Comparison of the THOR 5th to the Hybrid III 5th in Full Scale Frontal Crash Tests

Kathy Tang, Suzanne Tylko, Alain Bussières

Abstract The objectives of the study were to observe the interactions of the THOR 5th percentile ATD with the second-row restraint system in passenger cars undergoing frontal crash tests and to compare the responses of the THOR 5th with the Hybrid III 5th. The THOR 5th was placed in the second-row seats of 13 vehicles undergoing 48 km/h moving car-to-moving car frontal offset tests and four vehicles undergoing 56 km/h full-frontal rigid barrier tests. The frontal offset sample included seven pairs of vehicles where the Hybrid III 5th and THOR 5th were each placed in the same seat position of identical vehicles crashed in the same configuration. In the frontal barrier tests, the Hybrid III 5th and THOR 5th were placed in adjacent outboard positions of the same vehicle.

The THOR 5th appeared to display greater rotation about the shoulder belt than the Hybrid III 5th and greater forward excursion when the lap belt penetrated the abdomen. In frontal offset tests, torso flexion and frequency of lap belt penetration were greater for the THOR 5th than for the Hybrid III 5th. The improved motion and advanced sensing capabilities of the THOR 5th have highlighted the potential to advance protection for female passengers in second-row seats.

Keywords frontal impact, Hybrid III 5th, THOR 5th, pressure sensors, rear seats.

I. INTRODUCTION

The Canadian Motor Vehicle Safety Standard for frontal occupant protection (CMVSS 208) includes requirements assessed in a 56 km/h full-frontal rigid barrier (FFRB) test. The test protocol requires that the Hybrid III 5th percentile female anthropomorphic test device (ATD), which is representative of a small female, be seated in the driver and first-row passenger seats in the foremost track position. A similar test also exists in the United States' Federal Motor Vehicle Safety Standard (FMVSS 208). In North American regulatory standards, frontal impact protection of the 5th percentile female occupant is not assessed for any other passenger vehicle seating position.

Recent shifts in commuter preferences as well as the increasing adoption of advanced and autonomous vehicle technologies have highlighted the need to investigate occupant safety in seating positions other than those specified by the current regulatory protocols. In accident analyses of newer passenger vehicle models, the risk of fatality was found to be greater in the second row than in the first row [1-2]. At the same time, accident analyses revealing a disparity in crash outcomes between adult male and adult female occupants [3-5] has highlighted the need for improved test devices that can better represent female occupants.

In consumer test programmes around the world, the addition of the Hybrid III 5th in second-row seats of passenger vehicles is being implemented in frontal crash test protocols. In the upcoming Moderate Overlap 2.0 test of the Insurance Institute for Highway Safety (IIHS), a Hybrid III 5th will be placed in the second-row left-side seat [6]. In the European New Car Assessment Programme (Euro NCAP), the full width rigid barrier test introduced in 2015 includes a Hybrid III 5th seated in the driver and second-row right-side positions [7].

Transport Canada conducts research to provide the scientific evidence necessary for the development of regulations. Since 2003, crashworthiness research programmes at Transport Canada have included frontal impact testing with the Hybrid III 5th seated in positions other than that defined by the CMVSS 208 protocol [8-11]. In frontal offset and FFRB tests, motions of the Hybrid III 5th were found to be more variable when placed in second-row seats than when placed according to regulatory protocols. For example, rearward rotation of the torso and translation of the ATD to the front edge of the seat cushion were found to occur in second-row seats only [10-11]. The results of previous studies have suggested that certain limitations of the Hybrid III 5th may become apparent only in vehicle environments where ATD motions can be greater than those observed in the foremost track position of first-row seats [11].

The THOR 5th percentile ATD was designed to have better biofidelity than the Hybrid III 5th [12]. The THOR 5th is equipped with advanced instrumentation, such as four IR-TRACC sensors and abdominal pressure twin sensors

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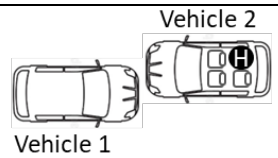
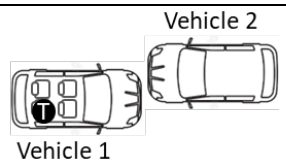
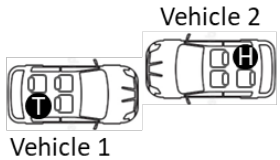
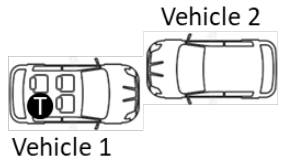
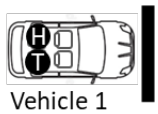
(APTS) [13]. Unlike the Hybrid III 5th, which is a scaled down version of the larger Hybrid III 50th percentile male ATD [14], the THOR 5th was designed with female-specific geometries. The pelvis geometry of the THOR 5th, for example, was derived from a small female pelvis model that accounts for differences in shape between male and female pelvises [12][15-16]. In this study, we compared the responses of the THOR 5th and Hybrid III 5th percentile ATDs in the second-row seats of vehicles undergoing frontal offset and FFRB impacts.

II. METHODS

Test Matrix

The test sample (TABLE I) consisted of 14 moving car-to-moving car frontal offset tests conducted at 48 km/h (Figure 1A, left) and four FFRB tests conducted at 56 km/h (Figure 1B, left). The frontal offset vehicle-to-vehicle configuration is a representative collision scenario in the field and is well-suited for paired comparisons. The overlap in frontal offset tests was 40% of the width of the narrower vehicle. Vehicles were propelled by a Messring closed loop electrically powered system and guided by a Messring MicroTrack rail (MESSRING Systembau GmbH, Krailling, Germany).

TABLE I
TEST MATRIX

Test #	Crash configuration	Vehicle 1	Vehicle 2	Schematic of THOR 5th (T) and HIII 5th (H) placement
1	Frontal offset	2016 Toyota Camry	2019 Nissan Leaf	
2	Frontal offset	2019 Nissan Leaf	2016 Toyota Camry	
3	Frontal offset	2020 Chevrolet Equinox	2019 Toyota Camry	
4	Frontal offset	2019 Toyota Camry	2020 Chevrolet Equinox	
5	Frontal offset	2020 Hyundai Accent	2018 Chevrolet Sonic	
6	Frontal offset	2018 Chevrolet Sonic	2020 Hyundai Accent	
7	Frontal offset	2021 Honda Civic	2021 Toyota Corolla	
8	Frontal offset	2021 Toyota Corolla	2021 Honda Civic	
9	Frontal offset	2019 Nissan Micra	2020 Kia Forte	
10	Frontal offset	2020 Jeep Cherokee	2021 Volvo XC-40	
11	Frontal offset	2014 Chevrolet Impala	2021 Genesis G70	
12	Frontal offset	2021 Subaru Crosstrek	2020 Mitsubishi Eclipse Cross	
13	Frontal offset	2021 Nissan Sentra	2020 Chevrolet Bolt	
14	Frontal offset	2020 Chevrolet Bolt	2021 Subaru Crosstrek	
15	FFRB	2021 Nissan Murano	N/A	
16	FFRB	2022 Honda Civic	N/A	
17	FFRB	2021 Ford F150	N/A	
18	FFRB	2022 Subaru Impreza	N/A	

Vehicle models were selected based on restraint characteristics (e.g. anchorage locations, seat geometry and distance to front seat) as well as availability of a compatible striking vehicle. In 13 of the 14 frontal offset tests, the THOR 5th (Humanetics Innovative Solutions, Farmington Hills, Michigan, USA) was placed in the second-row right-side seat of Vehicle 1 (Figure 1A, middle). Seven of the frontal offset tests using the THOR 5th were matched with another test in the sample for which the Hybrid III 5th was placed in the same seat of the same vehicle model impacting the same striking vehicle model. The remaining six frontal offset tests with the THOR 5th were added to the test sample to investigate the capabilities of the THOR 5th in a greater variety of vehicle environments. In

each of the four FFRB tests, the Hybrid III 5th and THOR 5th were placed in adjacent second-row outboard seats (Figure 1B, middle).

