Effects of Variations in Belt Geometry, Double Pretensioning and Adaptive Load Limiting on Advanced Chest Measurements of THOR and Hybrid III

Andre Eggers, Burkhard Eickhoff, Jan Dobberstein, Harald Zellmer, Thorsten Adolph

Abstract

The sensitivity of thorax deflection of the THOR and Hybrid III was evaluated in sled tests. THOR was equipped with 3D-IR Traccs and strain gauges on the ribs, the Hybrid III with multi-point deflection measurement. The sensitivity regarding changes of restraint parameter like D-ring position, pretensioning and belt load limiting was investigated.

As an outcome, the regions with maximum deflection are similar for both dummies under same loading conditions. Reduced mid sternum deflection of the Hybrid III with a belt path close to the neck is measured. In contrast, the maximum deflection difference of the Hybrid III is higher compared to lower belt routings. The THOR thorax shows higher differences in deformation by variation of the belt path.

Double pretensioning reduces the deflection of both dummies being higher for THOR. An increased reduction is found in the lower chest area with Hybrid III. THOR shows the highest differences in the upper area. Finally, a step down of belt force leads to a comparable relaxation of both dummies.

In conclusion, the updated THOR is more sensitive to changes in restraint parameters compared to Hybrid III showing potential for capturing a more detailed thorax response in order to develop injury criteria.

Keywords: Chest deflection, Hybrid III, sled tests, thorax, THOR

I. INTRODUCTION

The number of road fatalities continues to decline due to improvements in vehicle safety technology. However, data from the European Road Safety Observatory indicates that in 2010 still around 31,000 people were killed and more than 1.4 million injured in European road accidents [1]. Due to these figures a further improvement of vehicle safety is desirable.

Car occupants show a high risk of being injured, especially in frontal impacts [2]. In this accident configuration the thorax is the body region at highest risk, as shown in several studies based on accident data analysis, such as [3]. Carroll et al. [4] did an analysis with in-depth accident data of occupant injuries in frontal impacts in vehicles manufactured after 2000. They found that rib fractures have the highest share of AIS3+ injures.

To address this issue by development of improved vehicle technology including advanced restraint systems, a frontal impact dummy with a more biofidelic thorax and appropriate measurement capability is needed. For this purpose, within the EU-project THORAX a thorax demonstrator with improved chest and shoulder design was developed and implemented in the THOR dummy [5-6].

To assess whether this new chest enables the development of improved restraint systems, it is important to investigate the sensitivity of the dummy chest measurements to restraint system parameters like adaptive load limiter or pretensioner concepts. In other studies the restraint system sensitivity of the Hybrid III was already investigated [7-10]. Previous versions of the THOR dummy were also tested regarding restraint system sensitivity [11-12]. However, the new dummy chest devolved in the THORAX project has not yet been evaluated in this respect.

Therefore, the objective of this study was to investigate the sensitivity of the new dummy chest to changes in belt system parameters and furthermore to compare the results to Hybrid III chest measurements including multi-point chest deflections.

II. METHODS

To investigate the restraint system sensitivity of the dummies Hybrid III and THOR, a series of sled tests was done in a generic environment representing a driver position. A variation of three belt system parameters was done to investigate the effect on chest measurements in the dummies.

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Test rig

The generic test rig was developed to represent a driver position in an average vehicle environment. It was based on a test setup used in previous studies with the Hybrid III [10] [13]. The sled setup with the THOR dummy is shown in Figure 1. A production seat cushion with deformable seat pan of a compact class vehicle was used; it was changed after each test. The seat back was rigid and covered with foam. A production steering wheel with airbag was mounted to a rigid steering column. The steering wheel was changed after each test.

The belt restraint system consisted of a production 3-point seat belt with retractor pretensioner, which was fired in all tests. In some tests also an anchor plate pretensioner was used. A constant retractor load limiter (about 4 kN shoulder belt load) or an adaptive shoulder belt load limiter with a step down from about 4.5 kN to 2.5 kN shoulder belt load was used. All belt attachment points were adjustable to investigate different belt geometries.

Figure 1. Test rig with THOR dummy

Dummy positioning

For positioning of the dummy a reference H-point was determined with the SAE H-point manikin. Hybrid III as well as THOR were placed as close as possible to the reference H-point. Due to the different anthropometric dimension of the dummy this resulted in different distances relative to the steering wheel and different leg positions as shown in Figure 2 and Figure 3. Some characteristic measurements are provided in Table 1. Both dummies were adjusted to a pelvis angle of 21.5° (+/-1°).

