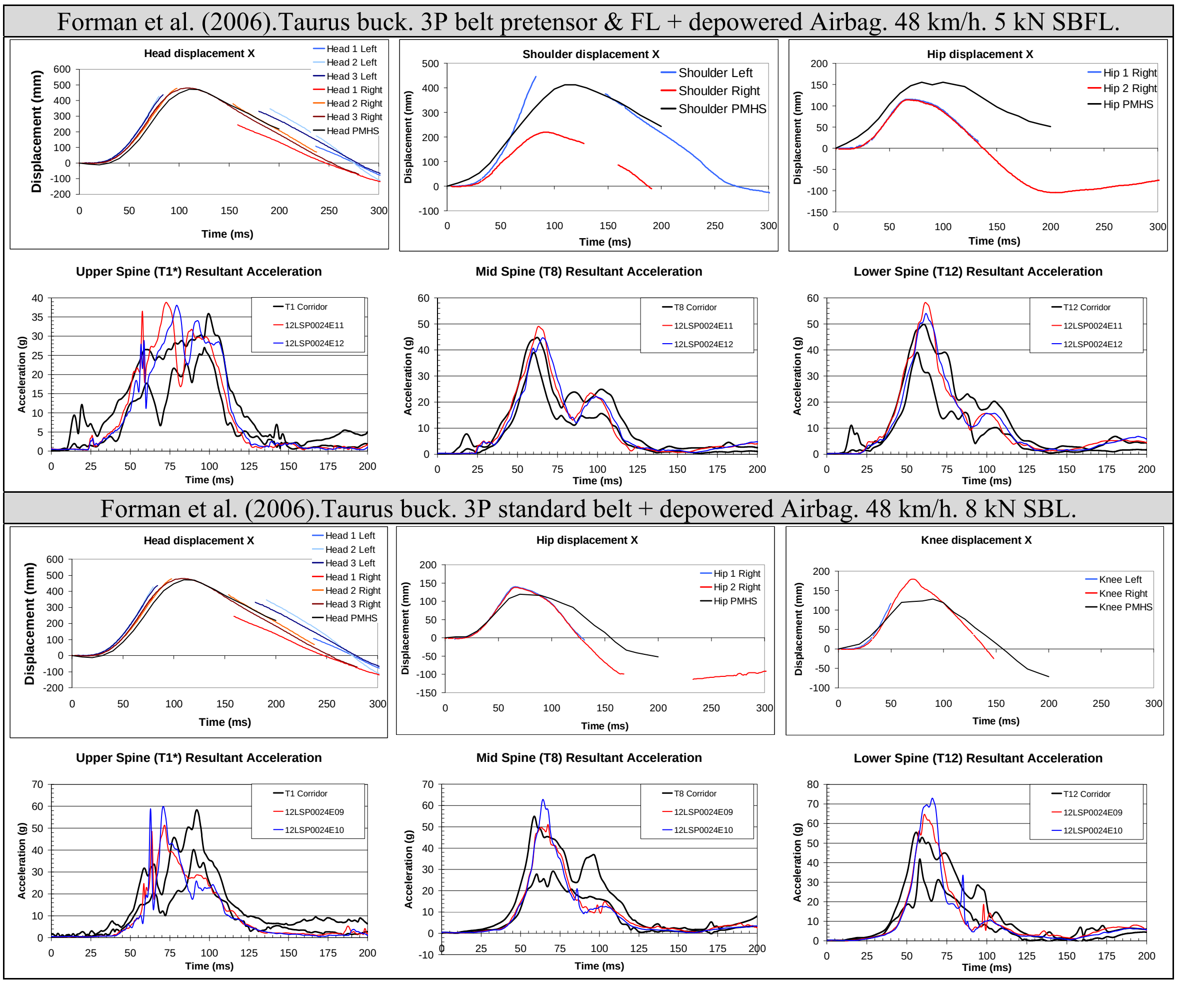

Figure 19 – Head, T1 and hip x-displacements; upper spine, mid spine and lower spine resultant accelerations for tests with 3-point force limiting belt (5 kN) and de-powered airbag (top rows) and tests with 3-point standard belt no-force limitation (maximum shoulder belt load of 8 kN) with de-powered airbag by Forman et al.[20].

	2P belt + Full-powered Airbag			3P belt pretensor & FL + depowered Airbag				
	THOR	PMHS	THOR	THOR	PMHS			THOR
	Right	Sternum	Left	Right	Right	Sternum	Left	Left
Upper	-12.2%	-11.0%	-11.1%	-10.4%	-25.9%	-27.6%	-24.8%	-17.0%
Lower	-4.1% (5.9%)	-	-4.1% (6.3%)	-4.4% (4.3%)	6.2%	-6.9%	-11.5%	-16.3% (1.7%)

	3P standard belt + NO Airbag			3P standard belt + depowered Airbag				
	THOR	PMHS	THOR	THOR	PMHS			THOR
	Right	Sternum	Left	Right	Right	Sternum	Left	Left
Upper	-6.7%	16%	-14.3%	-16.7%	-33.5%	-34.1%	-38.0%	-18.5%
Lower	-5.2% (2.4%)	7%	-13.0% (1.4%)	-6.6% (3.4%)	7.1%	-5.9%	-13.4%	-20.7% (2.7%)

Figure 20 – Comparison of chest x-deflections (as a percentage of the chest depth at measurement location) tests for all four passenger load conditions considered by Forman et al. [20] and *Bolton et al.* [21].

