SENSITIVITY OF CHEST DEFLECTION MEASUREMENTS IN THOR-5F AND HYBRID III SMALL FEMALE DUMMIES TO DIFFERENT SEAT AND BELT SETTINGS

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ABSTRACT

In frontal impact test procedures, the Hybrid III small female dummy is used to increase the protection of small car occupants. To address the increased thoracic injury risk for elderly occupants it is planned to introduce more stringent chest assessment criteria. However, previous studies raised concerns regarding the efficiency of criteria based on chest deflections measurements in the Hybrid III due to sensitivity of the measurements to variations in belt routing due to seat and D-ring settings. The seat in the most forward position and the D-ring in the highest position is mostly used in assessment tests. These settings result in a belt routing closer to the neck and reduced mid sternum chest deflection, which is not presentative of the actual peak deflection and therefore not meaningful to assess the chest injury risk.

The objective of this study was to investigate the effect of chest deflection sensitivity in the Hybrid III small female dummy in a generic sled test setup to variations of belt routings representative of contemporary vehicles. The study was complemented by sled tests with the THOR-5F in the same configurations to investigate the potential of this dummy as a future alternative. Furthermore, an analysis of field data was done to evaluate the preferred seat and D-ring settings of real small car occupants.

The results of the tests with the Hybrid III small female could confirm the findings from previous studies with shoulder belt routings representing contemporary vehicles. A routing with the belt closer to the neck showed a reduced sternal chest deflection in the Hybrid III small female. Corresponding tests with the THOR-5F showed a similar reduction of peak chest deflection at the maximum loaded IR-TRACC, but an increase at another location. Therefore, THOR-5F multi-point criteria might have the potential to address the issue of belt routing sensitivity.

The analysis of field data showed that small occupants representing the small female dummy in terms of height prefer to set the D-ring to the lowest position (driver and passenger). For the front seat passenger, the seat longitudinal and height setting mid/mid is preferred.

In conclusion the recommendations regarding seat and D-ring settings that were provided in previous studies can be confirmed. To enable an effective evaluation of chest injury risk with the Hybrid III small female the D-ring should be set to the lowest position for the driver as well as for the passenger side. For the passenger side the seat should be set to the mid/mid-position. Furthermore, these seat and D-ring settings are the most relevant preferred by small occupants based on field data.

For additional improvement of chest injury risk assessment considering the specific needs of small female occueepants further research is recommended related to the THOR-5F and advanced multi-point chest injury criteria, which might be less sensitive to test parameters and resulting variation of belt routing. Repeatability and reproducibility of the chest deflection response of the THOR-5F dummy related the sensitivity of multi-point defection measurements should be further investigated and improved if necessary.

INTRODUCTION

To increase the level of protection for all occupants involved in a frontal impact accident a frontal full-width test with a Hybrid III small female dummy in a front seat position was introduced by consumer testing organizations as well as in regulations. NHTSA (National Highway Traffic Safety Administration) introduced a full-width test to US NCAP in 2011 with a Hybrid III small female dummy on the front passenger seat. Euro NCAP introduced a 50 km/h full width rigid barrier test in 2015 with a Hybrid III small female dummy in the driver and front passenger seat as well as in the rear seat row.

Several studies have shown that elderly occupants have an increased risk of thoracic injury in frontal impact accidents. Wisch et al. 2017 identified the thorax as the most frequently injured body region for car occupants in frontal impacts with a risk of thoracic injuries at least two times greater for older car occupants. Forman et al. 2019 came to the conclusions that risk reduction in the thorax has lagged other body regions, resulting in increasing prevalence among skeletal injuries in newer vehicles especially in the elderly. Digges et al. 2013 recommended the application of older occupant risk to increase the level of protection of elderly car occupants. Age-specific injury risk functions were proposed by Laituri et al. 2005 and Prasad et al. 2010. Following those recommendations Euro NCAP will reduce the Hybrid III small female chest deflection lower performance and capping limit form the year 2023 onwards from 42 mm to 34 mm (Euro NCAP, 2022).

However, several studies have previously reported concerns related to the currently applied test tool and chest deflection instrumentation, which is the Hybrid III small female dummy with a rotational potentiometer measuring the chest deflection at one single point in the mid sternum. Therefore, to address the increased thoracic injury risk of small elderly occupants it might not be sufficient to use stricter chest deflection performance limits. Improvements to the tests tool or at least updates to the test and assessment procedure that result in reasonable chest deflection measurements are necessary.