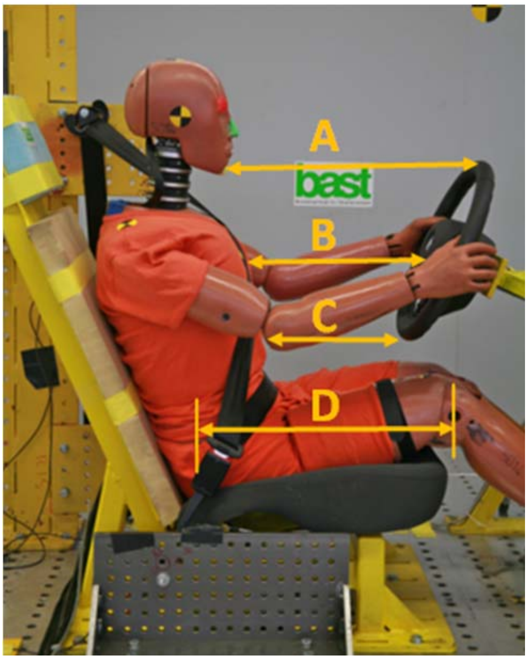

Figure 2. Positioning measurements of Hybrid III

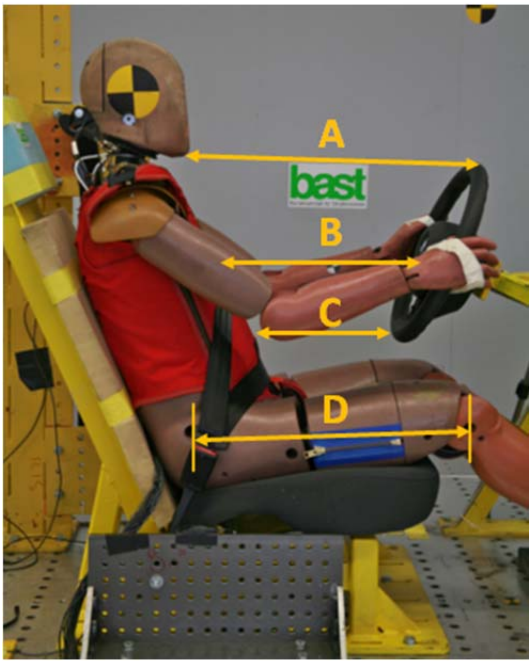

Figure 3. Positioning measurements of THOR

Table 1. Dummy positioning measurements

Measurements in mm (Tolerance +/- 10 mm)		Hybrid III	THOR
Distance chin to top of Rim	A	465	545
Chest to StW center (horizontal)	B	360	420
Stomach to rim (horizontal)	C	265	280
HP to Knee joint (x-distance)	D	390	415

Dummy Instrumentation

A Hybrid III dummy with standard instrumentation was used. Additionally, the chest was instrumented with the multi-point deflection measurement system RibEye. The location of the LEDs to measure the deflection of the ribs is shown in Figure 4 and Figure 5.

The THOR dummy used for this study was originally a THOR-NT. It was upgraded with the mod-kit including pelvis, femur and knee. Furthermore, the new thorax and shoulder design of the EU-project THORAX was implemented. This consisted of the SD3-shoulder, a new set of ribs, which were tuned for improved biofidelity, four 3D-IR-Traccs (see Figure 6) and 72 strain gauges, 6 on each rib left and right (Figure 7). For a detailed description of the dummy updates derived from the THORAX-project, see [5] [6].

Figure 4. Positioning of the RibEye LEDs on the ribs in the Hybrid III

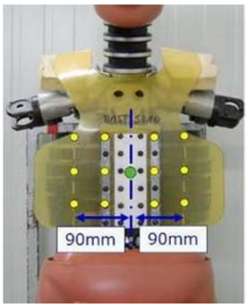

Figure 5. Location of 12 RibEye LEDs

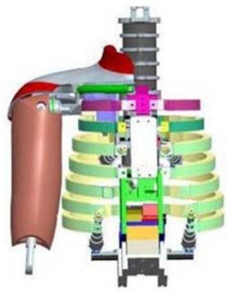

Figure 6. SD3 shoulder and four 3D-IR-Traccs in the updated THOR chest

Figure 7. Ribs 2 to 7 each equipped with 6 strain gages left and right

Parameter tuning in Baseline Configuration

A Euro NCAP pulse representative for an average midsize vehicle was selected from a pulse database. The pulse was recorded in a full-scale crash test. The pulse is shown in Figure 8.

Several tuning tests were performed with the objective to have a baseline configuration which shows average performance dummy assessment values with the Hybrid III dummy. During the tuning of the system, trigger times of the restraint system were adjusted (retractor pretensioner and airbag) and the location of the shoulder belt attachment point was set. The driver airbag used in this test series was comparably soft, resulting in a belt-dominated restraint system. This enables an investigation focusing on belt parameters. The Hybrid III injury values of the baseline test after tuning is shown in Table 2.

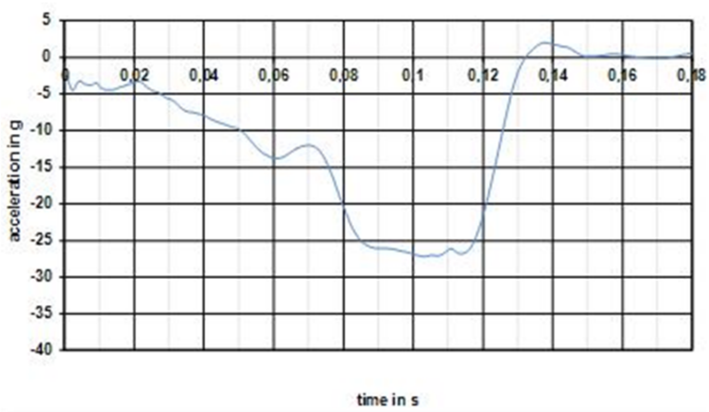

Figure 8. 64km/h ODB Euro NCAP crash pulse

Table 2. Hybrid III injury values in the baseline test configuration

HIC 36	273
Head Acceleration Resultant in g	49
Head a3ms cumulative in g	48
Neck Shear Force Fx+ in kN	0,2
Neck Shear Force Fx- in kN	-0.5
Neck Tensile Force Fz+ in kN	0.6
Neck Extension My- in Nm	-6.8
Chest Deflection in mm	-24
VC max in m/s	0.05
Chest Acceleration Resultant in g	38
Femur Left Force Fz- in kN	-0.6
Femur Right Force Fz- in kN	-0.4

Test parameters

The baseline test configuration was done with Hybrid III and THOR. The following three belt parameters were changed in tests with both dummies and compared to the baseline tests:

1.) Belt geometry
2.) Double pretensioning (retractor and anchor)
3.) Adaptive load limiter (4.5 kN to 2.5 kN shoulder belt load)

1. Belt geometry

The sensitivity of THOR and Hybrid III to belt routing variations was investigated for two different belt routings on the dummy chest by modifying the location of the upper belt attachment point as shown in Figure 9. The resulting belt routing on the THOR dummy is shown in Figure 10 and Figure 11. In belt routing configuration A, which was defined as baseline belt routing variation, the belt path is higher on the chest, closer to the neck and more inboard on the shoulder. The shortest distance between neck and webbing was 75 mm in this configuration. This belt routing is also used in all other tests presented here. Moving the upper D-ring anchorage point down by 90 mm resulted in belt routing B shown in Figure 11. The belt path is lower on the chest (shortest distance between neck and webbing 100 mm) and more outboard on the shoulder. The distance to the neck is higher.

