Comparison of Hybrid III and THOR 5th percentile female dummies in frontal crash tests

Jolyon Carroll, Dion Kruse, Ekant Mishra, Krystoffer Mroz, Nils Lubbe

Abstract Female occupants have higher injury risks than males in frontal impacts. The Hybrid III 5th percentile female dummy is the predominant tool to assess these injuries, however adoption of the THOR-05F is expected.

Frontal impact sled tests were performed in the SENIORS buck setup with both the Hybrid III 5th and THOR-05F dummies. Two different crash pulses were used, at 35 km/h and 56 km/h. The components of the restraint system were also changed to provide variety in the test conditions.

Whilst there was similar forward excursion measured at the top of the torso in these tests, the lap belt restrained the Hybrid III 5th pelvis better than that of the THOR-05F, reducing the forward excursion at the pelvis level. Differences between the two dummies were also seen in the chest deflection. The left (buckle-side) of the THOR-05F chest recorded much larger deflections than the central Hybrid III measurement.

The interaction of these two dummies with the restraint systems was demonstrably different. The high chest loading and large forward pelvis excursion with the THOR-05F indicate the need for a different optimisation of the balance between pelvis and torso loads for the THOR-05F compared with the Hybrid III 5th percentile.

Keywords 5th percentile dummies, Hybrid III, Injury risk, Restraints, Sled tests, THOR

I. INTRODUCTION

To assess injury risk and demonstrate levels of protection offered, vehicle crash tests primarily use dummies or Anthropometric Test Devices (ATDs) designed to conform with the anthropometry of the human body and mimic its structural response. ATDs must be biofidelic and robust, which is achieved by using suitable materials and designs for the dummies so that they have humanlike responses to an impact but do not break. They must be repeatable and reproducible, so that scientific results can be replicated and relied upon. They must also be sensitive to potentially injurious loading, with a variety of sensors that record parameters in a crash. These parameters are then used to determine the injury risk using specific criteria, often including age as another variable, with risk functions relating the measurements to a risk of injury. Injury Assessment Reference Values (IARVs) are used as critical thresholds taken from the risk functions with which safety assessments can be compared [1]. The Hybrid III family of dummies has been the industry standard for frontal crash testing since the 1970s. The current injury countermeasures have been predominantly established based on the Hybrid III 50th percentile male dummy, which represents an average adult American male [2].

While mid-sized male dummies have been the focus for evaluating the performance of current injury countermeasures, it is also important to have other ATDs that can reflect the diversity of the population [3]. Statistical studies have shown that the risk of injury and fatality for belted females is higher than for belted males [4][5]. Also, females have a higher risk of injuries, such as spinal fractures, from airbags and belts [6]. In fact, for shorter-than-average females, the risk of injuries to the lower extremities is higher, too [4]. These studies indicate the importance of an advanced small female dummy. Females of this size represent a large section of the vehicle occupants suffering serious and fatal injuries [7]. As a result, there is growing consensus among different stakeholders about the importance of the 5th percentile female. Regulations for USA, Europe, Japan, and South Korea have made it mandatory to include the Hybrid III 5th female dummy, a scaled down version of the Hybrid III 50th male, for full width frontal tests. Moreover, the Hybrid III 5th female ATD has also been included in test procedures by Euro NCAP, U.S. NCAP, JNCAP, C-NCAP, and KNCAP [8].

The Hybrid III dummy was not designed for the sophisticated restraint systems of today [9]. Studies have shown that under seat belt loading, the thorax of the dummy is stiffer than the human counterpart.

J. Carroll (jolyon.carroll@autoliv.com; +46-723611476) and D. Kruse are Biomechanics Specialists, E. Mishra is a Research Engineer, K. Mroz is a Senior Research Engineer and N. Lubbe is Director of Research all within Autoliv Research, Vårgårda, Sweden.

Furthermore, the biofidelity of the dummy is dependent on the restraint system [9], a critical limitation for predicting injuries under varying restraint conditions. To overcome these issues, NHTSA supported biomechanical research to build an advanced dummy to supersede the Hybrid III. This resulted in the development of the Test device for Human Occupant Restraint 50th percentile male (THOR-50M) ATD, with improved biofidelity and better injury-detecting capabilities [10]. The THOR offers more sensors for judging injury risk than the Hybrid III [11] and is capable of measuring chest deflection at multiple points. In terms of the biofidelity, the THOR-50M offers enhanced restraint interaction with the shoulder and thorax, and flexible joints in the thoracic spine as well as the lumbar.

A 5th percentile female version of the THOR dummy (THOR-05F) has also been in development over the years [7][12]. Similar to the THOR-50M, the THOR-05F provides a more biofidelic and advanced ATD than the equivalent Hybrid III [13], with an overall biofidelity ranking of 1.52 (less than 2 and therefore equal to 'Good'). Changes to the THOR-50M include female-specific features, such as integrated sternum and breast design to improve belt position and female-specific pelvic bone geometry. Some other key characteristics of the THOR-05F include pressure sensors instead of Infra-Red Telescoping Rod for the Assessment of Chest Compression (IR-Traccs) in the abdomen (as used in the abdomen of the THOR-50M), a combined skull and facial load cell, offset of the humerus at the shoulder joint, and a redesigned ankle for better repeatability [12].

Currently, the THOR-50M is being specified by NHTSA and Euro NCAP for use in frontal crash tests, replacing the Hybrid III 50M. It is also expected that validation of the THOR-05F will follow soon: it may replace the Hybrid III 5th percentile. Therefore, it is important to study the performance of the THOR-05F in crash tests. The purpose of this study was to carry out a series of frontal crash tests on a sled under varying restraint conditions, in order to compare the restraint system interaction, forward displacement and thoracic injury risk assessment of the THOR-05F dummy with the Hybrid III 5th percentile dummy. The information was sought to understand the relatively new physical THOR-05F dummy, but also to generate data that could be used as a reference in the development of a model of the dummy in computer simulations.

II. METHODS

Test Setup

The 5th percentile THOR and Hybrid III female dummies were seated in a generic frontal occupant sled test setup as shown in Figure 1. This setup was developed within the EU project SENIORS [14] to provide an environment to test PMHSs with a generic, but modern, restraint system. It consists of a rigid seat base with two cable supports for the seat back. Tests using the THOR-50M in this buck were performed within the original project (Figure 1(a)), but the setup was not developed for testing with occupants of smaller size (Figure 1(b)).

Fig. 1(a). The previous test setup with THOR-50M.

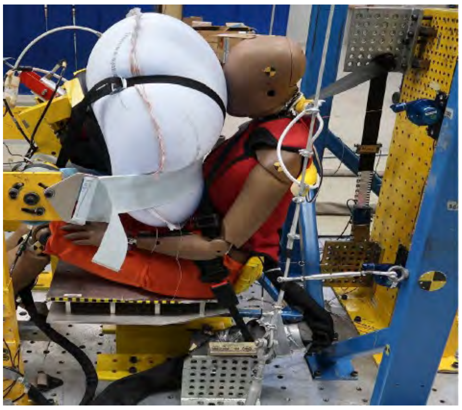


Figure 1(b). The test setup with THOR-05F.

An initial Computer-Aided Engineering (CAE) study was done to plan the test positions, building on experience from the THOR-50M percentile dummy, as its H-point (hip position) is known relative to the seat. The THOR-05F position was set with the same H-point as the THOR-50M; but, to compensate for its smaller size, with the whole seat moved, translated, 100 mm forward as shown in Figure 2 (a). The Hybrid III 5th percentile had the same H-point as the THOR-05F. To achieve this, the seat height of the Hybrid III 5th had to be raised by 20 mm to match the vertical (z-direction) hip-position, and further adjustments were made to align the positions of the head, neck, and torso. In addition, the footrest was moved (with respect to the 50th male position) to make sure that the heels were at the same point for both the 5th percentile dummies. The comparison of H-III 5th and THOR-05F positioning is shown in Figure 2 (b).

The CAE output provided target positions and tilt angles for the body segments that form the basis of the seating position for each dummy. The sequence followed to position the dummy was then: to place the dummy on the seat and foot-pans; position the H-point, feet and knees; check the pelvis tilt and thigh angles; check the thorax tilt (lower, middle and upper); position the head tilt, belt systems, hands and arms. This was run in a loop until tilt angles were within ± 2°, pelvis position was within ± 1 mm and the head position was ± 5 mm, for each dummy in each condition. These pre-test postures were then recorded with pictures, manual and digital measurements. The comparative positions of the head, the base of the neck and H-point between the Hybrid III 5th percentile and the THOR-05F in the airbag and no airbag conditions, all related to an H-point line on the seat base, is shown in Figure 2 (c). The alignment of the string potentiometers between the seat frame and rear of the dummy was checked in the same way as other positions, using a 3D measurement arm (Figure 2 (d)).

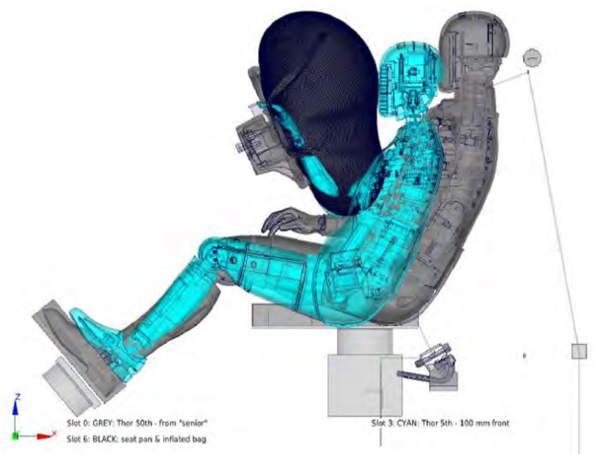


Fig. 2(a). Comparison of THOR-50M (grey) and THOR-05F (cyan) positioning.

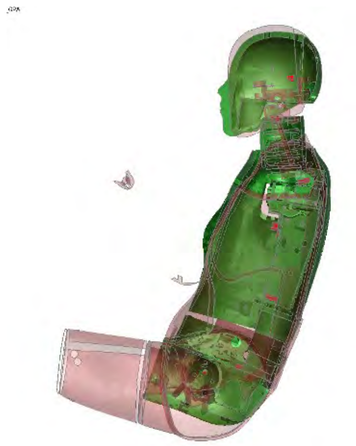


Fig. 2(b). Comparison of THOR-05F (maroon) and Hybrid III 5th (green) positioning.