Yamasaki et al. 2011 reported that in full-scale crash tests comparing different belt positions on the chest of a Hybrid III small female a reduction of chest deflection with the belt positioned closer to the neck was observed. Further studies investigated the effect of seat track settings and D-ring position on the belt path on the dummy chest and the resulting chest deflection measurements. Keon et al. 2016 conducted frontal impact crash tests according to the Euro NCAP test procedure with a Hybrid III small female dummy on the front passenger seat. Tests with the seat in mid track and most forward position were compared. The most forward seat position resulted in a belt routing closer to the neck and a lower chest deflection compared to the mid track seat position with a belt routing on the center of the sternum and a reductions of measured chest deflection. Digges et al. 2017 evaluated the chest deflection in the Hybrid III small female with the seat in the most forward position and the D-ring in the highest position, which is the setting preferred by vehicle manufactures and mostly used in NCAP tests. This was compared to tests with the seat in mid-track position and the D-ring in the lowest position. A significant increase in chest deflection was observed. They pointed out that is especially relevant for the protection of elderly occupants. Therefore, an improved test and assessment procedure is needed to make sure chest deflection risk is assessed in a reasonable way. Digges et al. 2019 further investigated the sensitivity of chest deflection measurements in NCAP crash tests for the Hybrid III 5% dummy to positioning of the seat and D-ring related to routing of the shoulder belt. Based on these studies the authors provided recommendations to address this issue.

One recommendation is to prescribe the seat and D-ring setting in the test procedure. The recommended setting for the passenger seat would be seat track in mid longitudinal position, mid height seat position and the D-ring set to the lowest position. This would result in a belt path closer to the center of the chest and a more meaningful chest deflection measurement.

Another recommendation from previous studies would be the use of multi-point chest deflection measurement systems like RibEye or IR-TRACC in the Hybrid III dummy (Eggers at al. 2014, Keon et al. 2015, Digges et al. 2019). In these studies, it was demonstrated in tests with multi-point chest deflection measurement in the Hybrid III that it would be possible to identify higher peak chest deflection which do not occur at the mid sternum and usually are higher for belt routings closer to the neck. However, so far, no biomechanical injury criteria are available for multi-point chest deflection measurements in the Hybrid III. Further research is needed. Meanwhile a more a biofidelic small female dummy, the THOR-5F (Wang et al. 2017), is becoming available which has multi-point chest deflection capability and could be a future alternative.

Another option proposed in the previous studies by Digges et al. is a landmark based belt routing procedure. However, after placing the belt on the mid center of the sternum with a landmark based procedure if the seat is in the most forward position and the D-ring in the highest setting the belt might move close to the neck again due to dummy movement during the deceleration pulse or already during the activation of a pretensioner.

Thus, the most effective and immediately applicable solution to achieve a more meaningful chest deflection measurement and chest injury risk assessment in the Hybrid III small female dummy would be to prescribe the seat and D-ring settings based on recommendations from previous studies in the relevant test and assessment procedure.

However, to make sure these seat and D-ring setting are not in contradiction with the preferred settings used by real car occupants field data should be analyzed understand how small occupant are using the seat and belt.

Furthermore, before recommending the test settings to be implemented by Euro NCAP or other worldwide consumer or regulatory test procedures the relevance of the findings observed in previous studies to other contemporary vehicles should be confirmed in additional tests.

The objective of this study was to investigate the effect of chest deflection sensitivity in the Hybrid III small female dummy in a generic sled test setup representing characteristic variations of belt routings in contemporary vehicles. The study was complemented by sled tests with the THOR-5F in the same configurations to investigate the potential of this dummy as a future alternative test tool to address the above-mentioned issues. Furthermore, an analyses of field data was done to evaluate the preferred seat and D-ring settings of small car occupants.

METHODS

Sled tests with Hybrid III small female and THOR-5F in a generic sled setup

To investigate the sensitivity of chest deflection measurements for different belt routings resulting from different settings of the front seat and D-ring height a series of frontal impact sled tests with the dummies Hybrid III small female and THOR-5F (build level SBL-A) was conducted. The tests were done in a generic sled test setup. The test setup with the THOR-5F is shown in Figure 1. It consisted of a rigid seat with a seat pan angle of 10°. The seat was covered with 40 mm Neopolen® foam. The seat back angle was 23°. The feet of the dummy were placed on a footrest covered with carpet. A production 3-point belt system was used with a 3.5 kN shoulder belt load limiter and a shoulder belt retractor pretensioner. The pretensioner was activated at 16ms. In all tests a 50 km/h full-width deceleration pulse was used (Figure 2).

Figure 1. Sled test setup: Rigid seat, 3-point belt system with shoulder belt pretensioner and load limiter

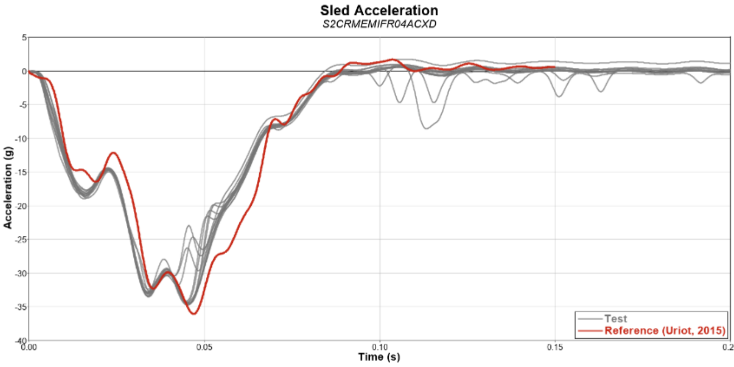

Figure 2. 50 km/h Full-Width Pulse (Reference Pulse Uriot, et al. 2015)

The belt anchorage points of the D-ring, buckle and anchor were adjustable to simulate different positions and settings of the D-ring, different longitudinal seat track positions and different seat height adjustments representing different vehicle geometries. Two different combinations of the belt anchorage points were used. The purpose of the two belt anchorage point settings was chosen to represent possible combinations and resulting belt routing of contemporary vehicles currently available on the European market.