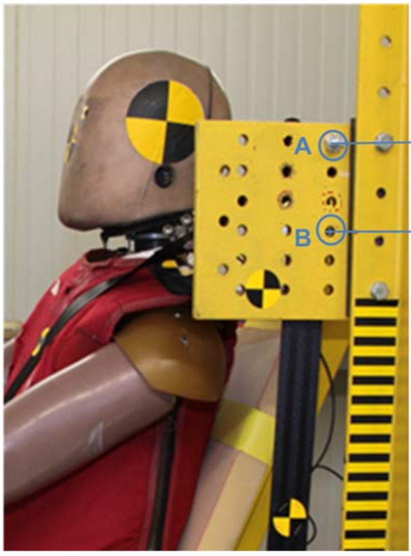

Figure 9. Upper belt anchorage of belt routing A vs. B

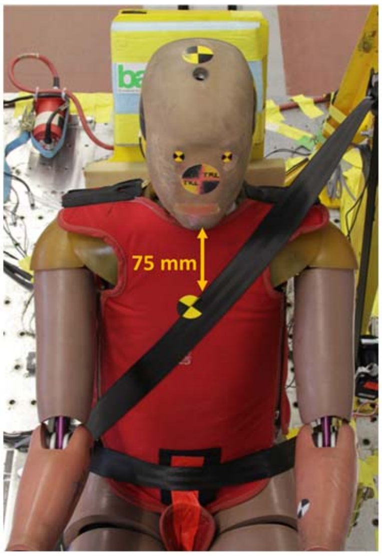

Figure 10. Belt routing A

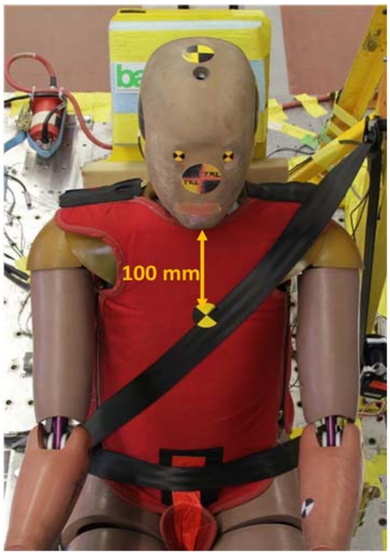

Figure 11. Belt routing B

2. Pretensioning

An anchor plate pretensioner was added to investigate the effect of double pretensioning on THOR compared to Hybrid III. The belt routing A was used and the retractor pretensioner was fired as in the baseline tests. The anchor plate pretensioner was fired with a delay of 7 ms after the retractor pretensioner.

Table 3. Overview of tests, baseline tests given in italic

Dummy	Belt routing	PPT	Load limiter	TTF Retractor	TTF Anchor	TTF Load limiter	TTF Airbag
Hybrid III	*A*	*Single*	*Constant*	*22 ms*	--	--	*28 ms*
THOR	*A*	*Single*	*Constant*	*22 ms*	--	--	*28 ms*
Hybrid III	B	Single	Constant	22 ms	--	--	28 ms
THOR	B	Single	Constant	22 ms	--	--	28 ms
Hybrid III	A	Double	Constant	22 ms	29 ms	--	28 ms
THOR	A	Double	Constant	22 ms	29 ms	--	28 ms
Hybrid III	A	Single	Adaptive	22 ms	--	95 ms	28 ms
THOR	A	Single	Adaptive	22 ms	--	95 ms	28 ms

3. Adaptive load limiter

To investigate the effect of an adaptive load limiter, the shoulder belt load was reduced by an adaptive load limiter from about 4.5 kN to 2.5 kN at the shoulder. For these tests also the belt routing A was used as in the baseline tests.

An overview of all tests considered here is given in Table 3. The table also provides the trigger times of pretensioner (retractor and anchor), adaptive load limiter and airbag.

III. RESULTS

The results of the investigated parameters including belt geometry, pretensioning (single vs. double) and adaptive load limiting are shown and compared to the results of the baseline configuration (belt routing A, single pretensioner, constant load limiter).

1. Belt geometry variation

Figure 12 and Figure 13 show the Hybrid III deflection measurements for the belt geometries A and B. The maximum multi-point measurements are higher than the deflection measured with the chest pot. The measurements indicate the highest deflection in the upper right quadrant of the chest for both belt geometries. The highest deflection can be observed at the 1st right rib at 90 mm from the sternum midline. The deflection measured close to the sternum is slightly lower. The multi-point measurements show an asymmetric distribution of the deflection on the chest with a high difference between the corresponding points on the right and left side of the rib cage. The highest difference between left and right can be observed on the 5th rib level for these tests.

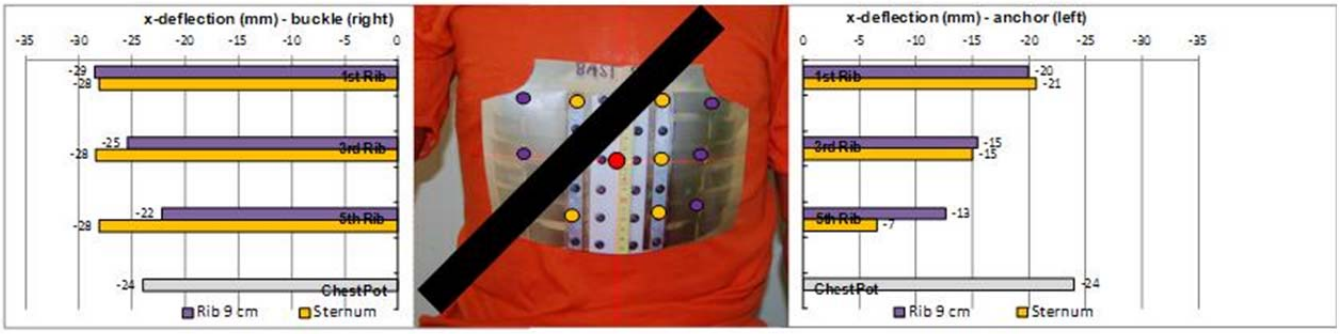

Figure 12. Hybrid III RibEye x-deflections belt routing A

Figure 13. Hybrid III RibEye x-deflections belt routing B

Figure 14 summarizes the characteristic indicators derived from the multi-point measurements in the Hybrid III chest comparing the belt routings A and B. The maximum deflection measured with the standard chest potentiometer is also provided.