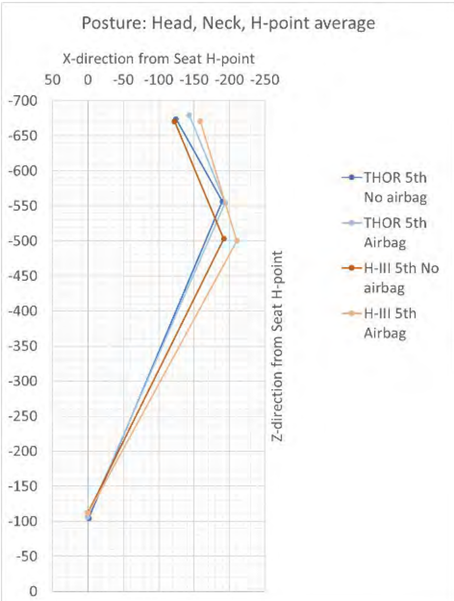


Fig. 2(c). Overlay of pre-test positions for the Hybrid III 5th and THOR-05F in tests with and without an airbag.

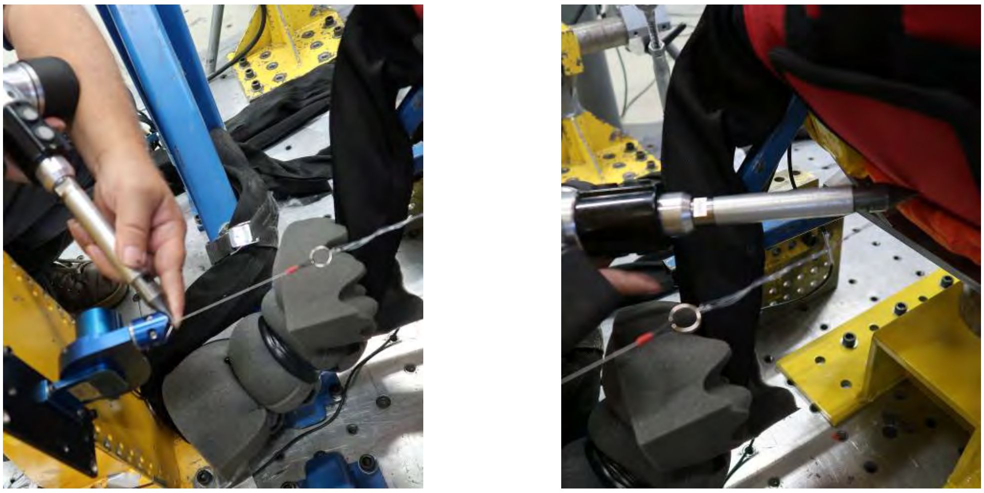


Fig. 2(d). Digital measurement of string potentiometer attachment points, lower rear (left) and lower front (right).

Restraint systems and test conditions

A B-pillar mounted belt system was used in all test conditions. Two different shoulder belt load limits were available, of either 2 or 4 kN. The time-to-fire for the load limiters was set to 20 ms after 'T0' (the start of the test acceleration). A retractor pretensioner and lap belt pretensioner were also used. They were triggered at 8 and 15 ms, respectively.

For most of the tests, a generic airbag was used, pre-inflated with compressed air (to 19 kPa). The airbag venting was controlled with an active device with a ventilation area of 8320 mm^2, triggered to vent at 10 ms. The generic bag from the SENIORS setup had to be modified with a simple strap placed around it so that it fitted between the steering wheel and dummy.

As in the SENIORS project, two different crash pulses were used (35 km/h and 56 km/h, as shown in Figure 3). The 4-kN load limiter was used only for the 56 km/h tests, while the 2-kN load limiter was used for both the 35 km/h and 56 km/h tests. With respect to pre-tensioning, both the retractor and lap belt units were fired except in the no airbag test condition with 35 km/h pulse, where only the shoulder belt system was used (with retractor pretensioning, but without lap-belt pretensioning).

Bringing the restraint system and other variables together (pulse, retractor load limiter, lap belt pre-tensioner, and airbag) there were four test conditions as shown in the test matrix in Table I. Two tests were run with both dummies in the 35 km/h no-airbag test condition, whereas there were three tests with each dummy in the airbag-equipped conditions.

Table I
TEST MATRIX

Speed	Shoulder belt load limiter	Lap belt pre-tensioning	Airbag	Number of tests with each dummy
35 km/h	2 kN	No	No	2
35 km/h	2 kN	Yes	Yes	3
56 km/h	2 kN	Yes	Yes	3
56 km/h	4 kN	Yes	Yes	3

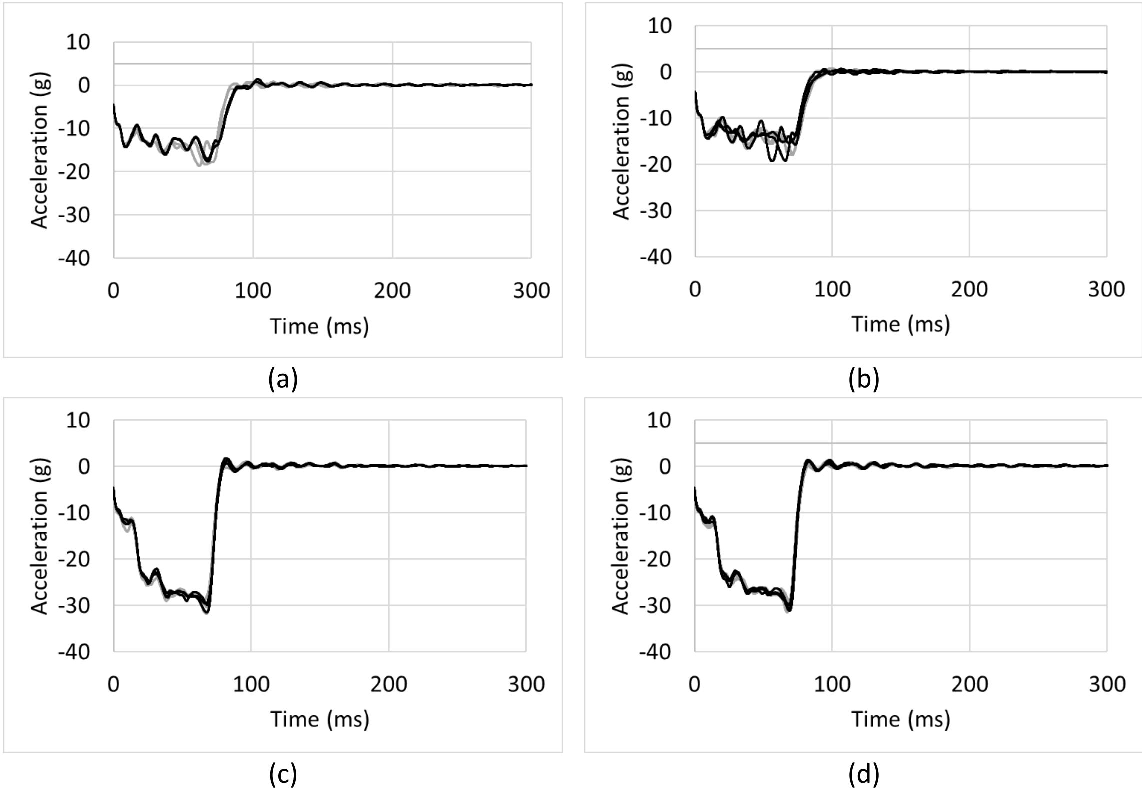


Fig. 3. Sled acceleration pulse for the test conditions (a) 35 km/h, no airbag; (b) 35 km/h, airbag; (c) 56 km/h, airbag, 2 kN; and (d) 56 km/h, airbag, 4 kN.

Measurements

Time-histories of the airbag pressure were derived from a pressure sensor (Kulite Semiconducter 8405-5-276). Belt forces were measured (using Messring DK-11-35-23 seat belt load cells) on the shoulder portion of the seatbelt between the upper anchorage point and the shoulder of the dummy and between the dummy and the buckle and also on the lap portion of the seatbelt between the dummy and the lower anchorage point. These measurements provided an assessment of the restraint being provided at the top of the thorax, the lower edge of the thorax and into the pelvis respectively.

The forward displacement of each dummy was measured via two string potentiometers (SpaceAge 162-2945-C8SS999) attached between the static framework on the sled and the back of the dummy. The lower measurement was taken at the back of the pelvis and the upper measurement was taken at the base of the neck, at the location of the bracket mounting the neck to the top of the thorax. The locations were not intended to be identical between the two dummies (Hybrid III 5th percentile and the THOR-05F). However, they were in similar locations and considered similar enough to support comparable observations on the general kinematics of the tests.

Loading to the chest of the dummies was assessed by the usual instrumentation: the sternal slider and rod potentiometer in the Hybrid III and the four-point IR-Traccs in the THOR-05F. The four points on the front of the chest in the THOR surround the central point in the Hybrid III. A comparison of the chest deflection locations in the two dummies is shown in Figure 4. The height of the anterior end of the Hybrid III slider (on the sternum) is expected to start close to the level of the lower points in the THOR, sliding upwards during compression of the chest. Displacements from the IR-Traccs in x, y and z-axes, as well as the resultant, were calculated from the raw IT-Tracc angles and change in length according to the THOR-50M 3D IR-Tracc User Manual [15] and the NHTSA procedures for the THOR-50M [16], but using a smaller calibration length. The largest peak resultant chest deflection value from any of the four IR-Traccs was used as the R_{max} criterion. The PC Score was also computed based on the four IR-Tracc outputs based on the published equation [17].