To define the combinations of belt anchorage points the respective points were measured in three real vehicles. The chosen vehicles were Volkswagen Golf 7, Tesla Model 3 and Renault Zoe. An H-point tool was positioned in the diver seat according to the Euro NCAP Full-Width-Frontal-Impact-Test-Protocol Version 1.2.1 (Euro NCAP, 2021). The seat was varied in longitudinal direction between the two settings “most forward” and “25% travel from most forward”. The variation of the seat height was done between the two settings “fully upward” and “75% downward” as defined in the Euro NCAP protocol. Addionally in combination with seat variations the D-ring was varied between the two settings “highest” and “lowest”. The combination of the different settings resulted in a maximum of eight different relative positions of the D-ring for the Golf and Tesla, which are shown in Figure 3. For the Zoe only four variations are shown as the seat was not adjustable in height. For the buckle only two different settings are shown in Figure 3 resulting from the two possible height settings for the seat of the Golf and Tesla. The fore-aft variation in longitudinal direction did not affect the related position to the H-point as the buckle was attached to the seat and therefore moving with the H-point in all of the three vehicles. The small variation of the buckle position in longitudinal (x-)direction results from the movement of the seat in x-direction related to the height adjustment.

Two characteristic combinations of anchorage points for the buckle and D-ring position relative to the H-point were chosen which are close to the possible variations representing the three vehicles. D1 is representing a belt routing more outboard on the shoulder of the occupant whereas D2 is representing a belt routing close to the neck. The location of the buckle and D-ring attachment points in relation to the possible coordinates measured in the three vehicles are shown in Figure 3.

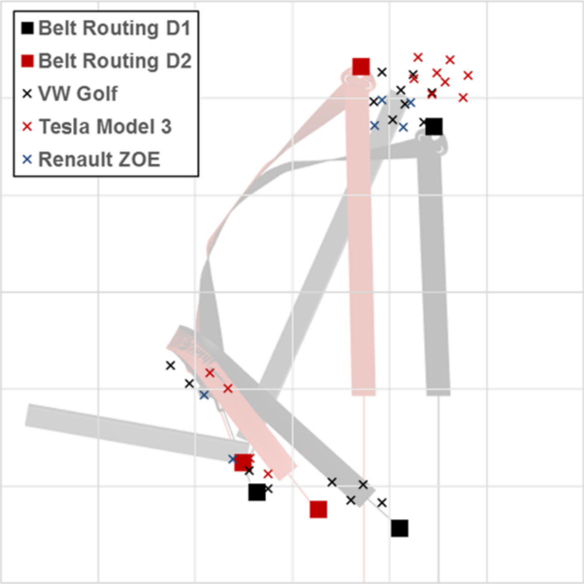

Figure 3. Buckle and D-ring anchorage points D1 and D2 chosen for the tests in the generic test setup relative to the possible points measured in three real vehicles.

The location of the buckle and D-ring attachment points for D1 and D2 were transferred to the generic test setup. The resulting belt routing with the two dummies Hybrid III small female and THOR-5F in the generic test setup are shown in Figure 4 and Figure 5.

Figure 4 shows the belt routing D1 with a chin to belt webbing distance of 125 mm for the Hybrid III and 100 mm for the THOR-5F. The belt routing is more outboard on the shoulder and covers the center of the chest. Figure 5 shows belt routing D2 with a chin to webbing distance of 105 mm for the Hybrid III and 65 mm for the THOR-5F closer to the neck. Three repeated tests were done with the Hybrid III small female and THOR-5F dummy for each of the belt routing configurations.

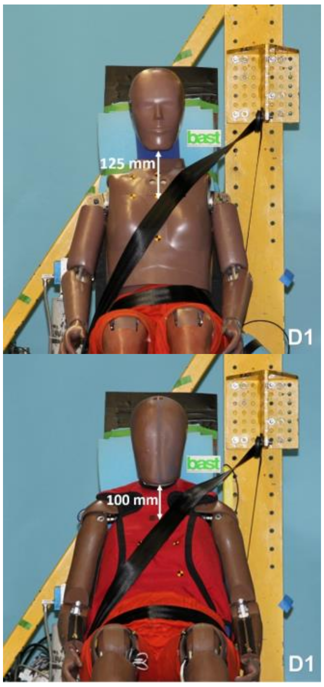

Figure 4. Belt routing D1 (shoulder belt more outboard on the clavicle)