Comparing the belt geometries by the chest pot readings, the higher belt routing A results in a lower mid-sternum deflection. In contrast, the peak RibEye deflection does not show a high variation between the two belt geometries. However, the asymmetry of chest deflection expressed by the difference between corresponding left and right ribs shows a clear decrease for belt routing B compared to routing A.

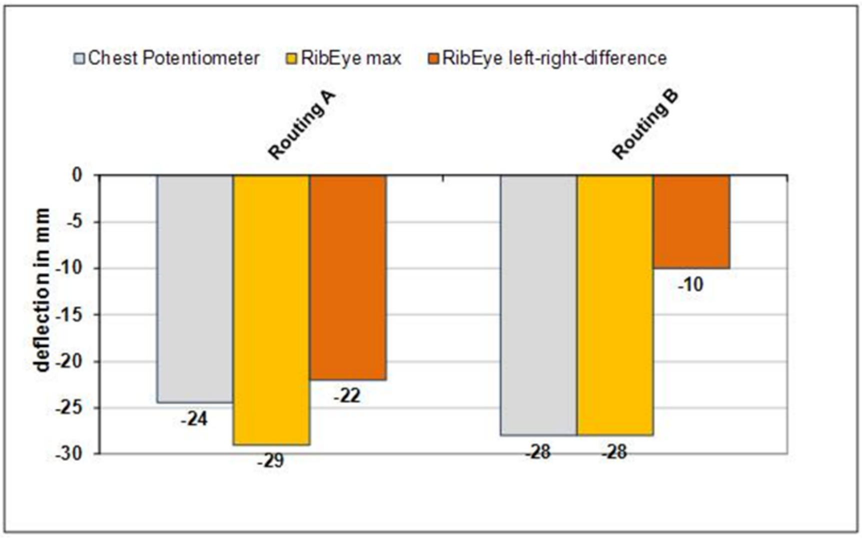

Figure 14. Hybrid III chest deflections for belt routing A vs. B

Figure 15 shows a comparison of THOR IR-Tracc readings for belt routing A vs. B. In general, the deflections measured with THOR are higher than the Hybrid III chest deflections. For the higher belt path on the chest (routing A) the upper right quadrant shows the highest readings. This is in line with the observations in the Hybrid III dummy. However, for the lower belt path (B) the IR-Tracc deflections in the lower right quadrant are higher, which is in contrast to the multi-point measurements in the Hybrid III dummy. In the lower left quadrant the Hybrid III measures the lowest deflection, THOR shows even reverse deflection indicating bulging out of the ribs. THOR deflection measurements also indicate an asymmetric chest deformation. The highest deflections are occurring at the right half of the chest, which is in line with the observations of the Hybrid III multi-point measurements.

Figure 16 shows the strain measurements of the THOR dummy for the two belt routings. A qualitative comparison suggests a similar sensitivity of the strains measured on rib 2 and rib 5 as the IR-Tracc measurements. Both IR-Tracc measurements as well as strain measurements indicate the same chest quadrant with the maximum loading, which is the upper right for high belt routing A, the lower right quadrant for the lower belt routing B. However, the strain measurements at the 6th rib provide additional information which is different to the IR-Tracc measurement. At the 6th rib the strain shows a value for belt routing B, which is even higher than the strain observed at the 1st rib for belt routing A.

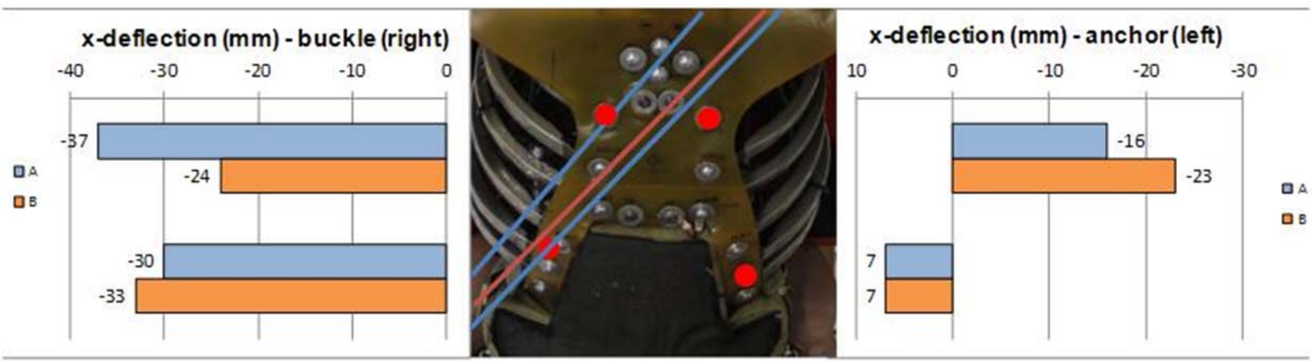

Figure 15. IR-Tracc x-deflection in the THOR dummy; Belt routing A vs. B

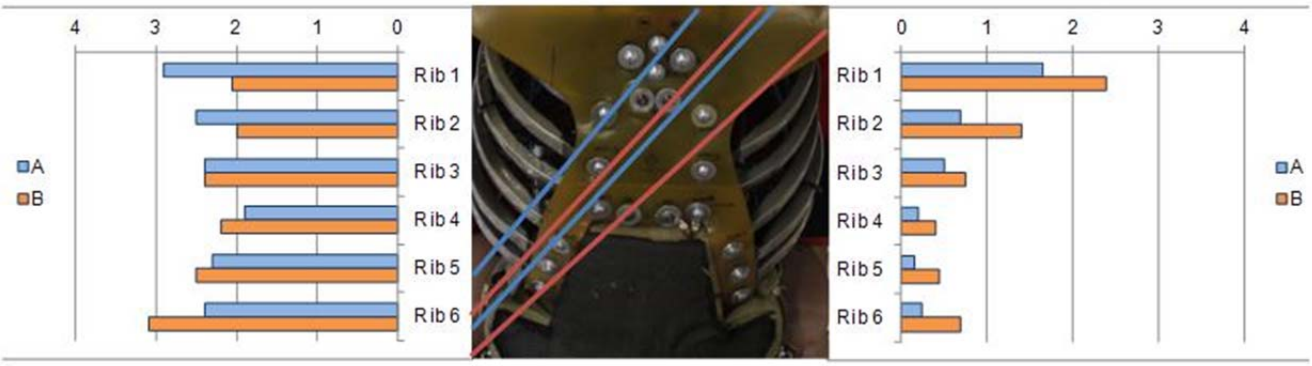

Figure 16. Peak rib strain in millistrain; belt routing A vs. B

2. Single vs. Double pretensioning

Figure 17 shows key values calculated based on Hybrid III deflection measurement comparing single and double pretensioning. All deflection-based values like chest pot measurement, maximum RibEye deflection as well as the left-right difference are reduced by double pretensioning compared to the baseline test with single pretensioning. Figure 18 shows a similar reduction of IR-Tracc deflection values in the THOR dummy. Maximum deflection as well as asymmetric chest deformation is reduced in the test with double pretensioning.