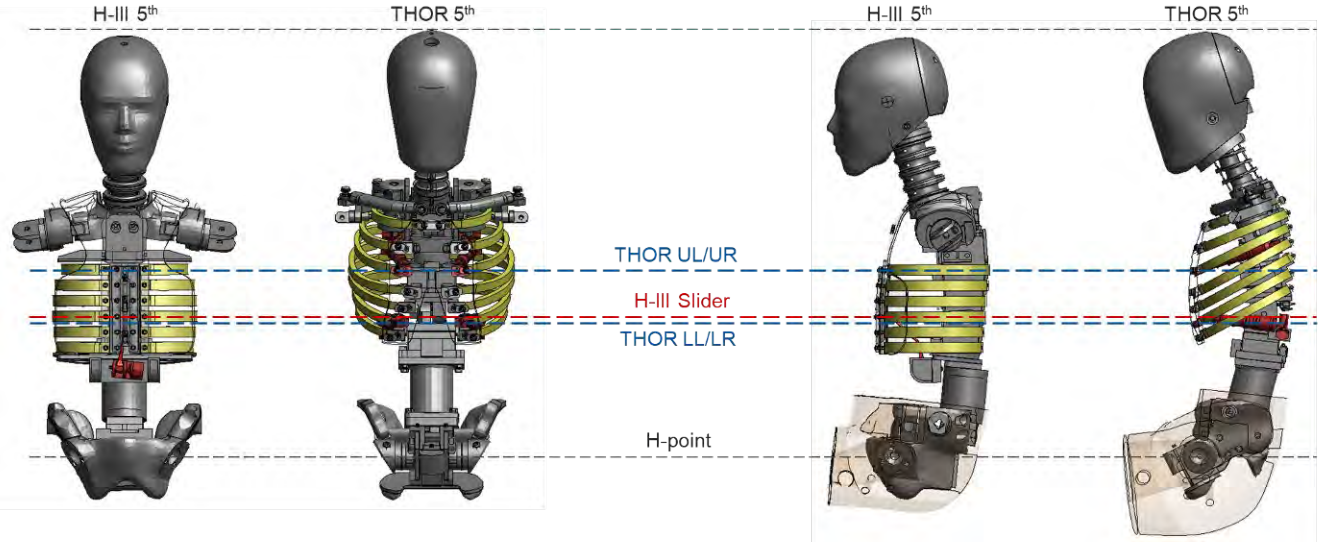


Figure 4. Locations of the chest deflection sensors in the Hybrid III 5th percentile and the THOR-05F.

III. RESULTS

To explore the behaviour of the 5th percentile female frontal impact dummies in this experimental setup with the SENIORS buck, results for the restraint system, dummy displacements and thorax deflections are presented. Small images taken from the high-speed video footage have also been included in the Appendix to show the overall dummy motion in example tests.

Three of the four test conditions featured an airbag and, as stated, the pressure started at a nominal value of 19 kPa, rose through occupant contact and then decreased to atmospheric pressure after about 100 milliseconds. The lower speed tests reached a lower peak pressure (approximately 25 kPa) than the higher speed tests (approximately 30 kPa).

The shoulder belt forces for the four test conditions, as measured between the shoulder of the dummy and the 'D-ring' upper anchorage, are shown in Figure 5. The effect of the load limiting function can be observed from this figure, as the shoulder belt forces with a 4 kN load limiter are about twice as high as the shoulder belt forces with a 2 kN load limiter. As with the differences in airbag pressure, the differences in upper shoulder belt forces for the two dummies were negligible.

The displacement of the upper part of the torso, as measured for each dummy by one of the string potentiometers, is shown in Figure 6. Peak excursion occurred about 100 milliseconds into the deceleration pulse when the shoulder belt forces and airbag pressure were returning to zero. Both the 35 km/h airbag test (with a 2 kN load limiter) and the 56 km/h airbag and 4 kN load limiter test had similar displacement time-histories. Both reached about 150 mm forward excursion at the top of the thorax. The test condition without an airbag generated twice this displacement. It should be remembered that the location for the attachment was not identical between the two dummies; therefore, small differences in total displacement were expected between them. However, the airbag pressure and shoulder belt force at the upper position showed similar results for the Hybrid III 5th and THOR-05F. Indeed, the neck displacement results indicate very similar behaviours between the two dummies. The most striking deviation between dummy results comes from the two THOR-05F tests without an airbag, where poor repeatability is shown in this parameter for that condition.

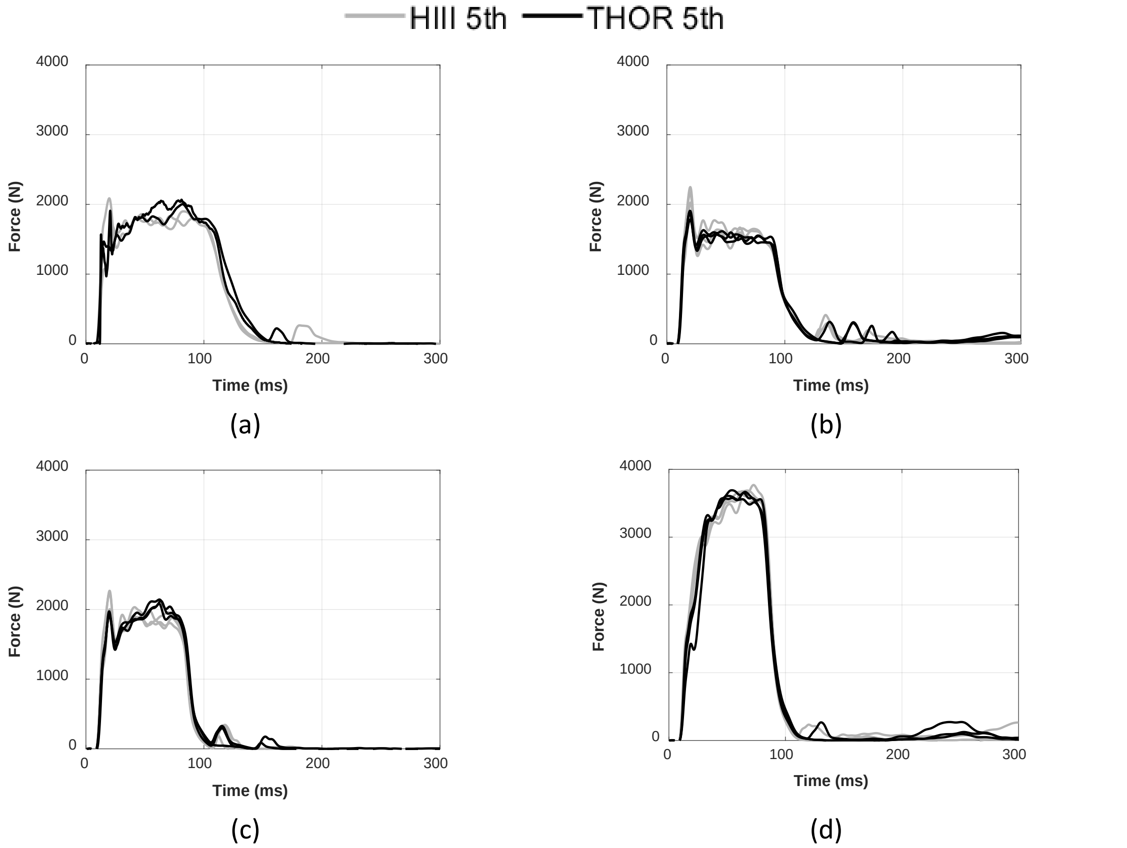


Fig. 5. Shoulder belt, upper, forces for the test conditions (a) 35 km/h, no airbag; (b) 35 km/h, airbag; (c) 56 km/h, airbag, 2 kN; and (d) 56 km/h, airbag, 4 kN.

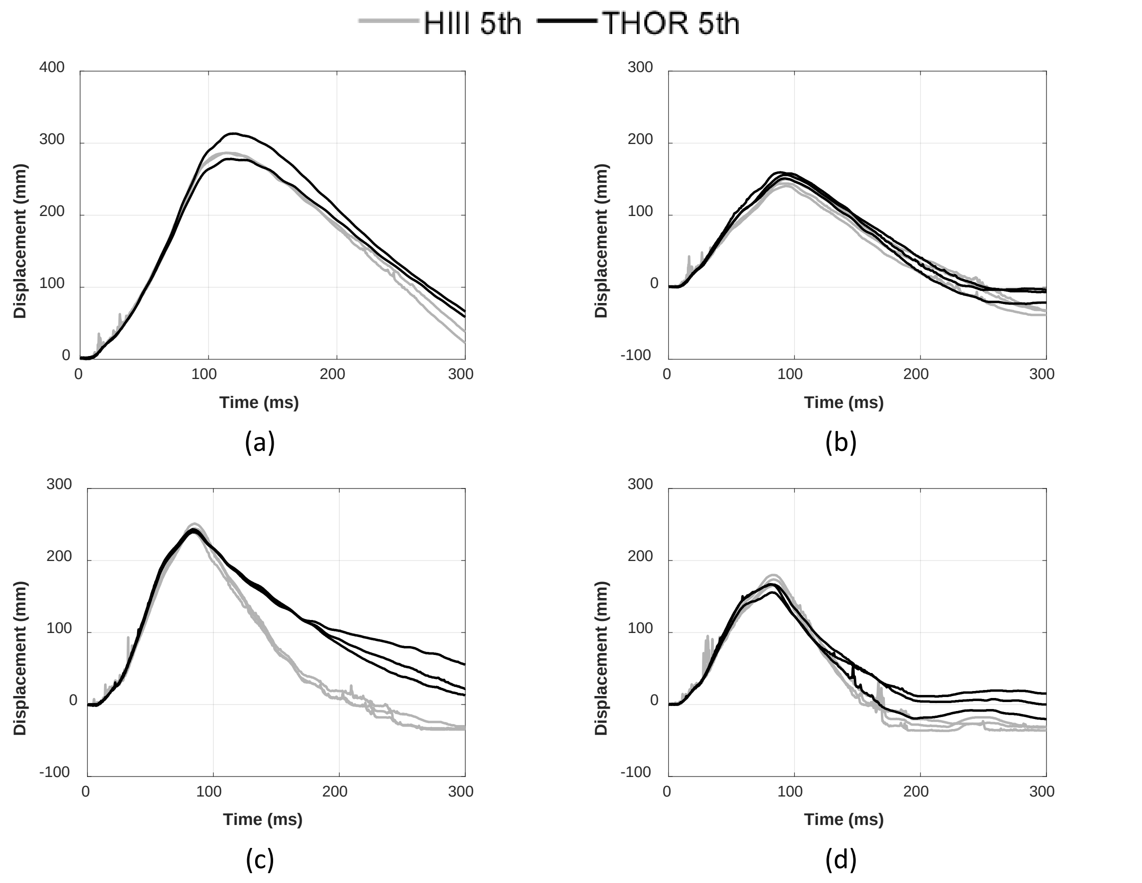
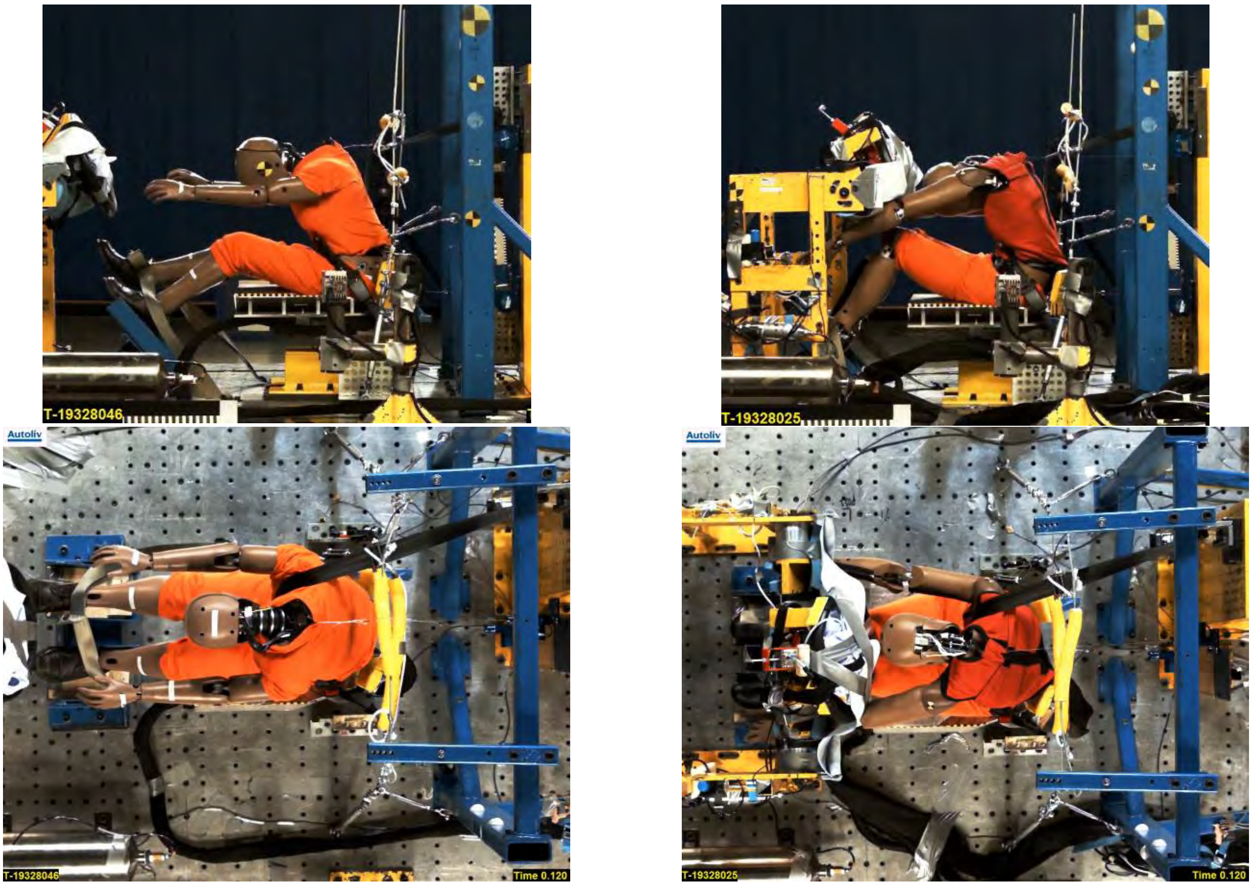