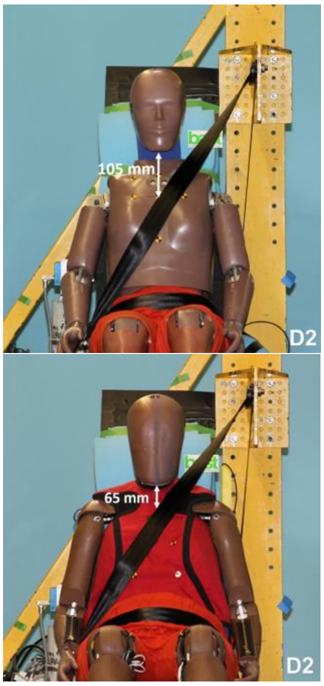

Figure 5. Belt routing D2 (shoulder belt close to the neck)

Field data study - seat adjustments and D-ring position

To evaluate how small occupants are represented by the small female dummy in terms of body height (Small female dummy reference standing height: 151 cm) field data from GIDAS (German In-Depth Accident Study, www.gidas.org) was considered. The database was not analyzed with the purpose to relate injury outcome to seat and belt settings, but only to evaluate the seat and belt settings of small car occupants.

The analysis was based on a GIDAS data set from June 2022 including passenger vehicles with first year of registration after 2004. Only accidents between passenger cars and cyclists were selected in this preliminary study as a high number of those cases exists in the database and to make sure the occupant of the vehicle of interest was almost never (even slightly) injured thus no modification of the seat and belt setting were expected during rescue after the accident. The selection criterion for the car occupant was a standing body height between 145 and 155 cm. The age of the occupant was not of further interest. For each driver or passenger fulfilling the above-mentioned criteria the settings of the D-ring (highest, mid or lowest) and the setting of the seat in longitudinal fore/aft position (most forward, mid or most rearward) and the seat height adjustment (highest, mid or lowest) was evaluated.

RESULTS

Dummy kinematics

Hybrid III small female D1 vs. D2

Upper body kinematics of the Hybrid III small female dummy are primarily influenced by the position of the D-ring with respect to the neck / clavicle (see Figure 4 and Figure 5). For belt routing D1 the belt is further away from the neck (more outboard on the shoulder), hence the belt force is applied further away from the spine and the leverage about the vertical axis of the dummy is consequently larger. Belt routing D2 is closer to the neck and the leverage accordingly smaller. Figure 6 shows the dummy kinematics at 75 ms and 100 ms. As a result of the different belt routings, rotation of the dummy's upper body about the vertical axis begins at approx. 60 ms for belt routing D1, while the dummy-to-belt interaction for belt routing D2 is more stable with no significant rotation of the upper body. The larger leverage for belt routing D1 does not only result in an earlier rotation of the dummy, also the overall rotation of the upper body is larger and the belt is close to slipping from shoulder.