Both ATDs were positioned in the centre of the seat with the calves touching the front of the seat cushion. The feet were flat with the heels contacting the floor, and the hands were placed on the thighs. The THOR 5th thoracic spine was set to the *neutral* position. The D-ring was not adjustable in the vehicles tested. ATD positioning was recorded using a FaroArm Platinum Arm 3D metrology system (FARO, Lake Mary, Florida, USA).

Fig. 1. Photos of crash configuration (left), THOR 5th installation (middle), and Hybrid III 5th installation (right) in (A) moving car-to-moving car 40% frontal offset and (B) FFRB tests.

Instrumentation and Post-Test Inspection

Uni-axial accelerometers (Endevco 7264B, Meggitt, Irvine, California, USA or MSI 64B, TE Connectivity, Schaffhausen, Switzerland) were mounted on a triaxial block and installed at the approximate centre of gravity of each vehicle. Uni-axial accelerometers were also placed at the base of each B-pillar.

Instrumentation of the THOR 5th and Hybrid III 5th are specified in TABLE II. In the Hybrid III 5th, rib deflections were measured using the potentiometer at the centre of the chest and the RibEye system (Boxboro Systems, Boxborough, Massachusetts, USA), which is an electro-optical measurement device described in [9]. The RibEye was installed at 12 locations across the chest as per the User's Manual for Model 7530B. Load cells were also installed on the shoulder and lap belts. Data were recorded at 20 kHz and filtered in accordance with SAE J211.

TABLE II
INSTRUMENTATION OF THE THOR 5TH AND HYBRID III 5TH

Instrumentation	THOR 5th	Hybrid III 5th
Accelerometer	Head	Head
	T1, T6, T12	Chest
	Pelvis	Pelvis
Load cell	Upper and lower neck	Upper and lower neck
	T12	Lumbar spine
	Left and right iliac spine	Left and right iliac spine
	Left and right acetabulum	Left and right femur
Angular rate sensor	T6, Pelvis	
Potentiometer		Chest
RibEye		Left and right, Ribs 1-6
IR-TRACC	Left and right upper chest	
	Left and right lower chest	
APTS	Left and right abdomen	

High-speed videos were recorded at 1000 frames/sec. Cameras were positioned to obtain a lateral view of the

outboard side of the ATD, an oblique view of the inboard side of the ATD, and a frontal view. The second-row right side door was removed in frontal offset tests to obtain an unobstructed lateral view. In FFRB tests, both second-row doors were removed.

Throughout testing, the data traces and videos were reviewed to identify signal abnormalities that could be indicative of potential ATD damage. The ATDs were stripped and visually inspected after each test.

Data Analysis

Occurrence of partial or complete lap belt migration was identified using the lateral, oblique, and frontal (Figure 2A-B) camera views. Partial lap belt migration was defined as the sliding of the lap belt off the pelvis and into the abdomen on one side of the ATD but not the other. Complete lap belt migration was defined as the sliding of the lap belt off of both sides of the ATD pelvis such that the entire length of the belt penetrated the abdominal cavity. The iliac loads were also examined to determine whether the ATD interaction with the lap belt could be considered submarining as defined by Euro NCAP [17].

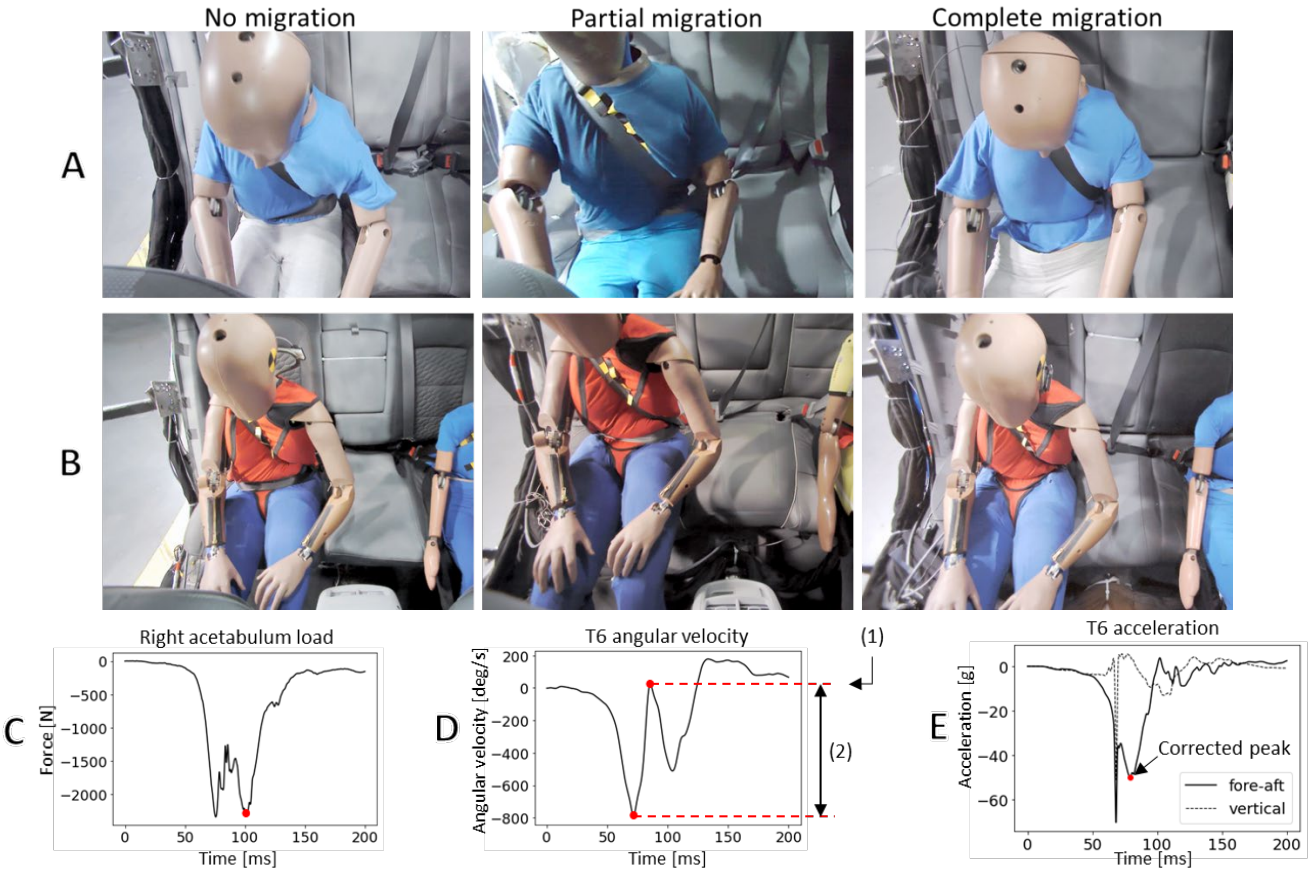


Fig. 2. (A-B) Freeze frames showing no lap belt migration, partial lap belt migration, and complete lap belt migration on the (A) Hybrid III 5th and (B) THOR 5th. (C) Estimation of the approximate time of leg rebound from acetabulum force-time response. (D-E) Peak detection in the T6 angular velocity and fore-aft acceleration responses of the THOR 5th.