Fig. 6. Neck displacements for the test conditions (a) 35 km/h, no airbag; (b) 35 km/h, airbag; (c) 56 km/h, airbag, 2-kN load limiter; and (d) 56 km/h, airbag, 4-kN load limiter.

Example images from the 35 km/h test with no airbag are shown in Figure 7 from 120 milliseconds into the test, around the time of peak forward excursion in this condition. Supporting the quantitative kinematic analysis of the excursion at the top of the thorax, the images show a similar position of this part of the two dummies. However, the angle of the thorax is different; the Hybrid III 5th percentile thorax is leaning further forward than the THOR-05F. From the overhead view another difference in the motions of the dummies can be seen; with the left shoulder of the THOR-05F moving further forwards than the right (being restrained by the shoulder portion of the seat belt). The Hybrid III 5th percentile exhibits less differential motion of the shoulders and less twisting of the thorax (rotation around the z-axis). Please note that the frame for supporting the airbag was closer to the seat in the THOR-05F tests than the Hybrid III 5th tests. On review there was some contact between the hands of the THOR-05F and the fixture. This may have contributed to differences in neck displacements between these two THOR-05F tests.



H III 5th THOR-05F

Fig. 7. Images taken 120 ms into tests at 35 km/h without airbag, side view showing orientation of torso to legs and overhead view showing how the upper body of the THOR-05F twists towards the upper anchorage.

At the lower end of the shoulder belt, the force was measured between the dummy and the buckle. Forces from this measurement are shown in Figure 8. Generally, the 56 km/h tests generated more force here than the 35 km/h tests, changing the forces from approximately 1 kN to 2 kN. However, some subtle differences between the Hybrid III and THOR time-histories are evident: the (grey) Hybrid III curves have higher forces than the (black) THOR curves in the first 30 milliseconds in all cases except the 35 km/h airbag condition. The THOR may have the highest peak forces, as in the 56 km/h airbag and 2 kN load limiter condition, but those peaks occur later, around 60 ms.

As introduced in the Measurements Section, the forces restraining the dummies' pelvises were also measured at the lower anchorage (outer) side of the lap belt. Results from that load cell are shown in Figure 9. In each test condition the lap belt force was higher for the Hybrid III 5th percentile than for the THOR-05F in the early part of the loading, from approximately 15 to 35 ms. The lower force with the THOR-05F coincides with visible deformation of the pelvis flesh by the lap belt; this is less evident with the Hybrid III 5th percentile dummy (Figure 10).

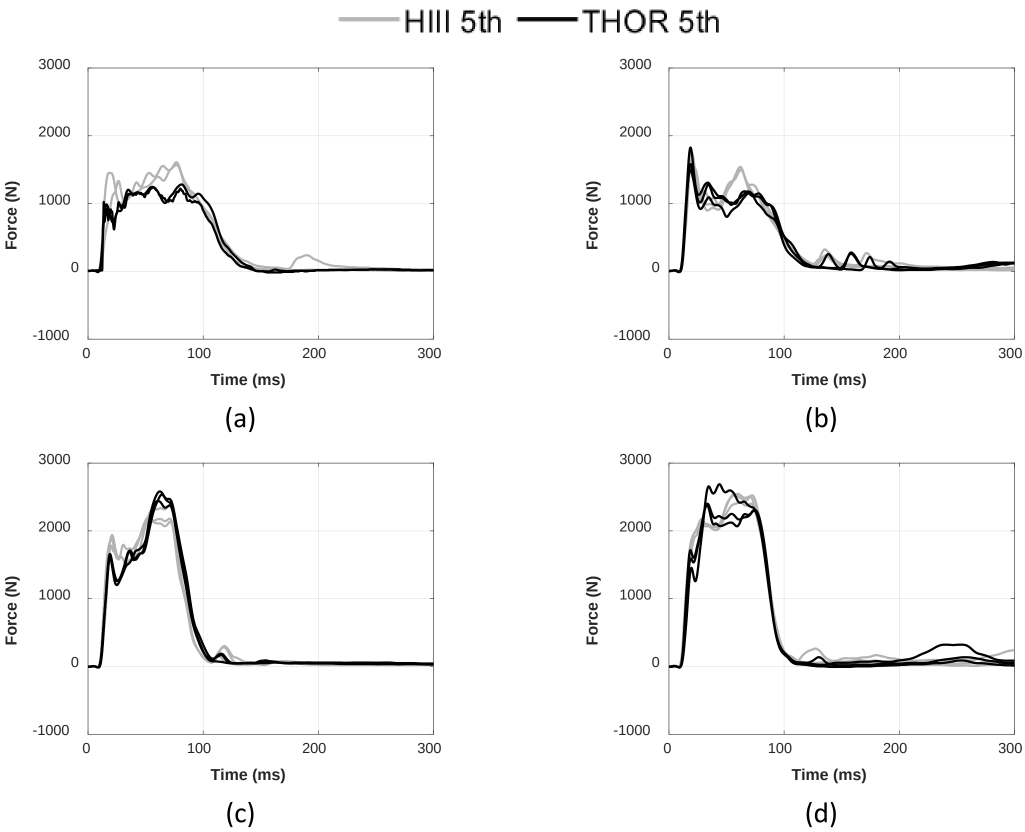


Fig. 8. Shoulder belt lower forces for the test conditions (a) 35 km/h, no airbag; (b) 35 km/h, airbag; (c) 56 km/h, airbag, 2 kN; and (d) 56 km/h, airbag, 4 kN.

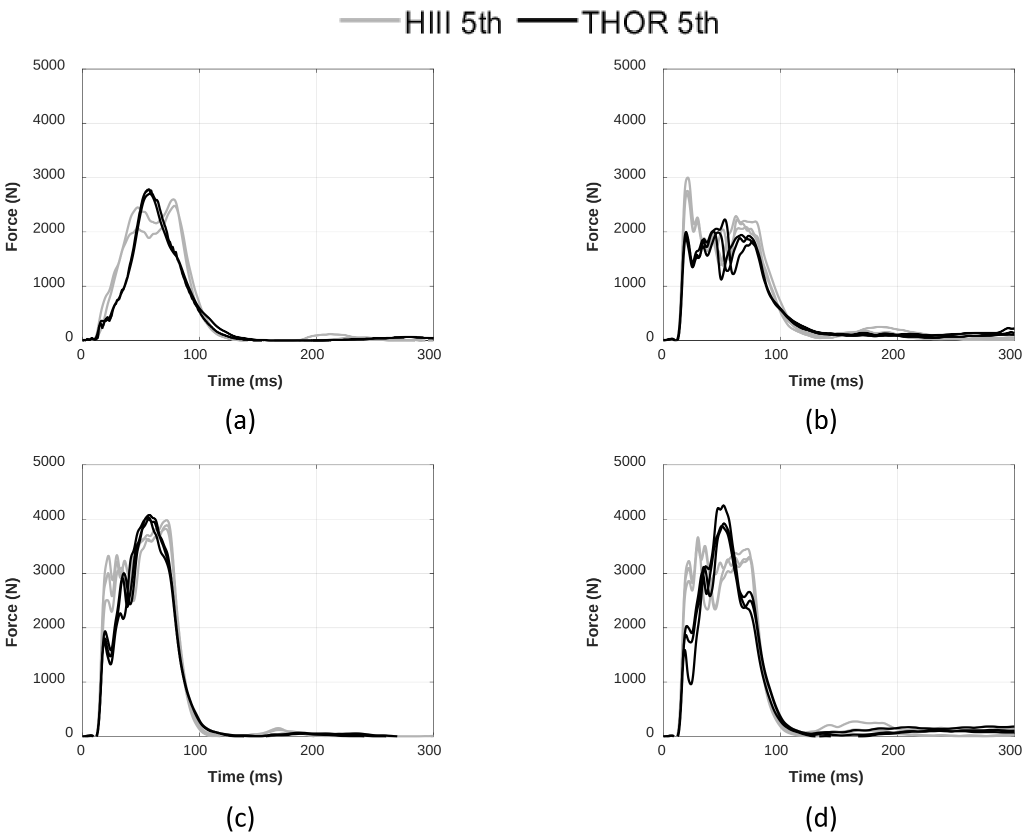
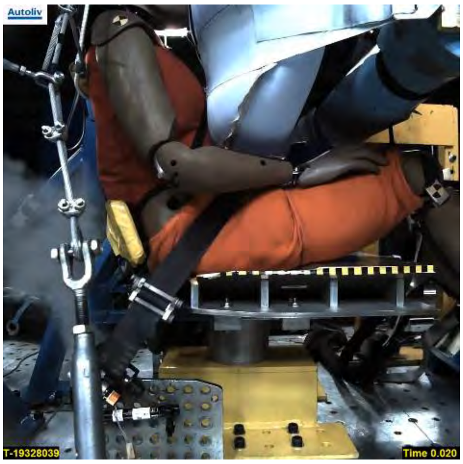


Fig. 9. Lap belt outer forces for the test conditions (a) 35 km/h, no airbag; (b) 35 km/h, airbag; (c) 56 km/h, airbag, 2 kN; and (d) 56 km/h, airbag, 4 kN.