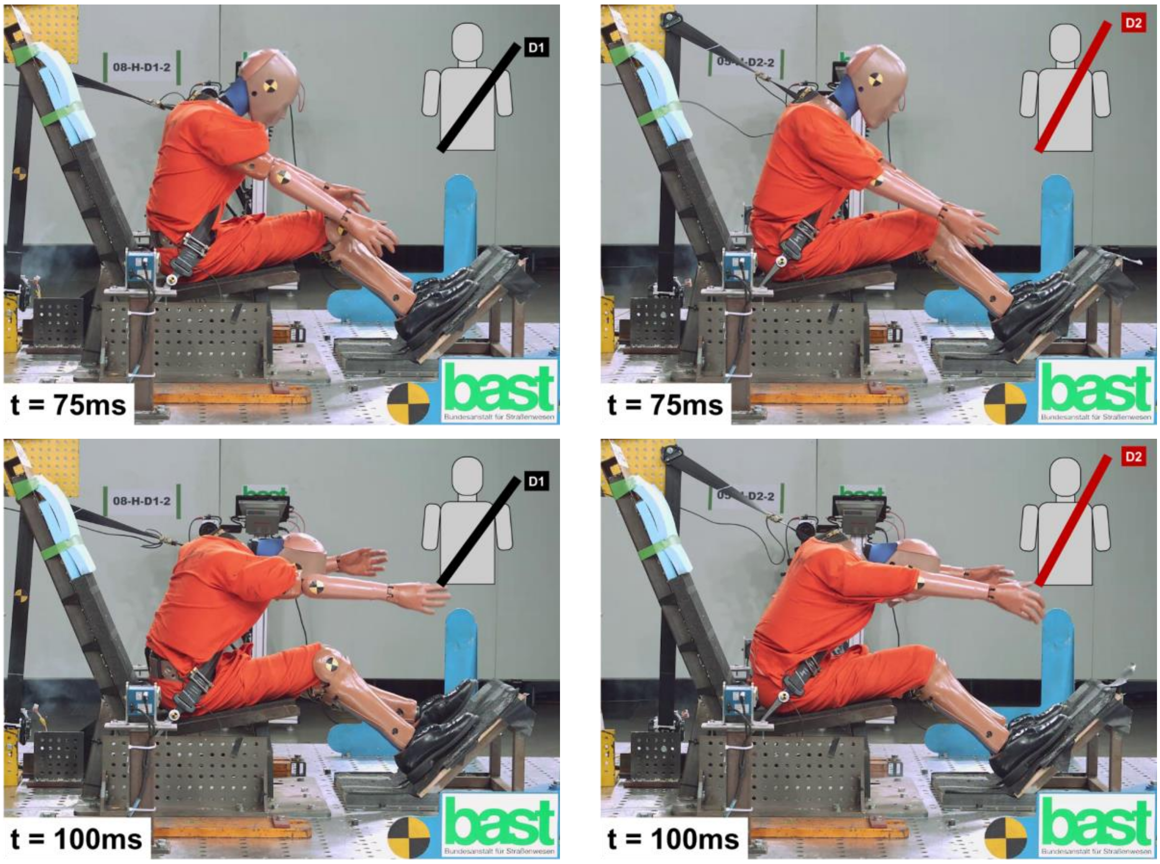

Figure 6. Hybrid III kinematics for belt routing D1 and D2 at 75ms and 100ms.

THOR-5F D1 vs. D2

As for the Hybrid III small female dummy, upper body kinematics of the THOR-5F are primarily influenced by the position of the D-ring with respect to the neck / clavicle and thus the leverage of the belt force (see Figure 4 and Figure 5). Figure 7 shows the dummy kinematics at 75 ms and 100 ms for both belt routings. As a result of the different belt routings, rotation of the dummy's upper body about the vertical axis begins at approx. 50 ms for belt routing D1 and results in an overall larger rotation of the upper body. For belt routing D2 the dummy-to-belt interaction is more stable, while the rotation of the upper body is delayed and reduced. The earlier rotation of the upper body for belt routing D1 reduces the head forward displacement while the risk that the belt slips off the shoulder is increased.

Hybrid III small female vs THOR-5F

Similar observations can be made with respect to the influence of the belt routing, however, the second flex-joint in the THOR-5F dummy increases the overall flexibility of the spine and thus the rotation of the upper body begins earlier and the overall rotation is greater. Furthermore, the bending of the spine and the forward displacement of the head is larger with the head almost contacting the femur or knees.

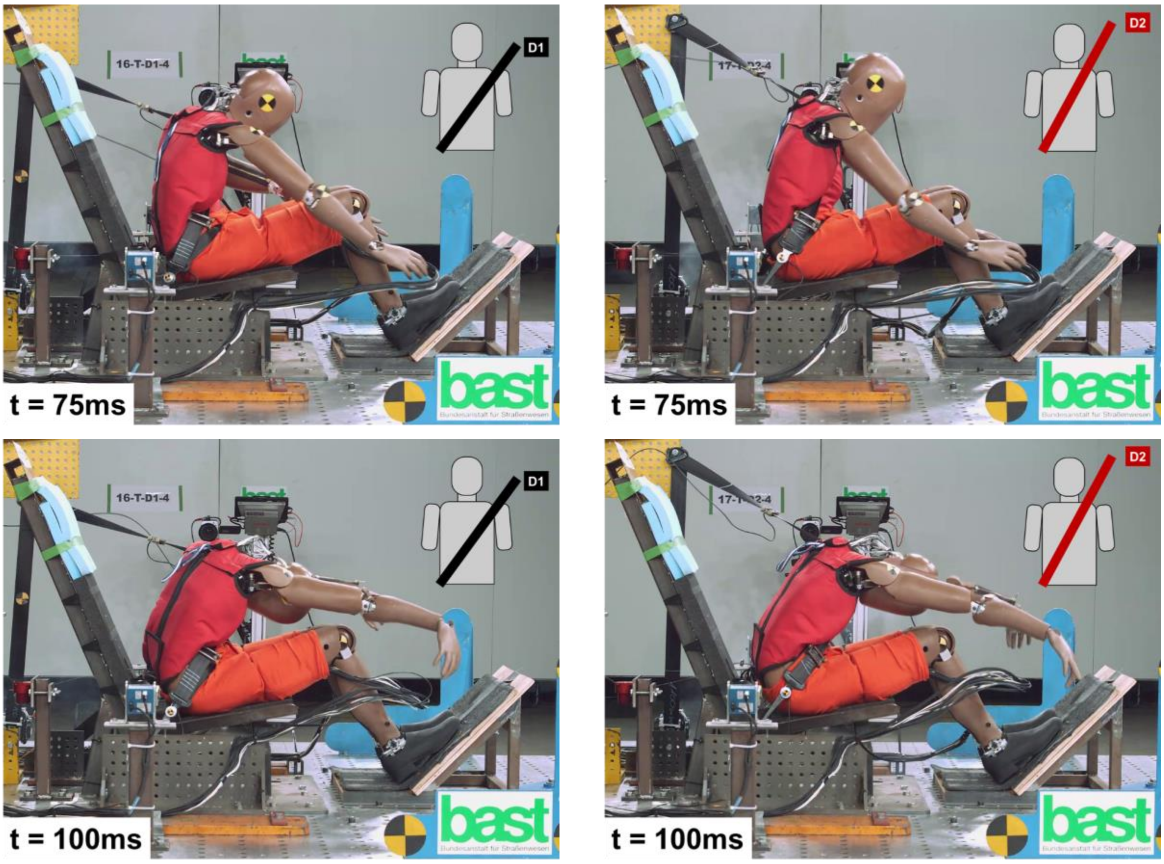

Figure 7. THOR-5F kinematics for belt routing D1 and D2 at 75ms and 100ms.