Signal interference in the RibEye deflection, characterised by a plateau at approximately 90 mm, was found in multiple tests. The interference of the RibEye signal was attributed to displacement of the abdominal insert. Ribs where signal interference was found were excluded from analysis.

In each test with the THOR 5th, the deflections recorded by the four IR-TRACC sensors were aggregated. The peak IR-TRACC deflection was defined as the magnitude of the greatest peak fore-aft deflection measured among the four IR-TRACC sensors. Similarly, the peak RibEye deflection of the Hybrid III 5th was defined as the magnitude of the greatest peak fore-aft deflection measured among the RibEye sensors.

In tests with the THOR 5th, the approximate time at which each of the legs began to rebound was estimated by inspection of the acetabulum force-time trace and review of high-speed videos (example for the right acetabulum shown in Figure 2C). The estimated time of rebound was that at which the acetabulum force reached its local minimum. If more than one local minimum was present in the force-time trace, the selected minimum was the one that occurred when the leg appeared in videos to begin its rebound. If the estimated time of rebound was

not the same for the left and right legs, the earlier of the two times was recorded.

Local extrema in two of the time-varying kinematic responses of the THOR 5th were detected using the *find_peaks* function of the Python package SciPy version 1.2.1 [18]. Briefly, the function searches for local extrema, defined as points whose magnitude is greater than those of its two adjacent neighbours, and returns the locations of local extrema that meet optional user-defined criteria. Three user-defined criteria were used: minimum thresholds for peak height, peak width, and peak prominence, where peak prominence is the height of a peak relative to its baseline. The computations of peak characteristics are detailed in the SciPy documentation [19-21].

Local extrema in the THOR 5th T6 sagittal plane angular velocity response were detected using *find_peaks* with the minimum peak prominence set to 50 deg/s (minimum height and width were not specified). Under the assumption that the first two peaks consisted of a local minimum followed by a local maximum, two values were recorded: (1) the value of the local maximum, and (2) the difference between the two local extrema (Figure 2D).

In multiple tests, the T6 fore-aft and vertical acceleration-time traces of the THOR 5th showed a sharp spike within the first 75 ms of the impact (Figure 2E). Video review revealed no evidence of contact between the ATD and either itself or the vehicle interior at the time of the spike. In tests where the spike appeared in both the fore-aft and vertical acceleration-time traces within 1 msec of each other, *find_peaks* was used to locate the greatest magnitude peak in the fore-aft acceleration after excluding the spike. The value, referred to hereafter as the *corrected* T6 peak, was required to have a height of at least 20 g and a width of at least 1 msec (prominence was not specified). Of the local minima identified by *find_peaks*, the local minimum with the greatest magnitude was the aberrant spike; the recorded corrected peak was the local minimum with the second-greatest magnitude.

The paired t-test was used to compute the statistical significance of the difference in peak kinematic and kinetic responses between THOR 5th and Hybrid III 5th in frontal offset tests.

III. RESULTS

Video Observations

In both frontal offset and FFRB tests, the THOR 5th appeared to exhibit greater torso rotation about the shoulder belt than the Hybrid III 5th. In frontal offset tests, thoracic spine flexion as well as the frequencies of lap belt migration and submarining (as defined by Euro NCAP), were greater for the THOR 5th than for the Hybrid III 5th (TABLE III). Furthermore, when complete lap belt migration occurred, both torso extension and pelvis excursion of the THOR 5th appeared to exceed that of the Hybrid III 5th. Finally, contact between the head and arm occurred for the THOR 5th but not the Hybrid III 5th. Example freeze frames of the two ATDs at the approximate time of peak head excursion in frontal offset and FFRB tests are shown in Figure 3.

TABLE III
SUMMARY OF LAP BELT INTERACTION WITH THOR 5TH AND HYBRID III 5TH

ATD	N	# tests with complete lap belt migration (% of N)	# tests with partial lap belt migration (% of N)	# tests with submarining (% of N)
Frontal offset tests – all tests				
THOR 5th	13	8 (61.5%)	1 (7.7%)	3 (23.1%)
Hybrid III 5th	7	2 (28.6%)	0 (0.0%)	0 (0.0%)
Frontal offset tests – only vehicle models in which THOR 5th and Hybrid III 5th were both tested				
THOR 5th	7	3 (42.9%)	1 (14.3%)	0 (0.0%)
Hybrid III 5th	7	2 (28.6%)	0 (0.0%)	0 (0.0%)
FFRB tests				
THOR 5th	4	2 (50%)	2 (50%)	1 (25%)
Hybrid III 5th	4	2 (50%)	2 (50%)	3 (75%)

In Example 1 (FFRB test), the THOR 5th and Hybrid III 5th remained upright as they translated forward and flexed at the lower neck. In the frontal view, the thorax of the THOR 5th appears to have rotated about the shoulder belt, with the belt displaced towards the distal end of the clavicle. By contrast, rotation of the Hybrid III 5th torso appears to be minimal, with the shoulder belt displaced towards the ATD neck. On the inboard side but not the outboard side of the two ATDs, the lap belt migrated into the abdomen.

In Example 2 (FFRB test), the lap belt migrated into the abdomen of both the THOR 5th and Hybrid III 5th. In lateral views, the THOR 5th pelvis translated forward to the front edge of the seat cushion. By contrast, translation of the Hybrid III 5th pelvis stopped before reaching the seat cushion edge. The torso of the Hybrid III 5th maintained a more upright posture than the torso of the THOR 5th. As in Example 1, rotation about the shoulder belt appeared to be greater for the THOR 5th than for the Hybrid III 5th, with the shoulder belt located more distally on the THOR 5th clavicle than on that of the Hybrid III 5th.

Finally, the lateral views in Example 3 (frontal offset test) reveal that THOR 5th flexed at the lower spine whereas the Hybrid III 5th remained upright. In the frontal views, the THOR 5th again appears to have rotated about the shoulder belt, but rotation of the Hybrid III 5th appears to be minimal. The shoulder belt has entered the gap between the shoulder and arm of the THOR 5th, while the belt remains on the clavicle of the Hybrid III 5th.

Following peak head excursion, the THOR 5th head continued to rotate towards its chest. The freeze frames in Figure 4, taken from the same tests as in Figure 3 but later in time, show the ATDs at the approximate time of greatest neck flexion. In Example 1, the THOR 5th remained upright, and the neck flexed such that the face of the ATD was rotated toward its chest. In Example 2, the THOR 5th pelvis remained in place while the lower torso extended. Again, the face of the ATD rotated toward the chest. Finally, in Example 3, the lower spine and neck of the THOR 5th continued to flex forward until the head contacted the thigh. In each of the three examples, the torso orientation of the Hybrid III 5th appeared to be comparable to the orientation observed at peak head excursion. In all three examples, the chin of the Hybrid III 5th appeared to have contacted the upper chest.