H III 5th



THOR-05F

Fig. 10. Images taken 20 ms into tests at 56 km/h, with airbag and 2 kN load limiter showing the lap belt deforming the pelvis flesh of the THOR-05F more than the Hybrid III 5th percentile.

The consequences of this difference in force transferred through the lap belt for the two dummies is evident in the displacement of the pelvises. The pelvis displacement results are shown in Figure 11. Largest displacements occured in the conditions either without airbag and lap belt pretensioner or in the 56 km/h test with a 2 kN shoulder belt load limit. In both of these conditions, the Hybrid III 5th percentile dummy pelvis moved forward about 50 mm, whilst the THOR-05F moved forward by about 100 mm. The 35 km/h test with the airbag and lap-belt pretensioning produced the smallest forward excursion of the pelvis for both dummies.

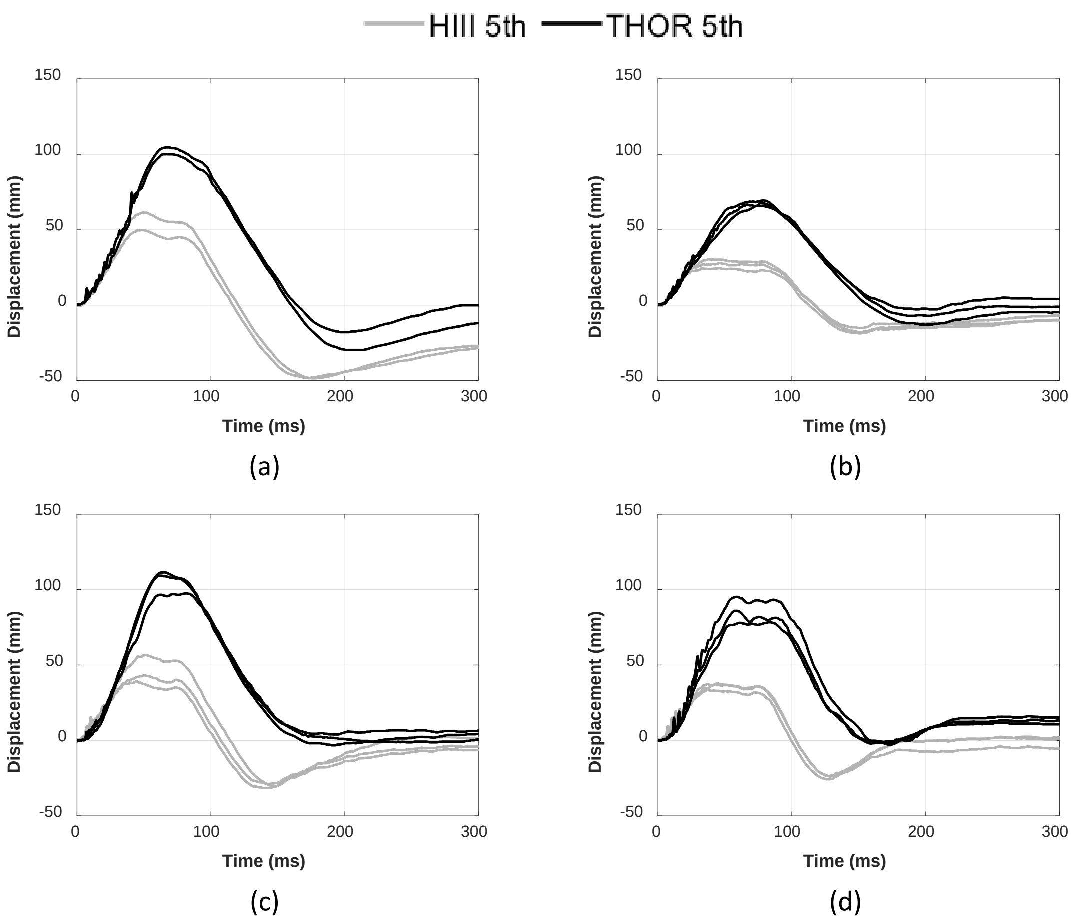


Fig. 11. Pelvis displacements for both dummies in the test conditions (a) 35 km/h, no airbag; (b) 35 km/h, airbag; (c) 56 km/h, airbag, 2 kN; and (d) 56 km/h, airbag, 4 kN.

In summary, the lap belt restrains the pelvis of the Hybrid III 5th percentile more than the THOR-05F. There is less compression of the pelvis flesh and so the belt force reaches a peak sooner with the Hybrid III than with the THOR-05F. The applied force limits the forward excursion, therefore the earlier rise in force can be said to 'restrain' the pelvis more. Comparisons of the mean peak displacements are summarised in Table II, along with the percentage difference in each condition. These results indicate the size of effect the lap belt to pelvis interaction can have on forward pelvis displacement.

TABLE II
MEAN PEAK PELVIS DISPLACEMENTS FOR THE HYBRID III 5TH AND THOR-05F,
SHOWING THE PERCENTAGE DIFFERENCE BETWEEN THE TWO DUMMIES IN EACH CONDITION (STANDARD DEVIATION IN PARENTHESES)

Displacements (mm)	35 km/h, no bag		35 km/h, airbag		56 km/h, airbag, 2kN		56 km/h, airbag, 4kN	
Hybrid III 5th	56	difference	28 (3)	difference	46 (9)	difference	36 (2)	difference
THOR-05F	102	184%	68 (2)	245%	106 (7)	228%	86 (8)	238%

Whilst the upper part of the torso appears to follow similar behaviour for the two dummies, the pelvis is different. Therefore, the Hybrid III and THOR achieved that same excursion of the top of the thorax in different ways. This may be important for assessing restraint system-induced injury risks; so, as a primary focus, the following results consider chest deflections for the two dummies. To provide a close comparison between them, the x-axis deflection from the THOR-05F IR-Traccs was compared with the sternal deflection from the Hybrid III 5th percentile. The single measurement output from the chest of the Hybrid III has been reproduced on the curves from both the upper (Figure 12) and lower measurement points in the THOR-05F (Figure 13): the Hybrid III results are the same in each figure. It should be noted that the upper-right deflection measurements from the THOR-05F are shown for only two of the three tests at each of the 56 km/h conditions, due to sensor damage.

The upper-right measurements from the THOR-05F (dotted black lines in Figure 12) follow the time-histories from the Hybrid III sternal measurements (grey lines) quite closely, at least for the first 100 milliseconds. The measurements from the upper left (solid black lines) have a similar shape but are much bigger in magnitude. The latter measurements indicate that, at the height of the upper measurement points in the THOR-05F, the shoulder belt was loading the left, buckle side of the chest more than the right, upper anchorage side. The effect of pretensioning the lap belt, as was done in all the airbag tests, is evident in the chest deflection results from the initial peak at around 25 ms. Notably, for the 35 km/h test with the airbag, the deflection from the pretensioning is larger than the subsequent restraint of the chest.

At the lower measurement points (shown in Figure 13), the same overall trends are seen. The right side of the THOR-05F sees compressions close in magnitude to that measured by the central sternum potentiometer in the Hybrid III 5th percentile. However, the extent of the difference between the left side of the THOR-05F (buckle side) and the Hybrid III is more pronounced. The overall deflections for the THOR-05F are greatest at the lower position, reaching almost 50 mm in the 56 km/h test condition with a 4 kN load limiter. The Hybrid III peak deflection in that condition is 22 mm, less than half that of the THOR-05F.

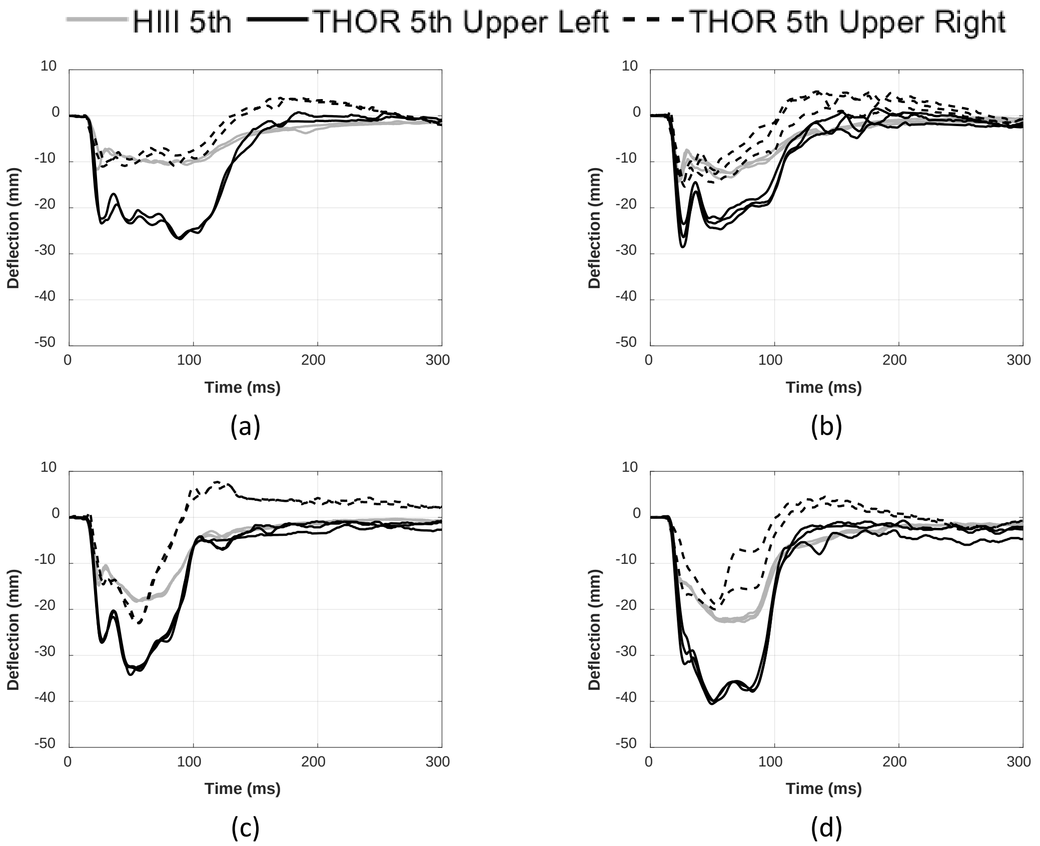


Fig. 12. Chest deflections from the Hybrid III sternum and the THOR upper measurement points in the x-axis (a) 35 km/h, no airbag; (b) 35 km/h, airbag; (c) 56 km/h, airbag, 2 kN; and (d) 56 km/h, airbag, 4 kN.