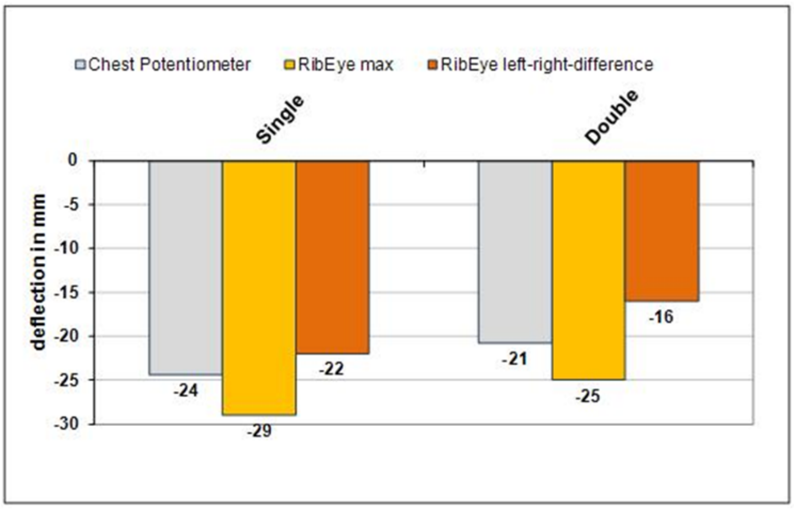

Figure 17. Hybrid III chest deflections for single and double pretensioning

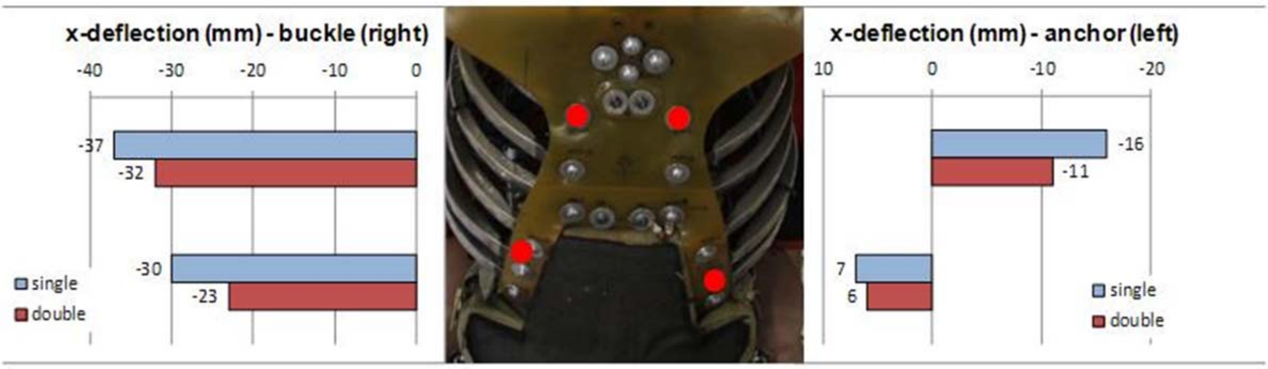

Figure 18. IR-Tracc x-deflection in the THOR dummy for single and double pretensioning

Figure 19 and Figure 20 show the time history of belt forces measured at the diagonal belt between shoulder and D-ring and the belt force at the outboard anchorage point. A clear difference in belt forces between Hybrid III and THOR can be observed. The shoulder belt force shows a faster increase for the Hybrid III compared to THOR indicating a better coupling of the belt to the dummy. The double pretensioning can be seen clearly in the Hybrid III shoulder belt force by an increase in force at about 30 ms whereas in the THOR this is not as prominent.

The lap belt force in THOR rises slower. The lap belt force shows a clear force peak due to the anchor plate pretensioner in the Hybrid III whereas a lower force peak due to anchor pretensioning can be seen for the THOR. However, the different increase of lap belt force due to anchor pretensioning can also be clearly seen in the THOR.