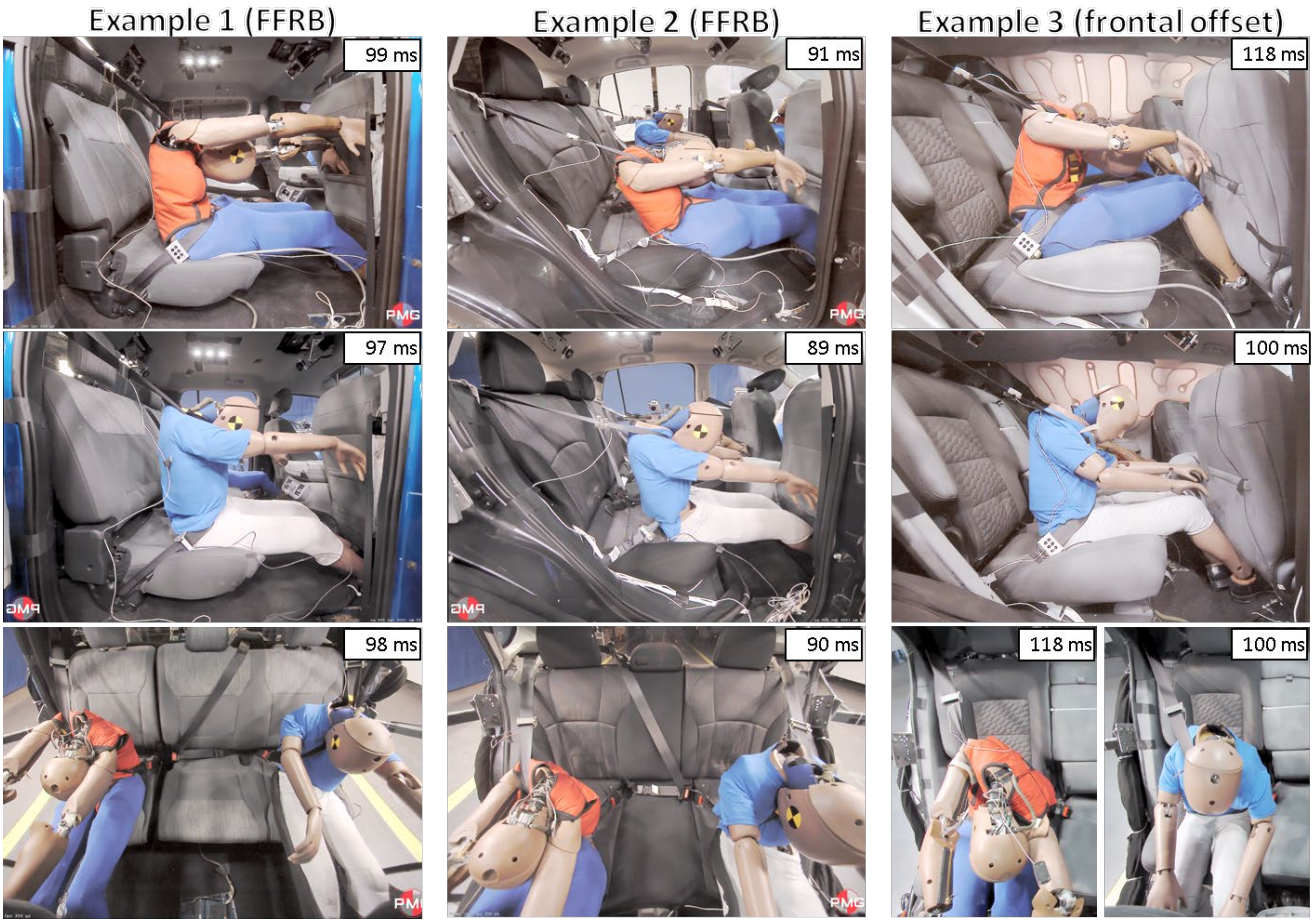


Fig. 3. Freeze frames taken from three tests showing lateral views of the THOR 5th and Hybrid III 5th (top and middle, respectively) and a frontal view of both ATDs (bottom) at the approximate time of peak head excursion. Lateral view freeze frames of the Hybrid III 5th were flipped to facilitate comparison with freeze frames of the THOR 5th.

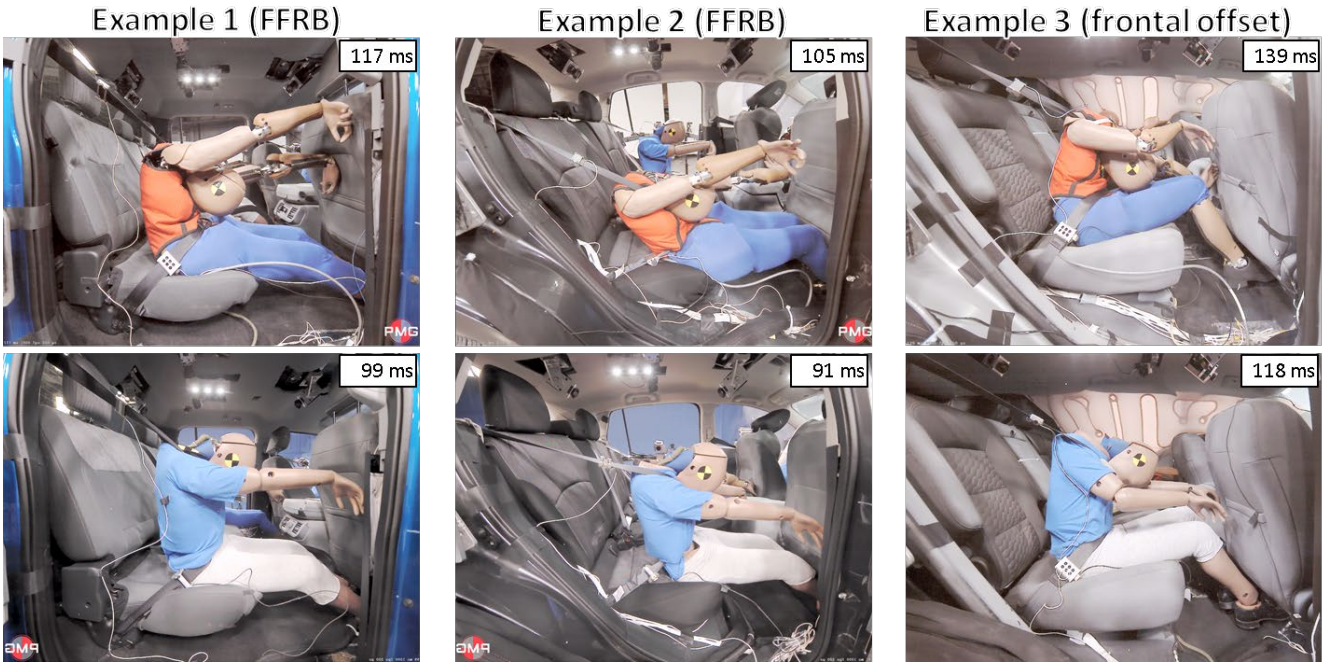


Fig. 4. Freeze frames taken from three tests showing lateral views of the THOR 5th and Hybrid III 5th (top and bottom, respectively) at the approximate time of peak neck flexion. Freeze frames of the Hybrid III 5th were flipped to facilitate comparison with freeze frames of the THOR 5th.

Comparison of THOR 5th and Hybrid III 5th Kinematic and Kinetic Responses

Peak kinematic and kinetic responses of the two ATDs were compared to each other after controlling for vehicle model. In the frontal offset test sample, responses of the THOR 5th were compared to those of the Hybrid III 5th tested in the same vehicle model impacting the same striking vehicle model (n=7, Figure 5, plotted in black). In this test sample, the difference in peak right B-pillar acceleration between vehicles of the same model ranged from 0.4 g to 8.4 g. In the FFRB test sample, the responses of the THOR 5th were compared to those of the Hybrid III 5th seated in the same vehicle (n=4, Figure 5, plotted in grey). The paired t-test was used to compute the statistical significance of differences in response in pairs of frontal offset tests where the THOR 5th and Hybrid III 5th were matched by vehicle model (TABLE IV).

On aggregate, the peak head fore-aft and resultant accelerations of the THOR 5th were not statistically significantly different from those of the Hybrid III 5th (TABLE IV, Figure 5A-B). However, differences in the head responses were influenced by contact between the ATD head and its arm or pelvis flesh, which was observed with the THOR 5th but not the Hybrid III 5th. The peak head fore-aft and resultant accelerations of the THOR 5th coincided with head contact on the arm or pelvis flesh in 12 frontal offset tests and one FFRB test.