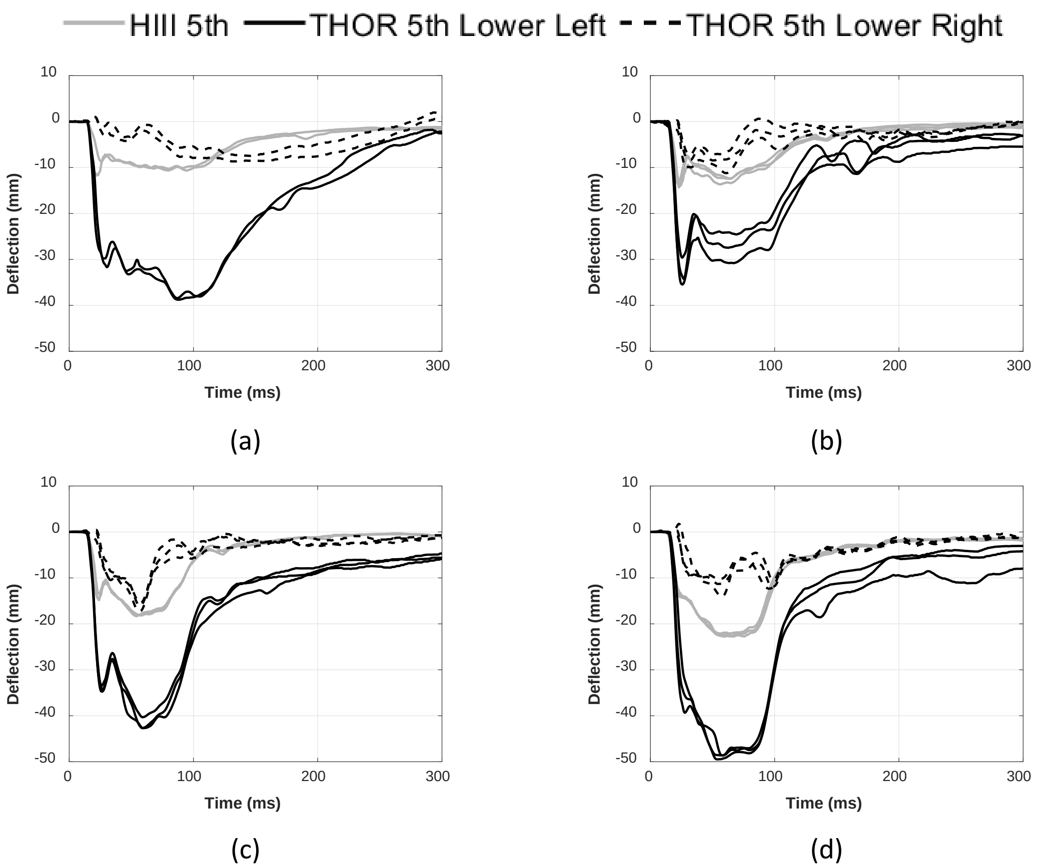


Fig. 13. Chest deflections from the Hybrid III sternum and the THOR lower measurement points in the x-axis (a) 35 km/h, no airbag; (b) 35 km/h, airbag; (c) 56 km/h, airbag, 2 kN; and (d) 56 km/h, airbag, 4 kN.

To aid comparisons of the magnitude of loading detected by the chest instrumentation in the Hybrid III 5th percentile and the THOR-05F, tables summarising the mean peak values are shown below. The mean peak values from the Hybrid III 5th percentile are shown in Table III for the four test conditions.

Peak loading to the chest of the THOR-05F was always registered at the lower measurement point on the buckle side. Darker shading is used in Tables IV and V to indicate the ranking of deflection values in each condition. Peak x-axis deflections are shown in Table IV and peak resultant deflections are shown in Table V. The size order of the peak deflections was always, lower-left, upper-left, upper-right and lower-right (the buckle being on the left in this experimental setup).

TABLE III
MEAN PEAK CHEST DEFLECTION MEASUREMENTS FOR THE HYBRID III 5TH PERCENTILE FEMALE
(STANDARD DEVIATIONS SHOWN IN PARENTHESES)

	35 km/h, no bag	35 km/h, airbag	56 km/h, airbag, 2kN	56 km/h, airbag, 4kN
Sternal deflection (mm)	11.0	13.7 (0.7)	18.2 (0.1)	22.5 (0.3)

TABLE IV
MEAN PEAK CHEST DEFLECTION (X-AXIS) MEASUREMENTS FOR THE THOR-05F (STANDARD DEVIATIONS SHOWN IN PARENTHESES)

Measurement point (mm, x-axis)	35 km/h, no bag		35 km/h, airbag		56 km/h, airbag, 2kN		56 km/h, airbag, 4kN	
UL *UR*	26.7	10.6	26.1 (2.5)	15.0 (0.7)	33.2 (0.7)	22.7†	40.1 (0.4)	19.4†
LL *LR*	38.6	8.1	33.1 (3.1)	9.0 (2.0)	41.6 (1.3)	16.2 (0.9)	48.9 (0.5)	12.4 (1.8)

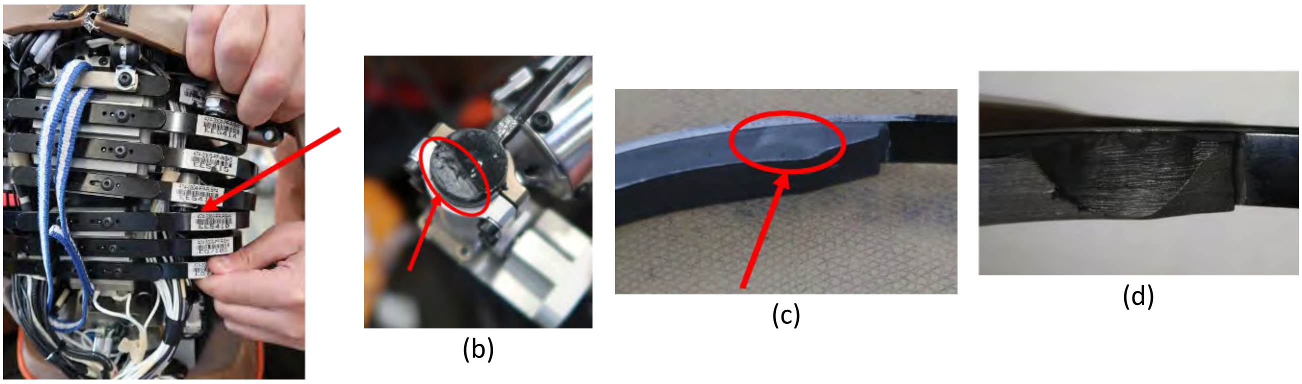
† MEAN OF TWO TESTS, NOT THREE

TABLE V
MEAN PEAK CHEST DEFLECTION (RESULTANT) MEASUREMENTS FOR THE THOR-05F
(STANDARD DEVIATIONS SHOWN IN PARENTHESES)

Measurement point (mm, resultant)	35 km/h, no bag		35 km/h, airbag		56 km/h, airbag, 2kN		56 km/h, airbag, 4kN	
UL *UR*	27.1	20.8	32.4 (3.1)	18.3 (1.9)	36.0 (1.1)	23.8†	42.1 (1.6)	20.0†
LL *LR*	39.8	13.4	34.3 (3.1)	14.8 (1.2)	41.9 (1.3)	18.4 (0.9)	50.5 (0.7)	18.1 (0.7)

† MEAN OF TWO TESTS, NOT THREE

One breakage was observed with the THOR-05F in this test series, leading to the removal of one of the upper-right chest deflection results from each of the 56 km/h test conditions (indicated by the '†' symbol in Tables IV and V). Images depicting the source of contact within the dummy are shown in Figure 14, with damage occurring to the z-angle sensor, after contact with the 5th rib and damping material. After discussion with Humanetics (the dummy supplier), some of the damping material was cut away from the rib and the test series was completed without other breakages.



(a) (b) (c) (d)

Fig 14. Damage to IR-Tracc in 56 km/h tests. (a) Extent of rib compression causing contact, (b) Contact mark on the IR-Tracc unit base, (c) Contact mark on rib damping material, and (d) Modification/removal of rib damping material to protect against further damage.

IV. Discussion

The kinematic observations from these tests are that, under the same test conditions, the Hybrid III 5th percentile and THOR-05F had the same forward excursion at the top of the thorax. However, the way this excursion was achieved differed between the two dummies. The THOR-05F showed greater forward excursion of the pelvis than the Hybrid III 5th percentile. Belt forces show earlier restraint of the Hybrid III pelvis than the THOR-05F (where belt forces stayed lower for longer). The lap portion of the seat belt compressed the flesh of the THOR-05F pelvic area. This allowed the pelvis 'bone' (dummy representation of the skeletal pelvis) to continue moving forwards and the pelvis excursion was based on this part, not the outer skin of the dummy.

Having the same excursion at the top of the thorax but not at the pelvis implies a different angle between the torso and legs. Whilst not confirmed quantitatively, this behaviour was observed in this study. With more forward leaning, the Hybrid III 5th will tend to have a greater portion of the shoulder belt force directed towards the top of the thorax and the clavicle. Potentially these kinetic belt interactions could be investigated further with computer simulations; however, at least we already observe large deflections of the THOR-05F thorax at the lower measurement point on the seatbelt buckle side.