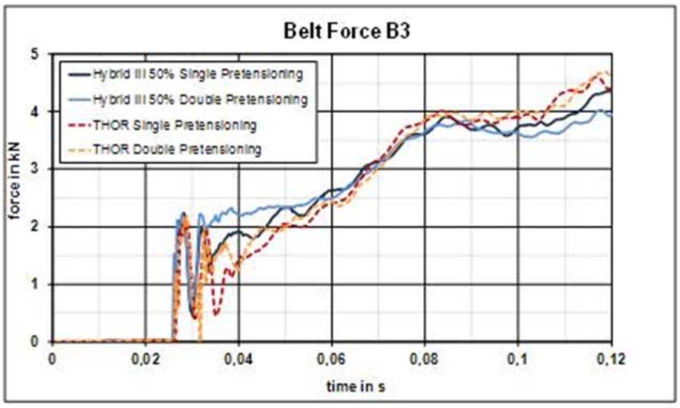

Figure 19. Upper shoulder belt force FB3

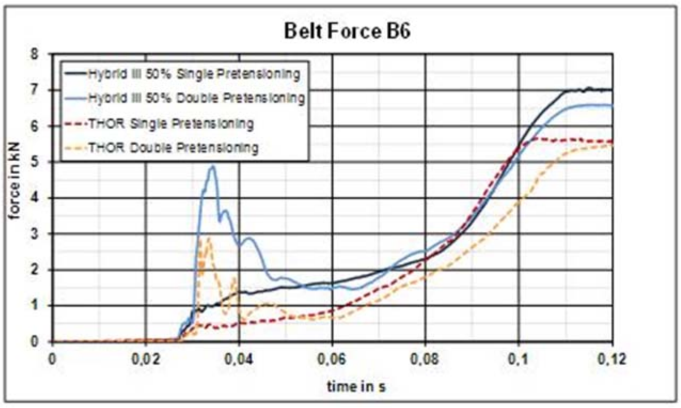

Figure 20. Belt force at outboard anchor FB6

Chest and pelvis accelerations for the tests with single and double pretension are shown in Figure 21 and Figure 22. Both acceleration readings show a clear peak due to the anchor plate pretensioner. However, only the maximum accelerations in the Hybrid III show a clear reduction for double pretension, whereas the maximum chest acceleration in THOR only shows a small reduction and the peak pelvis acceleration does not show any noticeable difference between the two pretensioning variations.

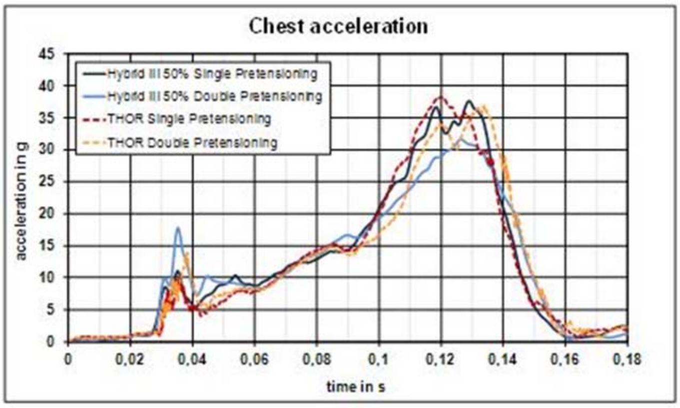

Figure 21. Chest acceleration

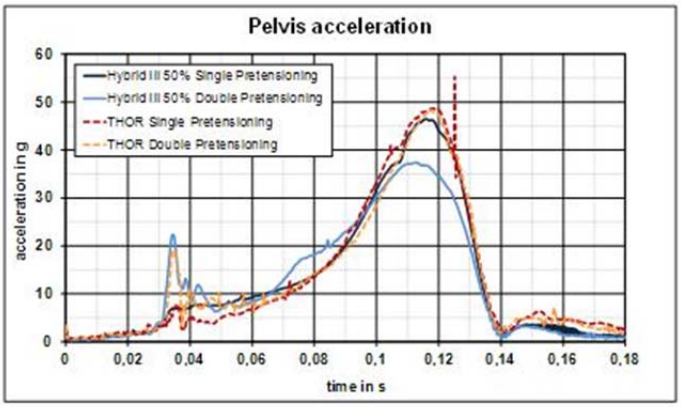

Figure 22. Pelvis acceleration

3. Adaptive load limiter

To investigate the effect of a step down in shoulder belt load, an adaptive load limiter was activated at 95ms reducing the shoulder belt load from about 4.5 kN to a lower level of about 2.5 kN at the shoulder as shown in Figure 23 for the THOR dummy as an example.

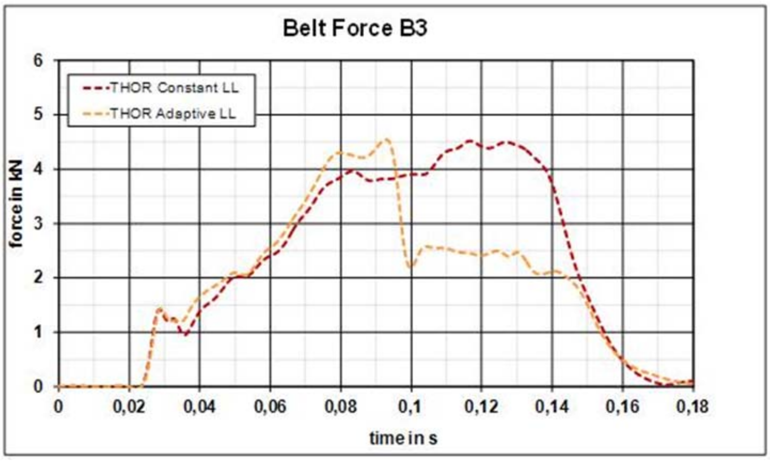

Figure 23. Upper shoulder belt forces FB3, constant vs. adaptive load limiter

In Figure 24 Hybrid III deflection-based values are shown for the constant vs. the adaptive load limiter. The chest potentiometer as well as the multi-point deflection measurement shows a reduction of its maximum values for the adaptive load limiter. In Figure 25 a similar tendency is shown by the IR-Tracc deflection values in the THOR dummy. The maximum IR-Tracc values as well as asymmetric chest deformation are reduced in the test with the adaptive load limiter.