At the upper neck, peak tension was greater for the THOR 5th than for the Hybrid III 5th (Figure 5C, p=0.006), whereas the opposite was true of peak flexion and extension (Figure 5D-E, p=0.003 and p=0.010, respectively).

In the chest, the peak IR-TRACC fore-aft deflection of the THOR 5th was always greater than the peak potentiometer deflection of the Hybrid III 5th (Figure 5F). In all but one test, the peak IR-TRACC fore-aft deflection of the THOR 5th also exceeded the peak RibEye fore-aft deflection of the Hybrid III 5th (Figure 5G).

The corrected peak T6 fore-aft acceleration of the THOR 5th was always greater than the peak chest acceleration of the Hybrid III 5th (Figure 5H). Interestingly, the magnitude by which the peak T6 acceleration of the THOR 5th exceeded the peak chest acceleration of the Hybrid III 5th remained fairly constant as a function of vehicle model. In any pair of tests conducted with the same vehicle model, the difference in the peak T6 and chest accelerations of the THOR 5th and Hybrid III 5th ranged 5.1 g to 11.8 g in frontal offset tests and 6.2 to 16.1 in FFRB tests. As a result, the response of the Hybrid III 5th was linearly correlated with that of the THOR 5th (Figure 5H, Pearson R=0.98 for responses recorded from frontal offset tests). No other correlations between the peak kinematic and kinetic responses of the THOR 5th and Hybrid III 5th were found.

While not statistically significantly different, the peak right iliac load and pelvis fore-aft acceleration of the Hybrid II 5th tended to exceed those of the THOR 5th (Figure 5J-K).

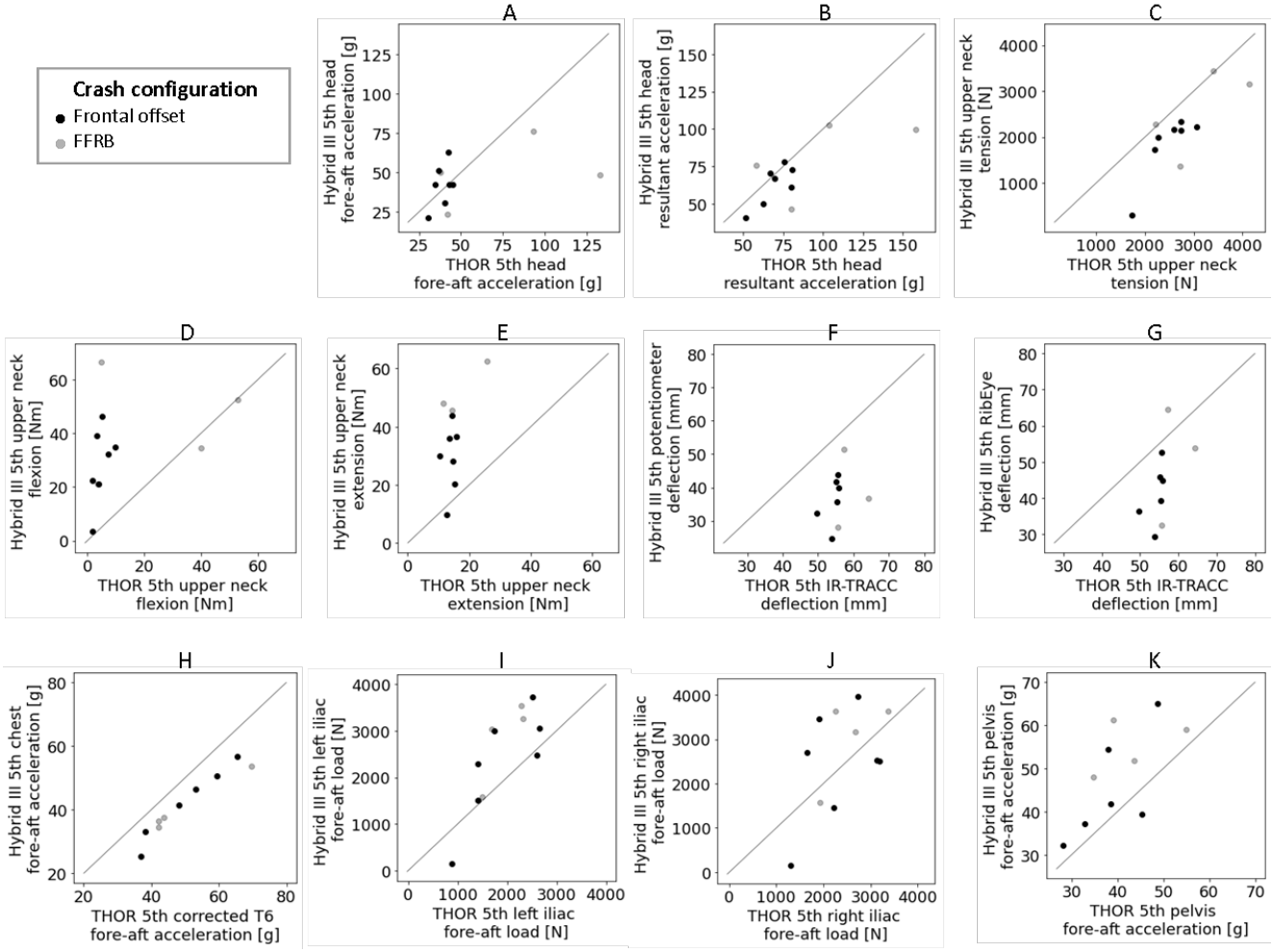


Fig. 5. Peak kinematic and kinetic responses of the Hybrid III 5th as a function of the THOR 5th response in the same vehicle model in frontal offset tests (black points) and FFRB tests (grey points).

TABLE IV

COMPARISON OF THOR 5TH AND HYBRID III 5TH RESPONSE IN VEHICLE MODEL-MATCHED FRONTAL OFFSET TESTS

THOR 5th response	Hybrid III 5th response	Direction of difference	Magnitude of paired difference	p	n
Head fore-aft accel.	Head fore-aft accel.	Hybrid III 5th > THOR 5th	3.0 ± 10.8 g	0.525	7
Head resultant accel.	Head resultant accel.	THOR 5th > Hybrid III 5th	6.7 ± 7.6 g	0.072	7
Upper neck tension	Upper neck tension	THOR 5th > Hybrid III 5th	633.2 ± 368.2 N	**0.006**	7
Upper neck flexion	Upper neck flexion	Hybrid III 5th > THOR 5th	23.7 ± 11.9 Nm	**0.003**	7
Upper neck extension	Upper neck extension	Hybrid III 5th > THOR 5th	15.4 ± 10.3 Nm	**0.010**	7
Corr. T6 fore-aft accel.	Chest fore-aft accel.	THOR 5th > Hybrid III 5th	8.0 ± 2.1 g	**0.0004**	6
IR-TRACC fore-aft defl.	Chest fore-aft defl.	THOR 5th > Hybrid III 5th	17.9 ± 5.6 mm	**0.0009**	6
IR-TRACC fore-aft defl.	RibEye fore-aft defl.	THOR 5th > Hybrid III 5th	12.9 ± 6.5 mm	**0.007**	6
Left iliac fore-aft load	Left iliac fore-aft load	Hybrid III 5th > THOR 5th	432.2 ± 679.3 N	0.170	7
Right iliac fore-aft load	Right iliac fore-aft load	Hybrid III 5th > THOR 5th	85.8 ± 1049.2 N	0.848	7
Pelvis fore-aft accel.	Pelvis fore-aft accel.	Hybrid III 5th > THOR 5th	6.4 ± 7.9 g	0.128	6

THOR 5th Abdomen Pressure

The abdominal pressures recorded by the APTS of the THOR 5th were examined in the full sample of frontal offset and FFRB tests. In frontal offset tests, the peak abdomen pressure appeared to vary according to occurrence of lap belt migration as well as the approximate time that the legs began to rebound (Figure 6A). The peak abdomen pressure was lower when no lap belt migration was observed (0.6-0.7 bar and 0.4-0.5 bar on left and right sides, respectively) than when partial or complete lap belt migration was observed (0.7-1.2 bar and 0.6-1.0

bar on left and right sides, respectively). In tests with partial or complete lap belt migration, peak pressures were lower when the leg appeared to rebound within the first 90 msec of the impact (0.7-1.0 bar and 0.6-0.9 bar on left and right sides, respectively) than when rebound began after 90 msec (0.8-1.2 bar and 0.9-1.0 bar on left and right sides, respectively).