Chest deflection

The chest deflection measurements of the Hybrid III small female chest potentiometer are shown in Figure 8 for the belt routing configurations D1 and D2. Three repeated tests were done in each configuration. In Table 1 the chest deflection peak values, mean values from three tests and coefficient of variation are shown. In

Table 2 the chest deflection values for D2 are shown respectively. The repeatability is excellent. The chest deflection mean value decreases from the belt routing configuration D1 to D2 by 22 % from 22 to 18 mm.

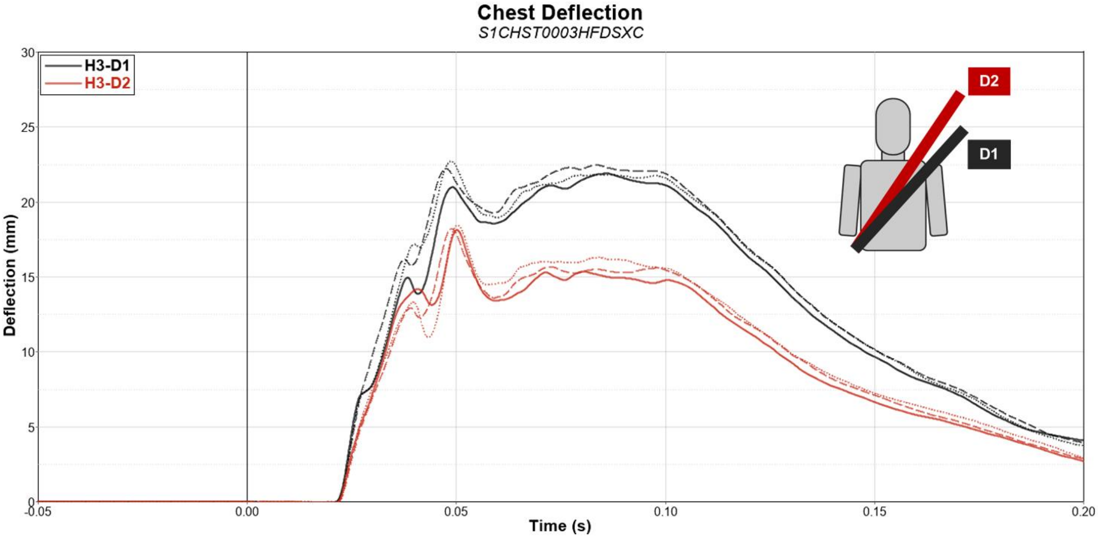

Figure 8. Hybrid III small female chest deflection for belt routing configurations D1 vs. D2.

Table 1. Hybrid III small female chest deflection measurements for belt routing configuration D1.

Test number	Displacement	Mean	Coefficient of Variation
07-H-D1-1	22 mm	22 mm	3%
08-H-D1-2	22 mm		
09-H-D1-3	23 mm		

Table 2. Hybrid III small female chest deflection measurements for belt routing configurations D2.

Test number	Displacement	Mean	Coefficient of Variation
04-H-D2-1	18 mm	18 mm	0 %
05-H-D2-2	18 mm		
06-H-D2-3	18 mm		

Figure 9 shows the resultant IR-TRACC deflections measured at the four locations at the chest of the THOR-5F. The peak values from three repeated tests, mean values and coefficients of variation are shown in Table 3 for belt routing configuration D1 and in Table 4 for D2 respectively.