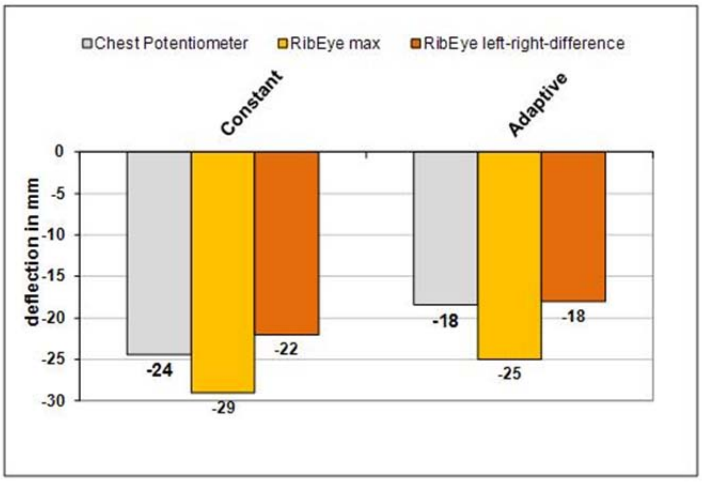

Figure 24. Hybrid III chest deflections for constant and adaptive load limiter

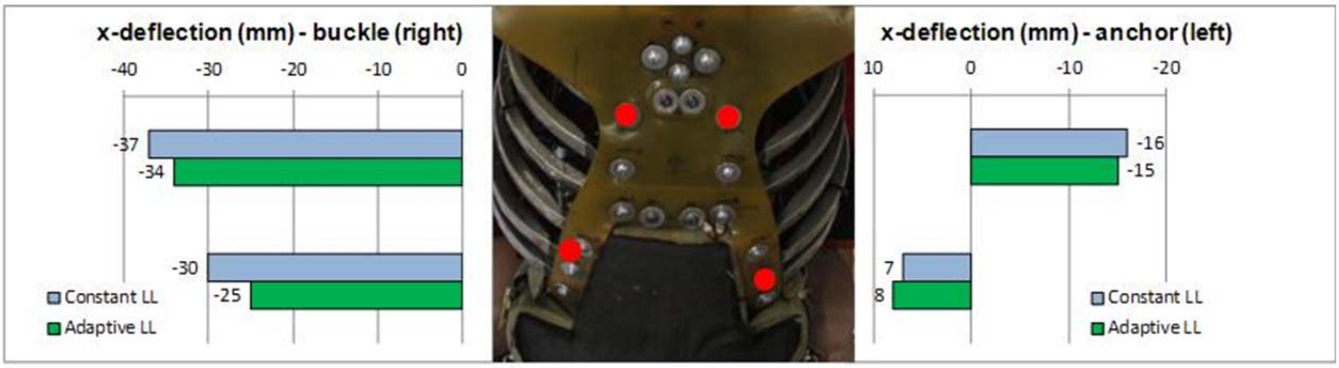

Figure 25. THOR IR-Tracc x-deflections for constant and adaptive load limiter

Figure 26 and Figure 27 show deflection time-history plots of the multi-point measurements in the Hybrid III. In Figure 27 the effect of the step down in shoulder belt load on the chest deflection can be seen. The adaptive load limiter reduces the maximum deflection peaks at all ribs, with the most pronounced reduction at the 1st right rib. The deflection time history shows a similar shape for all ribs. The timing of the decrease in deflection corresponds to the belt force, showing an immediate effect with only very small delay of 2 ms to 3 ms. After this reduction the rib deflection increases again and reaches its maximum peak, which is higher than the first peak before the step down in belt force.

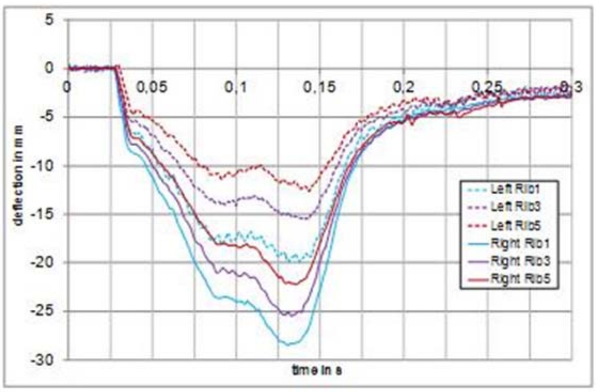

Figure 26. Hybrid III multi-point deflections, constant load limiter

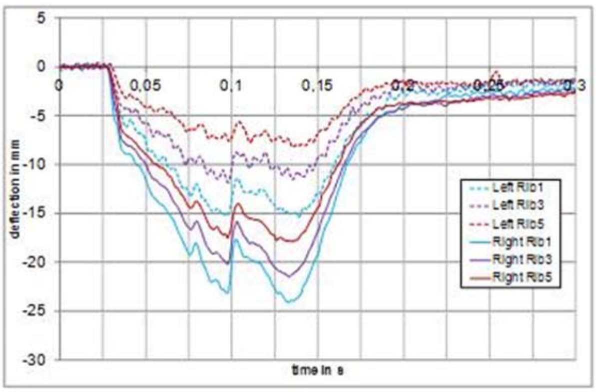

Figure 27. Hybrid III multi-point deflections, adaptive load limiter, 2nd stage at 95ms

In Figure 28 and Figure 29 time-history plots of the deflection measured by the IR-Traccs are shown. The step down in belt force shows a clearly visible reduction in deflection at the upper right and also the upper left IR-Tracc. However, in contrast to the Hybrid III the deflection measured at the upper right sensor – the sensor on which the total maximum in deflection occurs - does not increase again after the step down in belt force. The time-history plots of the IR-Traccs do not show a similar shape as observed in the Hybrid III tests. A time delay of 2 ms to 3 ms between force and deflection can also be noticed with the THOR dummy.

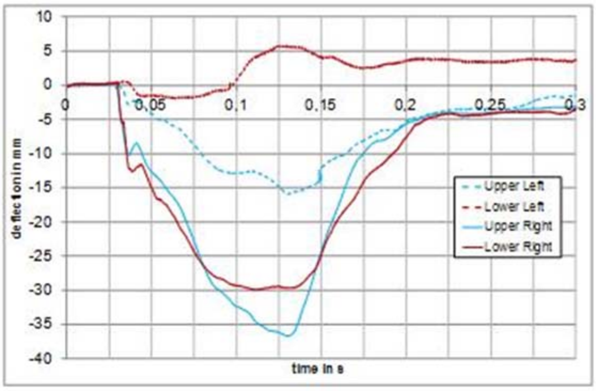

Figure 28. THOR IR-Tracc x-deflection, constant load limiter

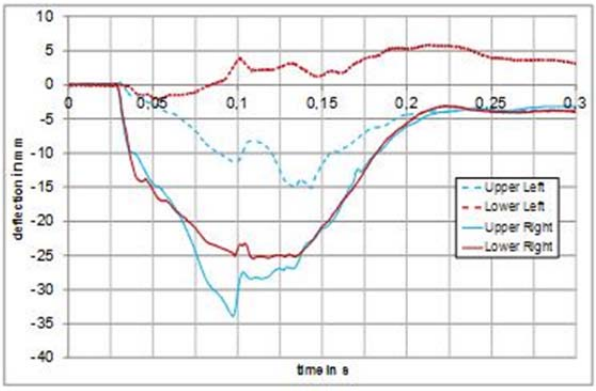

Figure 29. THOR IR-Tracc x-deflection, adaptive load limiter, 2nd stage at 95ms

IV. DISCUSSION

The influence of the belt system parameters belt routing, double pretensioning and adaptive load limitation on chest measurements in Hybrid III and THOR was investigated. All measurements show a sensitivity regarding these parameters.