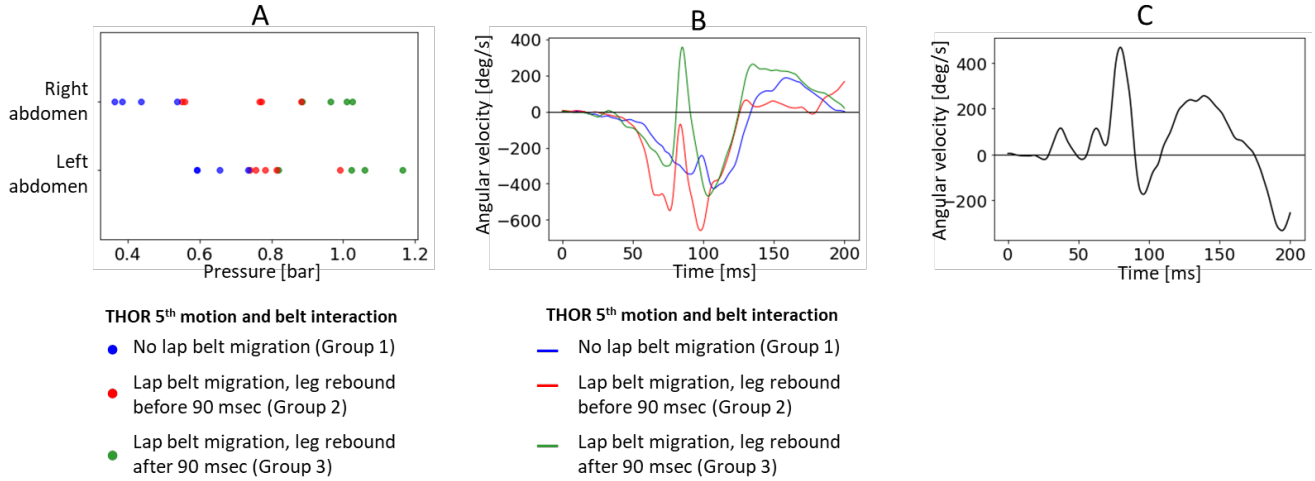


Fig. 6. (A) Peak abdomen pressures recorded in frontal offset tests as a function of the observed THOR 5th motion and interaction with lap belt. (B) Examples of T6 sagittal plane angular velocity associated with each group of ATD motions. (C) T6 sagittal plane angular velocity that did not follow the assumed response.

To investigate whether changes in abdomen load were associated with changes in any other kinematic or kinetic response, the results of each frontal offset test were categorised into one of three groups according to occurrence of lap belt migration and timing of leg rebound:

- Group 1: no lap belt migration;
- Group 2: partial or complete lap belt migration, leg rebound began within 90 msec;
- Group 3: partial or complete lap belt migration, leg rebound began after 90 msec.

Tests belonging to different groups could be differentiated by the T6 sagittal plane angular velocity response (examples in Figure 6B). Under the assumption that the initial two peaks of the angular velocity response consisted of a local minimum followed by a local maximum (Figure 2C, indicated by red points), two distinguishing characteristics were identified: (1) the value of the local maximum, and (2) the difference between the two extrema (Figure 2C). The local maximum was greater than 100 deg/s in tests belonging to Group 3 and below 100 deg/s in tests belonging to Groups 2 and 1. The difference between the two extrema was at least 400 deg/s in tests belonging to Group 2 but below 400 deg/s in tests belonging to Group 1.

The assumption cited above could not be applied to one frontal offset test (Figure 6C). In this test, the angular velocity initially oscillated in the positive regime, then reached a maximum of 466 deg/s at 80 msec before descending to a minimum of -173 deg/s at 96 msec. During the test, the lap belt completely migrated into the THOR 5th abdomen. The peak left and right abdomen pressures were 0.8 and 0.9 bar, respectively.

In FFRB tests, partial or complete lap belt migration occurred in every test. The peak right abdomen pressure was lower in tests with partial lap belt migration (0.4-1.0 bar) than in tests with complete migration (1.1-1.4 bar). The left abdomen pressure was excluded from analysis since the connector was disconnected in three of the four tests. Interestingly, the estimated time of leg rebound was slightly later for tests with partial lap belt migration (84-85 msec) than for tests with complete lap belt migration (80-81 msec). Finally, the local maximum of the T6 angular velocity exceeded zero only in tests with complete migration.

Post-test ATD Inspections

Signal abnormalities indicative of contact were not found for the Hybrid III 5th. In 11 of 13 frontal offset tests, the head of the THOR 5th appeared to have contacted the upper left arm as the ATD flexed forward (Figure 7A). The contact interfered with the calculation of peak head acceleration responses: the time of apparent contact coincided with the time of peak head fore-aft, lateral, and resultant accelerations (Figure 7B). In post-test examinations of the ATD, the left shoulder clevis was found to be bent (Figure 7C).

In frontal offset tests and one FFRB test, the lower left IR-TRACC fore-aft displacement appeared to reach a plateau, which ranged approximately 49 mm to 55 mm between tests (Figure 7D, black curve). Plateaus were

also observed in the unadjusted deflections and angles of the same IR-TRACC (Figure 7D, coloured curves). In multiple frontal offset and FFRB tests, a coincident spike was observed in the fore-aft and vertical accelerations at T6 within the first 75 ms of impact (Figure 7D). Post-test examinations revealed signs of contact on the lower left IR-TRACC (Figure 7E) and spine box (Figure 7F). FFRB tests were interrupted after four tests due to a severed cable harness supplying power to the DAS.