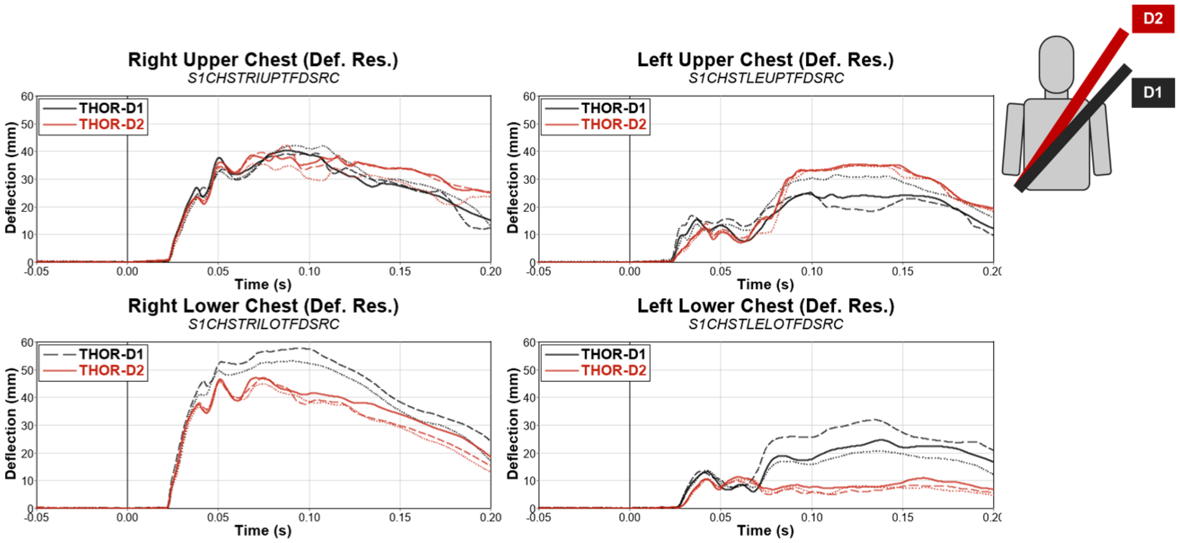

Figure 9. THOR-5F resultant IR-TRACC deflections for belt routing configurations D1 vs. D2.

For the configuration D1 with the belt more outboard on the shoulder the repeatability of chest deflection measurements is good at the right side of the chest. At the left side of the chest the variation is higher (14% to 22%). For D-ring configuration D2 the repeatability is higher at all four measurements location (between 0% and 9%).

The IR-TRACC resultant deflection are higher at the right side of the chest due to the higher loadings by the shoulder belt to this side of the dummy. The maximum resultant deflection of the four IR-TRACCs (R_{max}) can be observed at the right lower IR-TRACC for both belt routing configurations D1 (R_{max} = 55 mm) and D2 (R_{max} = 47 mm). In comparison to the peak deflections measured with the Hybrid III small female the maximum deflection R_{max} measured in THOR-5F is about 2.5 times higher for both belt routings.

Comparing D1 and D2 the mean values of R_{max} is reduced by 16% from 55 mm to 47 mm. The mean value of the maximum resultant deflection at the left upper IR-TRACC increases by 30% from D1 (27 mm) to D2 (35 mm). The deflections at the other two locations also decrease comparing D1 and D2 (right upper by 5% from 41 mm to 39 mm, left lower by 58% from 26 mm to 11 mm).

Table 3. IR-TRACC resultant chest deflection for belt routing configuration D1.

Test number	10-T-D1-1	11-T-D1-2	16-T-D1-4
Right Upper [mm]	40	39	42
Mean	41		
Coefficient of Variation	3%		
Right Lower [mm]	No data	58	53
Mean	55		
Coefficient of Variation	6%		
Left Upper [mm]	25	25	31
Mean	27		
Coefficient of Variation	14%		
Left Lower [mm]	25	32	21
Mean	26		
Coefficient of Variation	22%		

Table 4. IR-TRACC resultant chest deflection for belt routing configuration D2.

Test number	14-T-D2-2	15-T-D2-3	17-T-D2-4
Right Upper [mm]	39	42	36
Mean	39		
Coefficient of Variation	9%		
Right Lower [mm]	47	47	46
Mean	47		
Coefficient of Variation	2%		
Left Upper [mm]	35	35	35
Mean	35		
Coefficient of Variation	0%		
Left Lower [mm]	11	10	11
Mean	11		
Coefficient of Variation	5%		

Field data study - seat adjustments and D-ring position

In Table 5 and Table 6 the settings of the seat longitudinal and height adjustments for car occupant representing a small person in terms of standing height (145-155 cm) are shown. In Table 7 the height adjustments of the D-ring are provided. The majority of the drivers in the data set had the seat set to the most forward position (60%). In 40% of the cases it was set to mid position. The height adjustment was set to mid for 57% of the cases. For the small front passenger occupants, the preferred seat setting is the mid/mid position. The most often observed setting of the D-ring height adjustment is the lowest setting for both the driver (59%) and the passenger (65%).

Table 5. Seat longitudinal adjustment

	most forward	mid	most rearward
Driver	60%	40%	0%
Front Passenger	3%	97%	0%

Table 6. Seat height adjustment

	highest	mid	lowest
Driver	30%	57%	13%
Front Passenger	13%	74%	13%

Table 7. D-ring height adjustment

	highest	mid	lowest
Driver	16%	25%	59%
Front Passenger	6%	29%	65%

DISCUSSION AND LIMITATIONS

The results of the sled tests with the Hybrid III small female dummy could confirm the findings from previous studies in in generic environment with belt anchorage location representing possible shoulder belt routings of contemporary vehicles. The observation from Digges et al. 2019, Digges et al. 2017, Keon et al. 2015 and Yamasaki et al. 2011 regarding the effect of belt routing on reduction of mid sternum chest deflection were also seen in this study. The belt routing of test configuration D1 with a belt position more outboard on the shoulder also resulted in a higher chest deflection in the Hybrid III small female. The belt routing of test configuration D2 with a belt position close to the neck resulted in a reduction of chest deflection in the Hybrid III small female. Therefore, the recommendations regarding test settings of the seat and D-ring adjustments for a more meaningful effective chest deflection assessment with the Hybrid III small female dummy can be confirmed based on the results of this sled test study.