The intention with the SENIORS buck was to provide a simple and generic, but representative, sled test setup to add to information gathered using other, more severe, test conditions with known injury risks. The seat includes a rigid base and there was no sign of submarining in these tests. In this study we stepped away from the original setup in dummy size, airbag dimensions and seat position, varying the restraint system features to produce the test conditions described above. Therefore, we cannot be certain of the injury risk expected with these setups. However, some hypotheses can be made around the effect of increasing sled speed and increasing shoulder belt force which would be expected to increase thoracic injury risk. For instance based on real-world observations from collision data, at 35 km/h we may expect 5 to 15% risk of AIS2+ injury to the thorax from a production vehicle system, at 56 km/h between 10 and 50%, depending on the age of occupant [18-19].

The injury risk relationship to sternal deflection for the Hybrid III 50th percentile male dummy has been established [20]. Scaling factors have been provided to convert the injury risk relationship to dummies of other sizes [21]; that scaling has been applied to create risk curves for the Hybrid III 5th percentile female dummy [22]. The injury risk function was used to convert peak sternal chest deflection from the Hybrid III 5th percentile female dummy into a probability of AIS 3+ (serious to fatal) thoracic injury (for a 45 year old occupant; as used in NCAP, new car assessment programmes). As with the underlying deflection, thoracic injury risk based on the Hybrid III sternal deflections was lowest in the 35 km/h test with no airbag at a very low 0.9%. It increases slightly with the addition of the airbag and lap-belt pretensioning to 1.5%. The 56 km/h tests elicited higher risks than the 35 km/h conditions, and the 4 kN load limiter produced almost double the risk of the 2 kN condition (6.1% versus 3.2%, respectively).

Equivalent functions relating the THOR-05F thoracic deflection data to injury risk are not available yet; therefore, it is not known how the observations regarding dummy motions and chest deflection transform into assessment of risk. Without these functions it is not possible to determine how the results in this paper will influence future requirements for restraints systems. We do not know how the risk functions will accentuate or mitigate the differences between the Hybrid III 5th and THOR-05F chest deflections. To investigate potential risk, the same scaling used for the Hybrid III dummies was applied to some of the measures proposed for use with the THOR-50M. This meant adopting the factor of 0.817 [21] was applied to reduce the THOR-50M deflection variables to the THOR-05F scale. It should be noted that applying the principle of geometric similitude and maintaining chest compression would lead to a smaller factor (e.g., 0.76, as used by NHTSA in scaling the biomechanical response requirements [23]). However, as demonstrated in the following tables, the predicted risks from the THOR-05F are already high with respect to the real-world collision-data risks and using a smaller factor would elevate the THOR-05F predictions further.

The criteria considered for use with the THOR-05F chest deflection measurements were R_{max} [16], the maximum resultant deflection occurring at any of the four measurement points and PC Score [17], which includes the peak deflection at the upper points, the lower points and the side-to-side differentials too. Also, by calculating the peak mean deflection from either the top two measurement points, the bottom two points or all four, it was hoped that the THOR chest deflection could be related to the Hybrid III and hence the Hybrid III 5th percentile risk function could be used. Considering individual measurement points alone should lead to the situation where the multi-point deflection measurement of the THOR-05F over predicts risk compared with the Hybrid III 5th percentile. That is the value of having more deflection measurements, in principle it can reduce sensitivity to belt lie because the seatbelt should always lie over at least one of the points. In this case, peak deflection was measured at the lower left (buckle side) of the dummy suggesting good alignment with the shoulder belt.

The outputs from these trials relating observed peak deflections to injury risk predictions are shown in Table VI. For consistency, none of these metrics include the two tests in which damage to the upper-right IR-Tracc was observed. It should also be noted that there is no suggestion that Hybrid III 5th percentile risk function is to be used with THOR-05F measures without validation of the derived predictions. The initial assumption would be that the dummies and the instruments used to measure chest deflection are unequivocal. However, such an approach is applied here to stimulate discussion and show how sensitive the injury risk predictions are to potential approaches used to derive them.

Not only the THOR-specific injury measures (R_{max} and PC Score), but even the measures approximating those from the Hybrid III are higher from the THOR-05F than from the Hybrid III 5th percentile. In the low speed, 35 km/h test with an airbag and lap-belt pretensioning, the THOR values place the risk of serious thoracic injury at over 35%. That is, there is more than a one-in-three chance of receiving such an injury. Whereas in the same test, the Hybrid III 5th percentile places the risk of serious thoracic injury at 1.5%: a one-in-67 chance. These assessments are very different and give different impressions of the safety associated with the test condition.

Limiting the injury prediction to just the upper measurement points and taking the mean of left and right produces the closest prediction to that coming from the Hybrid III 5th. This finding helps explain two observations. Firstly, that (probably exacerbated by the rotation of the thorax about the z-axis and towards the upper anchorage) the belt has moved away from the centre of the thorax, even at the height of the upper thorax; therefore, a central measurement chest deflection measurement underestimates the loading to the left side. There is some compensation for that by taking the mean of left and right as the right-sided measurement is even further from the applied shoulder belt force. Secondly, with the forward movement of the pelvis and lack of pitching forward of the thorax, the THOR-05F exposes the lower thorax to shoulder belt loading that is not observed to the same extent and not measured with the Hybrid III 5th. By limiting the assessment to the upper chest deflection measurement points only, this THOR-05F specific loading is negated.

As mentioned, the THOR-specific injury risk values in Table VI indicate a much higher risk of AIS3+ injury than the measures approximating those from the Hybrid III. This is an 8-fold increase between the peak mean from all four points and the PC Score in the 35 km/h tests with an airbag. The impression of safety or understanding of risk is built on the dummy interaction with the restraint system, measurement capabilities and the interpretation of the measures to give predictions of injury risk. Each of these aspects is different between the Hybrid III 5th percentile and the THOR-05F. However, these results show how influential that final step (converting deflection measurements to a prediction of injury risk) can be in developing the impression of safety.

TABLE VI
MEAN AIS 3+ THORACIC INJURY RISK BASED ON CANDIDATE THOR-05F INJURY METRICS

Thoracic AIS3+ injury risk for a 45-year-old occupant (%)	35 km/h, no bag	35 km/h, airbag	56 km/h, airbag, 2kN	56 km/h, airbag, 4kN
R_{max}	53.0	38.5	58.2	78.1
PC Score	37.0	35.2	54.1	72.2
Mean of UL and UR	3.2	4.5	12.4	15.0
Mean of LL and LR	6.3	4.4	13.2	17.0
Mean or UL, UR, LL and LR	4.5	4.4	12.6	15.4

The intention with pretensioning is to provide early coupling between the occupant and the restraint system. Based on the measurements from the chest instrumentation in both the Hybrid III 5th percentile and the THOR-05F, it was observed that the peak in deflection (and therefore the injury risk value) in the lower speed 35 km/h with airbag test came from the pretensioning of the seat belt. The lower left measurement point in the THOR-05F was more sensitive to this loading than the central sternum deflection in the Hybrid III 5th percentile dummy. This observation may enable further optimisation of pretensioning force levels in comparison to the loading to the occupant during the inertial motion phase. However, caution should be used as the chest of the THOR-05F deflects more than the biofidelity target in lower thorax oblique loading [14].

V. LIMITATIONS

The design of this study derived key kinematics from the excursion measurements at the top of the thorax and the pelvis. At the time, that was thought to be appropriate for the developmental status of the THOR-05F and experience with that dummy. Further quantification of behaviour could be provided by 3D motion tracking. With funding, this could be a next step in evaluating the THOR-05F, along with reproduction of these early THOR-05F observations in another seating environment.

The experimental setup in the no airbag tests with the THOR-05F kept the steering wheel support frame closer to the dummy than for the equivalent Hybrid III 5th percentile tests. According to the plan, this frame should not have had any involvement in these tests but contact with the hands of the THOR-05F was noted. Unfortunately, these two tests exhibited poor repeatability of neck displacement, so it could be that a small error of judgement in practical test execution had a negative effect on the results. With more testing this could be confirmed. Another explanation could be some contact between the dummy's jacket or seatback cables with the string of the string potentiometer. It is difficult to conclude one way or the other based on the videos.

VI. CONCLUSIONS

The sled testing carried out for this study using the SENIORS Project buck (without any knee bolster or knee airbag) allows us to conclude that the lap portion of the seatbelt restrains the Hybrid III 5th percentile pelvis more than that of the THOR-05F dummy. The flesh of the THOR-05F pelvis deforms more than the Hybrid III 5th preventing early coupling of the rigid pelvis with the lap belt and allowing the THOR-05F to slide further forwards on the seat base.

Peak loading from the shoulder portion of the seatbelt to the THOR-05F chest always occurred on the left (buckle-side) and was greater at the lower measurement point than the upper. These left-sided chest deflections are substantially larger than (even at the upper point, being up to twice) those measured with the central sternum deflection sensor in the Hybrid III 5th percentile.

This generic buck setup was also able to demonstrate that the Hybrid III 5th percentile dummy is sensitive to changes in impact severity and changes in seat belt load limit and changes moving from 'seat belt only' to 'lap-belt pretensioned and airbag'. The THOR-05F is also sensitive to the features of the restraint systems used in our testing.

Thoracic injury risk values derived on the basis of chest deflection metrics showed substantially higher predictions of risk with the THOR-05F than with the Hybrid III 5th percentile. These injury risk predictions are not dummy-specific for either dummy (being scaled from a mid-size male dummy) and should be taken with caution.

Nevertheless, based on these observations, the THOR-05F will need different optimisation between pelvis and torso loads in order to manage better the forward pelvis displacement and give less predicted risk of thoracic injury.

VII. ACKNOWLEDGEMENTS

The THOR-05F used in this study was provided by Humanetics. This work received financial support from the FFI Fordonsstrategisk Forskning och Innovation partnership programme (FFI-Strategic Vehicle Research and Innovation; www.vinnova.se/ffi), through the Assessment of Passenger Safety in Future Cars Project, with funding from Vinnova (Sweden's Innovation Agency), the Swedish Energy Agency, the Swedish Transport Administration and the Swedish vehicle industry. The authors would like to thank Dr K. Mayberry for language revisions.

VIII. REFERENCES

[1] Crandall, J.R., Bose, D., et al. (2011) Human surrogates for injury biomechanics research. Clinical Anatomy, 24(3): p.362-371

[2] Kan, C.-D., Marzougui, D., and Bedewi, N.E. (2003) Development of a 50th percentile Hybrid III dummy model. *Proceedings of the Fourth European LS-DYNA Users Conference,* 2003,Ulm, Germany.

[3] Schneider, L. (1983) The University of Michigan Transportation Research Institute, *Development of anthropometrically based design specifications for an advanced adult anthropomorphic dummy family, volume 1. final report*, Michigan.