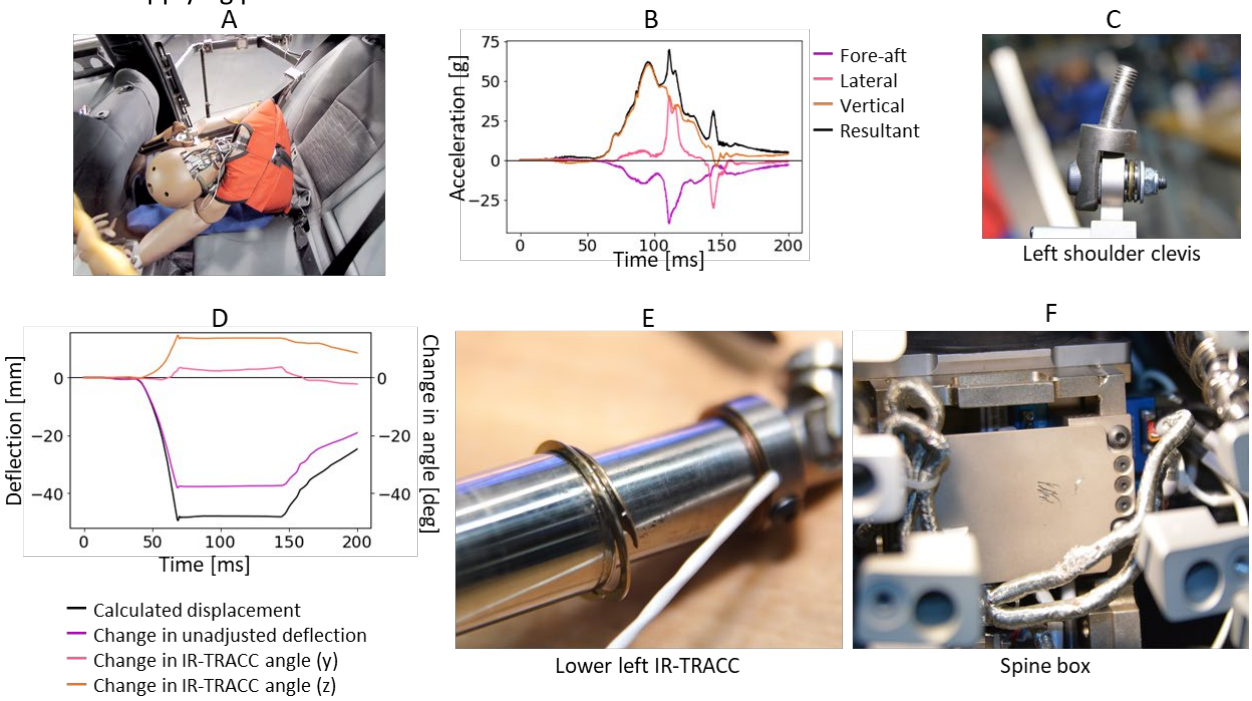


Fig. 7. (A-C) Freeze frames, head kinematic responses, and damage to the left shoulder clevis associated with head contact. (D-F) Plateau in the lower left IR-TRACC deflection, signs of contact on IR-TRACC and spine box.

IV. Discussion

In this test series, the motions as well as the kinematic and kinetic responses of the THOR 5th were found to differ from those of the Hybrid III 5th. In video footage, the torso of the THOR 5th but not the Hybrid III 5th appeared to rotate about the shoulder belt, and the shoulder belt was displaced more distally on the clavicle of the THOR 5th than on that of the Hybrid III 5th. The lap belt migrated more frequently into the THOR 5th abdomen than into the Hybrid III 5th abdomen. Although the current test sample includes only seven tests with the Hybrid III 5th, the frequency of lap belt migration reported here for the Hybrid III 5th (28.5%) is comparable to that reported in a previous study with a much larger sample size [11] (21/76 or 27.6% on the right side, 21/76 or 25% on the left side). Differences in the propensities for lap belt migration of the THOR 5th and Hybrid III 5th are likely associated with differences in the pelvis shapes of the two ATDs. The Hybrid III 5th pelvis is simply a scaled down version of the Hybrid III 50th pelvis. By contrast, the design of the THOR 5th pelvis is based on a small female pelvis geometry derived from a statistical shape pelvis model [12][15-16]. In a comparison between the small female pelvis geometry and the Hybrid III 5th pelvis [15-16], the height of the anterior-superior iliac spine (ASIS) on the small female pelvis model was found to differ from that of the Hybrid III 5th. The authors of the study commented that the disparity in ASIS height and differences in pelvis shape around the ASIS could lead to differences in how the small female pelvis and the Hybrid III 5th pelvis might interact with the lap belt.

Differences in the motions of the Hybrid III 5th and THOR 5th appeared to be consistent with observations reported in the literature. In frontal sled tests conducted to compare the THOR 5th to the Hybrid III 5th [22], torso rotation about the shoulder belt was also reported to be greater for the THOR 5th than for the Hybrid III 5th. The authors also reported greater pelvis excursion and torso flexion of the THOR 5th when compared to the Hybrid III 5th, while excursion of the neck was found to be comparable between the two ATDs.

Published studies involving comparisons between the Hybrid III 5th and THOR 5th relative to post-mortem human subjects (PMHS) were not found. However, in component and full body biofidelity evaluations, the performance of the THOR 5th has generally been ranked by objective scoring methods as “good” or “excellent” [23,24]. While a rigid seat was used in the sled tests conducted for biofidelity evaluations, sled tests were

conducted on a semi-rigid seat in [25] to compare the kinematics of small stature PMHS and the THOR 5th. The THOR 5th was reported to submarine under the same conditions that caused submarining of PMHS. In cases where submarining occurred, H-point displacements of the THOR 5th were similar to those of the PMHS. In cases with no submarining, the H-point displacements of the THOR 5th were reported to be greater than those of the PMHS.

In vehicle model-matched comparisons of the THOR 5th and Hybrid III 5th kinematic and kinetic responses, differences in the upper neck and chest responses were consistently observed across the sample. At the upper neck, peak tension was greater for the THOR 5th than for the Hybrid III 5th, but peak extension and flexion moments were greater for the Hybrid III 5th. Peak IR-TRACC deflections of the THOR 5th were greater than peak potentiometer and peak RibEye deflections of the Hybrid III 5th regardless of the vehicle model tested and its specific restraint environment (e.g. belt system, anchorage locations, seat geometry). Due to the plateau at the lower left IR-TRACC, the variability of peak IR-TRACC deflections of the THOR 5th (ranging 49 to 55 mm) was smaller than the variability of peak potentiometer (ranging 25 to 51 mm) and peak RibEye deflections (ranging 29 to 64 mm) of the Hybrid III 5th. The finding that peak IR-TRACC deflections of the THOR 5th exceeded peak potentiometer deflections of the Hybrid III 5th is consistent with results of frontal sled tests published in [22]. That both the peak deflections and the belt geometries of the THOR 5th differed from those of the Hybrid III 5th raises the possibility that the differences in belt geometry may have contributed in part to the differences in peak deflection. Studies of the Hybrid III 5th have reported that the peak potentiometer deflection decreases as the shoulder belt is moved towards the neck [9-10][26]. Although published studies investigating the effects of belt geometry on the THOR 5th were not found, the peak deflections measured by the IR-TRACCs in the THOR 50th have been found to vary with respect to belt geometry [27-28]. However, differences in belt geometry constitute only one of multiple possible factors that can contribute to the disparity in peak chest deflections between the ATDs. The existence of other contributing factors likely underlies the finding that the peak IR-TRACC deflection also exceeded the peak RibEye deflection, the latter of which is less sensitive than the potentiometer to belt geometry [11]. Pre-test positioning was controlled to the extent possible given the differences in ATD anthropometry, but may still have contributed to differences in response. Further studies are required to develop test methodologies that will allow for direct comparisons of positioning.

The corrected peak T6 fore-aft acceleration of the THOR 5th always exceeded the peak chest fore-aft acceleration of the Hybrid III 5th. Interestingly, a linear correlation was observed between the two responses. Correlations between other peak responses of the THOR 5th and Hybrid III 5th were not observed. The generally poor correlation between THOR 5th response and Hybrid III 5th response suggests the possibility that the two ATDs may currently provide conflicting information when comparing different vehicle restraint designs. The influence that this difference could have on vehicle assessment remains to be determined as improvements of the THOR 5th continue to be made and and injury criteria for the new ATD are developed. Additional matched pair testing with the THOR and Hybrid III 5th in the same vehicle should be continued as new developments are introduced.