THOR chest measurements are also sensitive to belt routing. The maximum peak deflection R_{max} measured at the right lower IR-TRACC was also reduced between D2 to D1. However, the left lower IR-TRACC is nearly unloaded for D-Ring position 2, while in D-Ring position 1 approx. 25 mm chest deflection are observed, which indicates increased coupling between left and right thorax for D-Ring position 1.

R_{max} means the highest peak resultant deflection values of the of the four IR-TRACC. R_{max} is currently used as chest injury criterion for the THOR-50M dummy. If a similar criterion would be used for the THOR-5F there might occur a similar issue with this dummy regarding non-biofidelic reduction of chest deflection with a belt routing close to the neck. However, if a multi-point chest injury criterion would be used which considers not only the peak value of one IR-TRACC but several IR-TRACCs measurements on both sides of the chest it could be a more robust criterion, which would not be sensitive to belt routing resulting from variations in D-ring and seat settings. Therefore, to give conclusions regarding the potential of THOR-5F as an alternative test tool advanced multi-point injury criterion are needed.

For a reasonable development and application of multi-point deflection-based injury criteria a good repeatability and reproducibility of these dummy measurements is a pre-requisite. The reproducibility was not assessed in this study as only one THOR-5F dummy was available. The repeatability of R_{max} based on the IR-TRACC deflection of the right lower was good (between 2% and 6%). However, the repeatability of IR-TRACC measurement at other locations which would be needed for a multi-point criterion was not good especially for configuration D1. However, in this configuration it might not be an issue of variability in the dummy chest itself or the deflection measurement system, but due to variations in belt sliding on the shoulder in this configuration with the belt more outboard on the clavicle. This needs to be further investigated.

A preliminary field data analysis of the seat setting preferred by small drivers indicate that the most forward position and the mid height setting is preferred. However, in some cases small drivers might change the seat setting before they exit the car to be able to get out more comfortable with more space. Therefore, these figures might be biased for the driver. The setting most forward in longitudinal direction in more cases would be more reasonable as the drivers need to reach the pedals. Also, the seat height setting "highest" would be expected in more cases as the drivers need to be able to look over the steering wheel. Therefore, no specific recommendation of a seat setting for the driver can be made based on this data.

The preferred seat for-aft and height setting in the field data for small passengers is the mid/mid setting, which seems to be reasonable. There is also no concern that the data is biased by change of the seat setting after the accident. Therefore, this setting is recommended as standard test position of the front passenger seat for an updated test procedure with a dummy respecting a small occupant.

The preferred adjustment of the D-ring by small car occupants based on field data is the setting "fully down" for both driver and passenger. Therefore, this setting could be recommended as a standard setting in tests with a small dummy in the driver as well as in the passenger seat.

Limitations

The sled tests with Hybrid III small female and THOR-5F were done in a simplified generic test setup. The generic test configuration can only reproduce the boundary conditions of a real vehicle to a limited extent. In this study a rigid seat was used. No airbag or knee support was used. Depending on the fore-aft adjustment of the seat, the feet-to-footrest contact and resulting feet support might change. The study should be repeated or complemented by investigations using full-scale tests or tests in a more realistic generic seat environment including other components like an airbag. In addition, the analysis of respective field data should be extended.

CONCLUSIONS AND RECOMMENDATIONS

The objective of this study was to provide recommendations to be considered in possible future updates to procedures, e.g. consumer testing like Euro NCAP for an improved safety assessment of chest injury risk with special focus on small (female) elderly occupants in frontal impact.

In conclusion the recommendations regarding seat and D-ring settings that were provided in previous studies can be confirmed. To enable a meaningful evaluation of chest injury risk with the Hybrid III small female dummy the D-ring should be set to the lowest position for the driver as well the passenger side. Furthermore, for the passenger side the seat should be set to the midtrack position. The height of the seat should also be set to the mid-position. These settings will result in a more meaningful belt routing on the dummy chest. Sled test with the Hybrid III small female dummy have shown that theses setting results in a more meaningful dummy chest deflection measurement. Furthermore, theses seat and D-ring settings are the most relevant preferred by small occupants based on field data.

For additional improvement of a chest injury risk assessment procedure considering the specific needs of small female occupants and further enhancement of the occupant protection level it is recommended to consider improved ATDs like the THOR-5F with advanced multi-point chest injury criteria. The THOR-5F chest measurement have shown the potential for improved chest injury risk assessment as they might be less sensitive to test parameters and resulting variation of belt routing.

However, to evaluate the potential of the THOR-5F to address the mentioned issues advanced multi-point deflection-based chest injury criteria are necessary. Further research related to this is needed. A pre-requisite for the development and reliable application of advanced multi-point chest deflection criteria is a sufficiently repeatable and reproducible chest deflection response of the dummy. The repeatability of chest deflection measurements in this test series looked promising. Repeatability and reproducibility of the chest deflection response of the THOR-5F dummy related to the sensitivity of multi-point defection measurements should be further investigated and improved if necessary.

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