[4] Kahane, C.J. (2013) National Highway Traffic Safety Administration, *Injury vulnerability and effectiveness of occupant protection technologies for older occupants and women,* Washington D.C.

[5] Bose, D., Segui-Gomez, S., Maria, and Crandall, J.R. (2011) Vulnerability of female drivers involved in motor vehicle crashes: an analysis of US population at risk. American Journal of Public Health, 101(12): p.2368-2373

[6] Parenteau, C.S., Zuby, D., et al. (2013) Restrained male and female occupants in frontal crashes: Are we different? *IRCOBI Conference Proceedings,* 2013, Gothenburg, Sweden.

[7] Shams, T., Huang, T., Rangarajan, N., and Haffner, M. (2003) Design requirements for a fifth percentile female version of the THOR ATD. *Proceedings of 18th International Technical Conference on the Enhanced Safety of Vehicles,* 2003, Nagoya, Japan.

[8] carhs. *Safety Companion 2020*, https://www.carhs.de/en/companion-poster/product/safetycompanion-2021-pdf-download.html. [2020]

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

[10] Ridella, S. and Parent, D. (2011) Modifications to improve the durability, usability, and biofidelity of the THOR-NT dummy. *Proceedings of 22nd ESV conference,* 2011, Washington D.C.

[11] Humanetics. "Next-gen ATD improves data" Internet secure.viewer.zmags.com/publication/a476aeeb#/a476aeeb/1. [retrieved 2020].

[12] Wang, Z., McInnis, J., Benfant, L., Feng, Z., Lee, E. (2017) THOR 5th Percentile Female ATD Design. *Proceedings of 25th International Technical Conference on the Enhanced Safety of Vehicles (ESV),* 2017, Detroit, Michigan.

[13] Wang, Z. J., Below, J., Loeber, B., Greenlees, B. (2020) National Highway Traffic Safety Administration, *Biofidelity report of the THOR 5th percentile anthropomorphic test device*. Report No. DOT HS 812 853.

[14] Eggers, A., Ott, J., et al. (2017) A new generic frontal occupant sled test set-up developed within the EU-project SENIORS. *Proceedings of Conference on the Enhancement of Safety Vehicles (ESV)*, 2017, Michigan.

[15] Humanetics. (2016) Humanetics Innovative Solutions Inc., *THOR-50M 3D IR-TRACC User Manual*, *TF-472-6000-9900.*

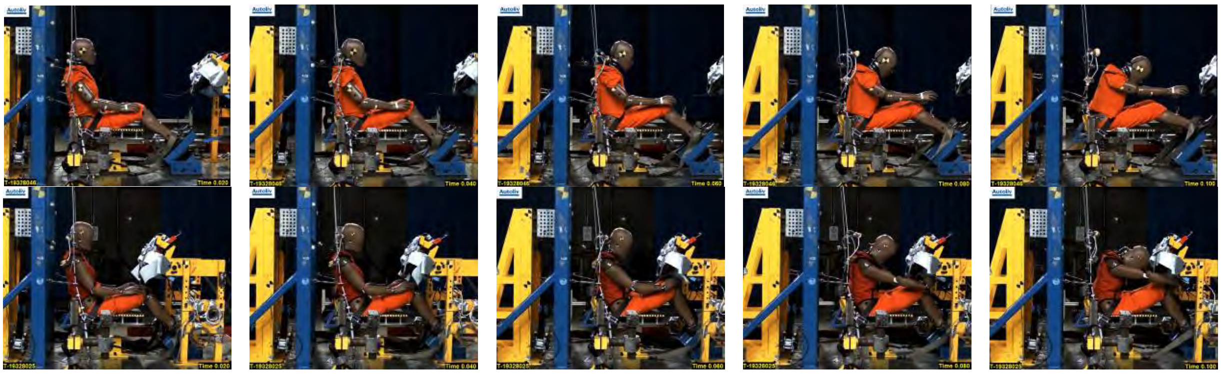
[16] Craig, M., Parent, D., Lee, E., Rudd, R., Takhounts, E., Hasija, V. (2020) National Highway Traffic Safety Administration, *Injury criteria for the THOR 50th male ATD*.
[17] Poplin, G.S., McMurry, T.L., Forman, J.L., Ash, J., Parent, D.P., Craig, M.J., Song, E., Kent, R., Shaw, G., Crandall, J. (2017) Development of thoracic injury risk functions for the THOR ATD. Accident Analysis & Prevention. Volume 106: p.122-130, https://doi.org/10.1016/j.aap.2017.05.007. 2017.
[18] Weaver, A. A., Talton, J. W., et al. (2015) Estimated Injury Risk for Specific Injuries and Body Regions in Frontal Motor Vehicle Crashes. Traffic Injury Prevention, 16:sup1, S108-S116.
[19] Wisch, M., Lerner, M., Vukovic, E., Hynd, D., Fiorentino, A., Fornells, A. (2017) Injury patterns of older car occupants, older pedestrians or cyclists in road traffic crashes with passenger cars in Europe. *IRCOBI Conference Proceedings, Antwerp,* 2017, Belgium.
[20] Mertz, H., Horsh, J., Horn, G., Lowne, R. (1991) Hybrid III sternal deflection associated with thoracic injury severities of occupants restrained with force-limiting shoulder belts. SAE Transactions Vol. 100, Section 6: Journal of passenger cars, pp.1108-1122.
[21] Mertz, H.J., Irwin, A.L., Prasad, P. (2016) Biomechanical and scaling basis for frontal and side impact injury assessment reference values. Stapp Car Crash Journal, Vol. 60: pp.625-657.
[22] Laituri, T., Prasad, P., Sullivan, K., Frankstein, M., Thomas, R. (2005) Derivation and Evaluation of a Provisional, Age Dependent AIS 3+ Thoracic Risk Curve for Belted Adults in Frontal Impacts. SAE Techincal Paper No. 2005–01–0297.
[23] Lee, E.L., Parent, D.P., Craig, M.J., McFadden, J., Moorhouse, K. (2020) National Highway Traffic Safety Administration, *Biomechanical response manual: THOR 5th percentile female NHTSA advanced frontal dummy, Revision 2. Report No. DOT HS 812 811*, Washington D.C.

IX. APPENDIX

Images from video footage

H III 5th

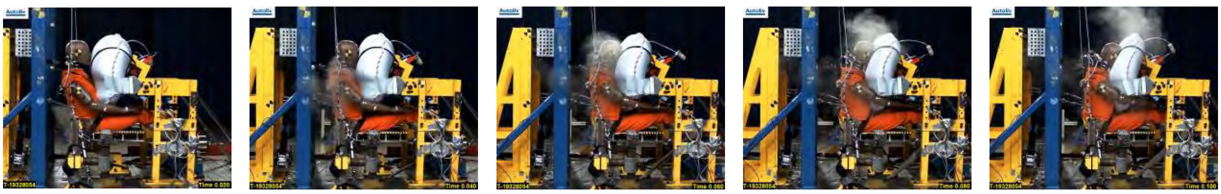
THOR-05F



Time (ms) 20 40 60 80 100

Fig. AI. Still images from example tests with condition 35 km/h, no airbag.

H III 5th



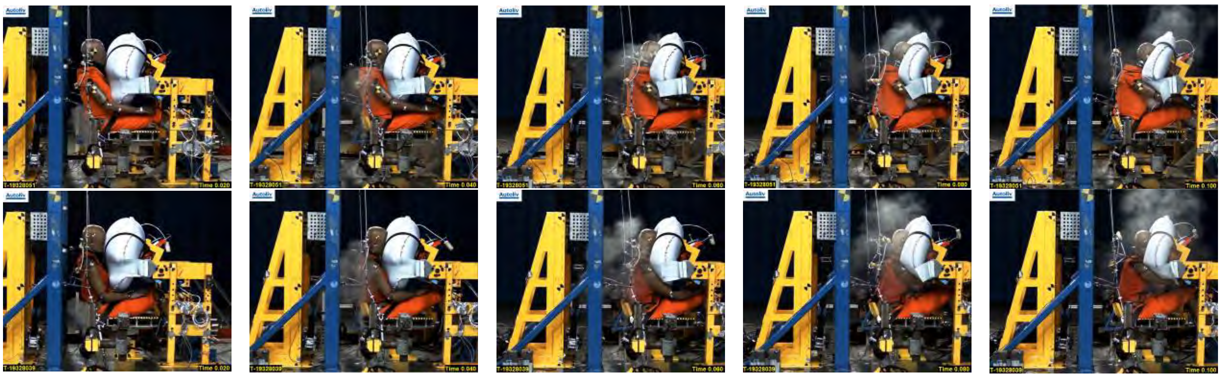
THOR-05F

Time (ms) 20 40 60 80 100

Fig. AII. Still images from example tests with condition 35 km/h, airbag.

H III 5th

THOR-05F

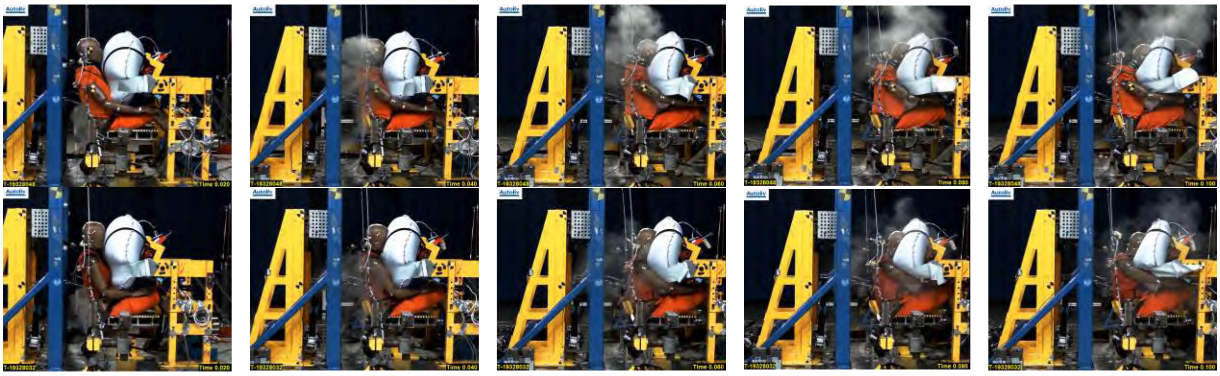


Time (ms) 20 40 60 80 100

Fig. AIII. Still images from example tests with condition 56 km/h, airbag, 2 kN.

H III 5th

THOR-05F



Time (ms) 20 40 60 80 100

Fig. AIV. Still images from example tests with condition 56 km/h, airbag, 4 kN.