The abdomen pressure was greater in tests with lap belt migration than in those without. Interestingly, tests where lap belt migration occurred could be further subdivided according to the approximate time of leg rebound. In frontal offset tests, abdomen pressures tended to be lower if leg rebound began within the first 90 msec of the impact than if rebound began after 90 msec. The peak abdomen pressure was found to also be related to the T6 angular velocity response in the sagittal plane. This change in orientation may contribute to a change in the direction of the load being applied by the lap belt to the pressure sensors. However, it was not possible to isolate and quantify this relationship any further for this dataset. The apparent association between characteristics of the THOR 5th motion and characteristics of the T6 angular velocity is indicative of a relationship between forward excursion, ATD orientation, and peak abdomen pressure.

In multiple tests, the THOR 5th head appeared to contact itself at the time of peak head fore-aft and lateral accelerations. The contribution of arm contact to the head response could not be isolated in our analysis. Detailed simulation studies may assist in the 11development of methods to compute peak responses in these situations.

A limitation of the study is that comparisons of ATD excursion were conducted by visual inspection. To date, we have been unsuccessful in sourcing commercially available technology to reliably measure pelvis excursion in second-row seats of vehicles undergoing frontal offset crashes. Another limitation in the analysis of kinematic and kinetic responses is the relatively small sample size. Future work includes continued matched pair testing of the THOR 5th and Hybrid III 5th in the same vehicle models to investigate if the trends observed in the current study will persist in a larger sample of vehicle models. A final limitation was the subjective nature of the parameter

selection when using the *find_peaks* function. A more systematic method of selecting the input parameters should be considered in future studies.

V. Conclusions

In full scale frontal crash tests, the motions of the THOR 5th are markedly different from the Hybrid III 5th. In the event of head contact of the THOR 5th on itself, a systematic method of computing peak head responses is needed. The improved motion and advanced sensing capabilities of the THOR 5th have highlighted the potential to advance protection for female passengers in second-row seats.

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VII. Disclaimer

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VIII. References

[1] Tatem WM, Gabler HC. Differential Fatality Risk between Rear and Front Seat Passenger Vehicle Occupants in Frontal Crashes. *Proceedings of IRCOBI Conference*, 2019, Florence, Italy.

[2] Durbin DR, Jermakian JS et al. Rear seat safety: Variation in protection by occupant, crash and vehicle characteristics. *Accident Analysis and Prevention*, 2015, 80:185-192.

[3] Parenteau CS, Zuby D, Brolin KB, Svensson M, Wang S. Restrained male and female occupants in frontal crashes: Are we different? *Proceedings of IRCOBI Conference*, 2013, Gothenburg, Sweden.

[4] Bose D, Segui-Gomez M, Crandall J. Vulnerability of female drivers involved in motor vehicle crashes: An analysis of US population at risk. *American Journal of Public Health*, 2011, 101:2368-2373.

[5] Forman J, Poplin GS, Shaw CG et al. Automobile injury trends in the contemporary fleet: belted occupants in frontal collisions. *Traffic Injury Prevention*, 2019, 20(6):607-612.

[6] IIHS. Moderate Overlap Frontal Crashworthiness Evaluation Crash Test Protocol for Front and Rear Occupants Version I. 2020.

[7] Euro NCAP. Full Width Frontal Impact Testing Protocol. 2015.

[8] Tylko S, Dalmotas D. Protection of Rear Seat Occupants in Frontal Crashes. *Proceedings of the 19th International Technical Conference on the Enhanced Safety of Vehicles*, 2005, Washington DC, USA.

[9] Tylko S, Charlebois D, Bussières A. Comparison of Kinematic and Thoracic Response of the 5th Percentile Hybrid III in 40, 48 and 56 km/h Rigid Barrier Tests. *Proceedings of 20th International Technical Conference on the Enhanced Safety of Vehicles*, 2007, Lyon, France.

[10] Tylko S, Bussières A. Responses of the Hybrid III 5th Female and 10-year-old ATD Seated in the Rear Seats of Passenger Vehicles in Frontal Crash Tests. *Proceedings of IRCOBI Conference*, 2012, Dublin, Ireland.

[11] Tang K, Tylko S, Bussières A. Responses of the Hybrid III 5th percentile ATD tested outside of regulatory protocols. *Proceedings of IRCOBI Conference*, 2021, Virtual.

[12] Wang Z, McInnis J, Benfant L, Feng Z. THOR 5th percentile ATD design. *Proceedings of 25th International Technical Conference on the Enhanced Safety of Vehicles*, 2017, Detroit, USA.

[13] Johannsen H, Alonzo F, Schindler V. Abdominal Sensors for Child Dummies of the Q Family, Injury Criteria and Injury Risk Curves. *Proceedings of IRCOBI Conference*, 2007, Maastricht, The Netherlands.

[14] Linder A, Svensson MY. Road safety: the average male as a norm in vehicle occupant crash safety assessment. *Interdisciplinary Science Reviews*, 2019, 44(2):140-13.

[15] Klein KF, Reed MP, Rupp JD. Development of geometric specifications for the pelvis of a small female anthropomorphic test device. *Proceedings of IRCOBI Conference*, 2016, Malaga, Spain.

[16] Klein KF, Reed MP, Rupp JD. Development of geometric specifications for the pelvis of a small female

anthropomorphic test device. *NHTSA Report No. DOT HS 812 339*, 2016, Washington DC, USA.
[17] Euro NCAP. Assessment Protocol – Adult Occupant Protection. 2017.
[18] Virtanen P, Gommers R, Oliphant T et al. SciPy 1.0: Fundamental Algorithms for Scientific Computing in Python. *Nature Methods*, 2020, 17(3):261-272.
[19] "scipy.signal.find_peaks" Internet: [https://docs.scipy.org/doc/scipy/reference/generated/scipy.signal.find_peaks.html], [2022-03-29].
[20] "scipy.signal.peak_widths" Internet: [https://docs.scipy.org/doc/scipy/reference/generated/scipy.signal.peak_widths.html], [2022-03-29].
[21] "scipy.signal.peak_prominences" Internet: [https://docs.scipy.org/doc/scipy/reference/generated/scipy.signal.peak_prominences.html], [2022-03-29].
[22] Carroll J, Kruse D, Mishra E, Mroz K, Lubbe N. Comparison of Hybrid III and THOR 5th percentile female dummies in frontal crash tests. *Proceedings of IRCOBI Conference*, 2021, Virtual.
[23] Wang ZJ, Lee E, Bolte J et al. Biofidelity Evaluation of THOR 5th percentile ATD. *Proceedings of IRCOBI Conference*, 2018, Athens, Greece.
[24] Wang ZJ, Ramachandra R, Bolte JH, Lee E. THOR 5th Female Biofidelity Evaluation in Gold Standard Sled Test Condition. *Proceedings of IRCOBI Conference*, 2021, Virtual.
[25] Richard O, Lebarbé M, Uriot J et al. THOR-05F Response in Sled Tests Inducing Submarining and Comparison with PMHS Response Corridors. *Stapp Car Crash Journal*, 2021, 65:91-138.
[26] Haight S, Samaha RR, Biss D. Analysis of Seat Belt Positioning in Recent NCAP Crash Tests. *SAE Int J Transp Saf*, 2013, 1(1):16-24.
[27] Eggers A, Eickhoff B, Dobberstein J, Zellmer H, Adolph T. Effects of Variations in Belt Geometry, Double Pretensioning and Adaptive Load Limiting on Advanced Chest Measurements of THOR and Hybrid III. *Proceedings of IRCOBI Conference*, 2014, Berlin, Germany.
[28] Shaw G, Lessley D, Ash J, Crandall J. Response Comparison for the Hybrid III, THOR Mod Kit with SD-3 Shoulder, and PMHS in a Simulated Frontal Crash. *23rd International Technical Conference on the Enhanced Safety of Vehicles*, 2013, Seoul, Korea.