The mid-sternal deflection in the Hybrid III measured by the rotational potentiometer shows an increase for a lower belt path on the chest. This is in agreement with observations in other studies ([8-9] [13]). For the upper belt path, the RibEye maximum deflection is higher than the deflection measured by the chest pot. For the lower belt path the maximum chest pot deflection increases but the one measured by RibEye stays almost the same. This result is in line with previous observations in other studies with the RibEye system [10] [13]. It can be noticed that the multipoint measurement system in the Hybrid III is better able to capture the real maximum chest deflection than the chest potentiometer. The IR-Tracc multi-point measurements in THOR also show the tendency to indicate a higher peak deflection for a higher belt path. Furthermore the left-right difference as an indicator for asymmetric chest deformation due to belt loading is reduced for the lower belt path in both dummies. For the Hybrid III this has also been shown in previous studies ([9] [13]).

For the lower belt path the multi-point systems in both dummies indicate the lower right quadrant as the one with the highest deflection. Furthermore, both systems indicate that the peak deflection for the lower belt path B occurring at the lower right quadrant is less than the peak deflection in the upper right quadrant for belt geometry A.

However, the strain-based measurements indicate the highest load at the 6th rib for the lower belt path. Based on the strain measurement, belt routing B would be rated the less favorable configuration. This suggests that the strain measurement provides additional relevant information, which is not captured by a multi-point measurement system as currently installed in the THOR dummy. Sensitivity to changes in belt geometry near the buckle should be further investigated. Correlation to injuries in PMHS tests or to loadings in human model simulations should be done to further understand this issue.

The bulging of the THOR rib cage at the lower left quadrant has also been reported in PMHS tests ([14] [15]). In these PMHS tests bulging out was also observed for the lower unloaded quadrant in 3-point –belt sled tests due to two possible mechanisms, which were asymmetrical belt loading and inertia of the underlying organs. In the THOR dummy tests the belt loading might be the main mechanism, because the internal organs are not fully represented in the dummy. However, only belt asymmetrical belt loading might not be able to produce this effect as reported by [16] who did not observe bulge out by asymmetrical loading in bench tests. Tests with EU-demonstrator THOR for biofidelity evaluation in the gold standard test configuration [6] did not show bulge out in contrast to the PMHS in gold standard configuration [14]. To further investigate this different observation the belt routing should be compared to that used within this study.

THOR as well as Hybrid III multi-point deflection measurements are sensitive to pretensioning and to changes in load-limiting level. The double pretensioning as well as the adaptive load limiting shows a reduction in peak deflection of RibEye and IR-Tracc. Also the left-right difference is reduced in both cases. However, also the single point mid-sternum deflection in the Hybrid III indicates a reduction for both belt system parameters.

Differences in belt forces for double pretensioning were observed between the two dummies. This indicates that the Hybrid III is stiffer and shows an immediate but short effect of double pretensioning right after the pretensioner is fired. In THOR the lap belt force shows a lower peak due to the anchor plate pretensioner. However, an increase in belt force over a period of 50 ms can be observed.

The comparison of the time history plots of multi-point deflection for Hybrid III and THOR with a step down in belt force shows comparable relaxation times of the ribs. However, in the THOR the decrease due to reduced shoulder belt load can only be seen clearly in the upper right measurement point. This indicates that the THOR ribs are less coupled by the sternum (see Figure 27). In contrast, all Hybrid III ribs show a very similar deflection time history. This indicates a much stronger coupling of the ribs by the sternum, because also the ribs in the lower left quadrant show the same time history of reduction in deflection like the upper right rib, which are directly loaded by the belt (see Figure 29).

The rib at the upper right IR-Tracc, which indicates the highest deflection in the THOR, did not increase again after being reduced due to the step down in belt load by the adaptive load limiter. In contrast, the Hybrid III rib deflection started to increase again to reach its absolute maximum in a second peak. As a result, different trigger times or tunings of adaptive restraint components might be necessary to reach optimal values for the THOR and Hybrid III.

Limitations

The tests were done in a simplified generic vehicle environment, which limits the possibility to draw conclusions as to the dummy performance in a full-vehicle crash test. The main simplifications compared to a full-vehicle environment are the missing knee contact and the non-deformable steering wheel support. The missing knee contact might lead to an overestimation of the benefit in reduction of chest deflection by double pretensioning. However, as it was made sure by adjustment of the components of the test environment to show dummy loadings being representative of an average vehicle, a transfer of the qualitative differences between dummies and test configurations should be valid. Furthermore only one generic crash pulse was considered. Further studies should involve the investigation of the dummy response to different pulses.

Furthermore the biofidelity of the sensitivity regarding the restraint system parameters investigated in this test series could not be analysed based the results of this study. No corresponding PMHS tests focusing on the effect of double pretensioiong or adaptive load limit are available are available. Also no information on these parameters is available from in-depth data. The question of biofidelity of the sensitivity of the restraint parameters of this study could be further investigated by corresponding human body model simulations, which are planned by the authors as a next step.

V. CONCLUSIONS

- The deflection measurements of the THOR dummy mod-kit upgraded chest are sensitive to the investigated belt restraint parameters.
- For most parameter changes investigated, the THOR is more sensitive than the Hybrid III.
- The multi-point deflection measurement in Hybrid III as well in THOR is able to indicate the chest area with the highest loading.
- The strain measurements in the THOR ribs can provide additional insight for the comparison of different belt routings to identify the more severe loading condition.
- Double pretensioning as well as a step down in belt force leads to a reduction of all deflection values of all measurement systems (chest pot, RibEye, IR-Traccs).
- The thorax behavior of THOR and Hybrid III concerning the relaxation time is comparable.
- The improvement of dummy design and measurement techniques show promising potential for capturing a more detailed thorax response in order to develop advanced injury criteria sensitive to restraint system parameters.

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