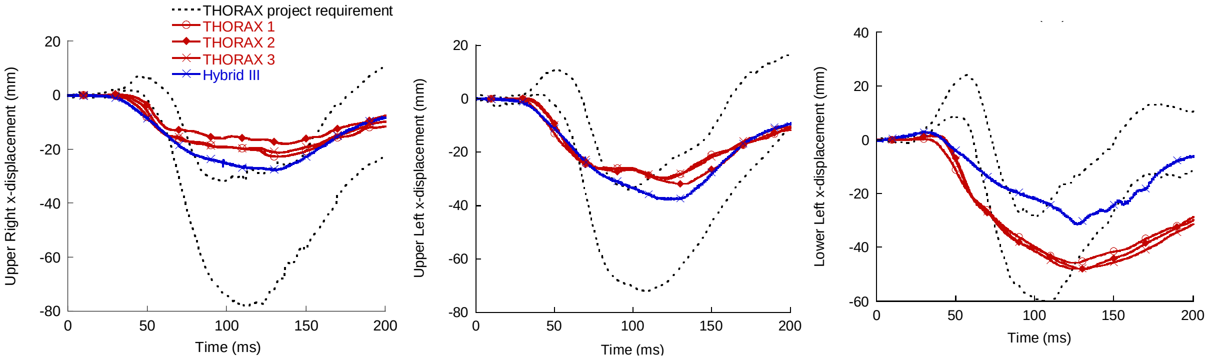

Figure 21 – Chest deformations relative T8 for THORAX demonstrator with SD3, Hybrid III compared with biofidelity target provided by Lebarbé and Petit [17].

- 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 2 to 4 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 behavior of the PMHS.

Gold Standard Shaw *et al.* sled tests

In a sled test series, commonly referred to as the ‘Gold Standard’, by Shaw *et al.* [26] and [27], eight PMHSs were positioned on a rigid planar seat with their torso and head supported 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 PMHSs were subjected to a peak acceleration of 140 m/s^2 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 [26], [27], [17].

The new THORAX demonstrator and Hybrid III dummy were subjected to Gold Standard sled tests using a replica of the original test rig [28]. 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 [12].

THORAX demonstrator upper chest deformations were larger than those of the THOR NT [28] but still lower than the response target (Figure 21). In the tests with the demonstrator dummy slightly larger belt downward sliding was observed compared to the original PMHS tests [27]. 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 PMHSs 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 (Figure 21).

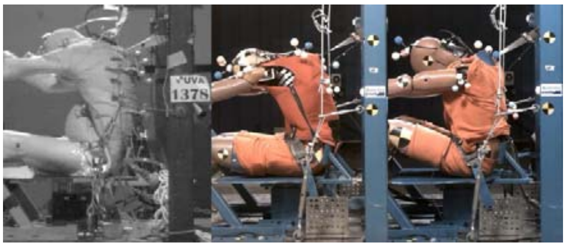

Figure 22 – Stills from high speed video of tests in Gold standard conditions with a respresentative PMHS, THORAX and Hybrid III at 120 ms.

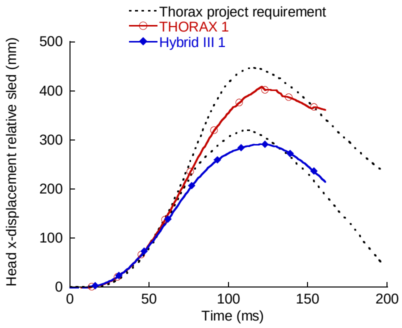

Figure 23 – Head displacement relative sled for THORAX demonstrator and Hybrid III compared with project requirments that were derived from Ash et al. [2012].

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 spine of the demonstrator and the PMHSs (Figure 22); the Hybrid III exhibited smaller head forward displacements than those specified in the project requirements (Figure 23). 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.

DISCUSSION

In the THORAX project a new shoulder-thorax complex to be fitted on the THOR-NT was developed and three demonstrator dummies were updated with this design. The dummies were then evaluated against a broad list of biomechanical requirements for the thorax and shoulder. Those requirements included, but were not limited to those published previously by NHTSA and Lebarbé. In summary the performance of the demonstrator dummies in each test condition was as follows:

1) In pendulum impactor tests generally a reasonable to good correlation between demonstrator dummy responses and corridors was obtained. Peak forces for frontal pendulum tests (Lebarbé) and oblique tests in the lower thorax region (Yoganandan) tended to be higher than the corridors. Penedulum penetration could not be determined accurately, however appeared to be a good match in both conditions.
2) In table-top tests the regional coupling, assessing the influence of loads in one part of the thorax on deflections in another part, was investigated. Comparison of the demonstrator dummy with corridors identified from PMHS table top tests by Cesari and Bouquet revealed that the dummy performs reasonably well compared with other dummies like the Hybrid III. However, slight deviations from the PMHS responses were still observed. Also, in sled tests, it appears that the balance of the upper to the lower measurement point deflections may not be the same as for PMHS. As injury risk development work now considers a combined deflection criterion incorporating the differential deflections from the four measurement points (left-right, top-bottom), it seems important that those efforts consider the biofidelity of the dummy. Implications of the performance of the dummy in terms of regional coupling and stiffness need to be viewed in relation to the injury criterion used.
3) In table-top tests considering the influence of loading condition (Kent), the demonstrator dummy also performed reasonably well. The stiffness of the dummy increased from the hub to the single diagonal belt to the double diagonal belt conditions as for the PMHS. Results were within the force-compression corridors for hub and initially for the diagonal belt loads while being too stiff for the double diagonal belt. This may indicate that the SD3 shoulder or the top of the thorax is too stiff compared to humans under the belt conditions tested. The consequences of this for the behavior in frontal impacts are not clear from this test environment though.
4) Very good correlation was obtained between dummy tests and corridors for the shoulder range of motion tests, matched with a new set of volunteer tests. The human shoulder motions in the forward and/or upward directions are represented well by the dummy including sufficient range. Rearward shoulder motions however, were found to be limited but still

showed a substantial improvement compared with the Hybrid III. The results for rearward shoulder loading with limited motion compared to volunteers might help explain the belt condition performance in the Kent table top tests, but this is to be investigated.

5) In sled tests (Forman, Bolton) representing various restraint conditions the demonstrator dummy generally shows good behaviour. Although, some differences with respect to the PMHS corridors were observed. It is to be noted that reproducing these test conditions is difficult in terms of finding representative test components like airbags, belts and seats. Furthermore for each restraint type only a very limited number of subjects were used to define the corridors. Therefore, the requirements could be biased to the specific subject characteristics and responses, for instance in their interaction with the knee bolster.
6) The gold standard tests were specified to address some of the limitations noted above by selecting subjects with anthropometry close to the average male. Also, the set-up was intended to be easily reproduced in other laboratories. In reproductions of these tests the demonstrator dummy showed improved overall kinematics in terms of head forward displacement and spine rotation and bending in comparison with the Hybrid III. Also the chest deformations were improved when compared to published THOR-NT results. However, the maximum upper right chest deformation was somewhat lower than the project requirements while the upper and lower left maximum deformations were within the required range. The reason for low upper left chest deformation may be due to higher stiffness of the upper ribcage quadrant but may also be due to the first rib-clavicle complex. This was also indicated in the comparisons with volunteer shoulder data, Kent table top test data, table top tests by Cesari and Bouquet and the Forman and Bolton sled test series.

Although for some of the individual test conditions the dummy response deviates from the project requirements, reasonable correlation is obtained over the broad range of conditions considered. Detailed comparison of chest deflections in various conditions indicates that the upper rib - clavicle complex appears stiffer than those of the PMHSs. No specific biomechanical data for this region was available and it is recommended to collect such data in future studies. The demonstrator exhibited differential displacements in upper and lower, as well as left to right thorax regions in line with PMHS data. The Hybrid III dummy also showed differential deflections but too a much lesser extent. These relative deflection components are input to injury criteria proposed in THORAX and regarded as important when distinguishing between different loading conditions. In defining such criteria the relatively stiff response in the upper thorax region should be kept in mind as it reduces dummy displacement readings in this part.

In some cases the lack of correlation could clearly be attributed to specifics of the set-up. As an example differences in kinematics in sled tests could be attributed to knee contact with the bolster which is highly dependent on subject size considered and seating position. This example also illustrates an aspect of certain test conditions which, other than table top and pendulum impactor, suffer from the fact that data for only a limited number of subjects are available. However, if broad evaluation in a variety of test conditions is deemed a priority, than also conditions of small subject count must be included. In this respect it should also be noted that at this stage of the research the comparison of the dummy responses with the biofidelity targets has been a subjective one. It is encouraged that future efforts will incorporate an objective validation of the dummy performance. This will require an approved set of requirements and assessment method, which are not formally available at the time of writing.

During the biofidelity evaluations it became evident that the THORAX demonstrator dummies showed sensitivity of the chest deflection measurements to the different restraint systems or loading devices used. This suggests that the THORAX demonstrator can be valuable as a tool to investigate performance differences between various types of restraint. However, to offer equivalent or comparable risk of injury predictions under localised or distributed loading a criterion which is independent of the restraint system should be used. The potential use of the THORAX demonstrators and injury criterion candidates is being investigated in sled tests using modern restraint systems within the final work package of the THORAX Project.

CONCLUSION

THORAX was a project under the European 7th Framework. Car manufacturers, suppliers, research groups and universities jointly investigated thoracic injury mechanisms and findings were implemented in

design tools meant to enable the design and evaluation of advanced occupant restraint systems.
Following accident surveys and biomechanical studies a new shoulder-thorax complex for the THOR-NT dummy was developed. This included a modified version of the SD shoulder representing realistic range of motion in this body section. 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.

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