

COMPARISON OF THE IMPACT KINEMATICS OF AN ELDERLY FEMALE, THE HIII 50TH MALE AND THE HIII 5TH FEMALE DUMMIES AS DRIVERS, FRONT PASSENGERS AND REAR PASSENGERS IN FULL-WIDTH FRONTAL IMPACTS

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ABSTRACT

The objectives of this study were to analyse and compare the impact kinematics of an early prototype version of an Elderly Female, the HIII 50th Male, and the HIII 5th Female dummies as drivers, front passengers, and rear passengers in full-width frontal impacts.

Three full-width frontal impact tests were conducted with a popular midsize station wagon based on Regulation UN R137 – except for the front passenger seat, which was adjusted in its longitudinal mid-position instead – in which the different ATDs were either placed in the driver, front passenger, or right back seats.

The measured loads indicate that second-row seats offer less protection than first-row seats. The HIII 50th Male dummy experienced the greatest torso forward rotation on all seats, with changes in the forward leaning angle of both the Elderly Female and HIII 5th Female dummies dependent on their respective seat positions.

More research into the biofidelity of the Elderly Female Dummy is necessary to improve ATD design and to develop injury assessment reference values and injury risk functions.

INTRODUCTION

Aside from being the only age group with an increase in road deaths since 2010, the elderly are also more susceptible to trauma [1-3]. Simultaneously, accident investigations have shown that women are more at risk of being seriously injured than men [4-7], while analyses of crash data of passenger vehicles of model years 2007 and newer show that rear occupants are exposed to a greater relative fatality risk than front occupants [8-9]. Occupant protection systems should therefore better account for female and senior occupants as well as seating positions outside of regulations to reduce the risk of sustaining serious or fatal injuries [10-11]. This highlights the necessity for Anthropomorphic Test Devices (ATDs) that not only better represent females, but also the elderly. To address this need, Humanetics is currently developing the Elderly Female Dummy, an ATD representative of a 70-years-old female car occupant [12-13].

DEKRA conducted three full-width frontal impact tests with an early prototype version of the Elderly Female, the HIII 50th Male and the HIII 5th Female dummies being either seated on the driver, front passenger, or right back seat. We have chosen the full-width frontal impact test based on Regulation UN R137 for being the toughest load case regarding restraint kinematics.

In a previous study [14], we have already investigated the thorax and head/neck dynamics of the three ATDs being seated on the front passenger seat. This seat position allowed us to use the same seat adjustments for every ATD, while the seatbelts were equipped with a pre-tensioner and load limiter – which are not installed in the rear – and thus to directly compare dummy behaviour. As the seat adjustments chosen differed from Regulation UN R137, we have observed changes in the HIII 5th Female dummy's kinematics. Moreover, the Elderly Female Dummy's thorax was the only one being reclined at time of airbag contact.

This study continues the previous research by analysing and comparing the impact kinematics of the Elderly Female, the HIII 50th Male and the HIII 5th Female dummies as drivers, front passengers, and rear passengers.

METHODS

Elderly Female Dummy

Clinical data of 80 women aged 67 – 73 were used to derive the anthropometry of the Elderly Female Dummy, resulting in a height of 1.61 m, a mass of 73 kg, and a Body Mass Index (BMI) of 28. Especially the mass distribution over the height represents much better the body shape of elderly females. The head and neck are those of the WorldSID Small Female, while the lower arms, hands, knees, and feet stem from the HIII 5th Female [12]. The remaining body parts were specially developed for this ATD. They comprise a new structure – which does not exist in current ATDs – to better address potential internal injuries. The supporting structure of the Elderly Female Dummy consists of a flexible spine, a movable rib cage and floating shoulders, while organ sacs representing the liver and spleen are placed in the abdomen. The stratified body flesh is mimicked by a representative fat layer covering the entire torso. Magnetic Resonance Imaging (MRI) scans were used to determine rib cage shape, flesh thickness, organ size and organ placement. The Statistical Body Shape Models of the University of Michigan Transportation Research Institute were used to derive the shape of the Elderly Female Dummy. The so-called Multi-Directional Measurement Thorax (MDMT) is equipped with four infra-red telescoping rods for the assessment of chest compression (IR-TRACCs) to measure chest deflection in both the x- and y-direction, enabling the ATD to be used in frontal and lateral impact tests.

The Elderly Female Dummy is manufactured by using new technologies such as 3D-printing, allowing for a greater freedom of design. However, more research is necessary before this ATD can be commercialised.

“The next steps in the industrialisation process are to: 1) conduct biofidelity component testing under both frontal and lateral impact conditions to advance thoracic and abdominal biofidelity; 2) perform tests for response and corridor validations; and 3) develop injury assessment reference values (IARVs), regulation limits, and injury risk functions” [14].

Test Setup

Three full-width frontal impact tests against a rigid barrier at 50 km/h were conducted at the DEKRA Crash Test Center in Neumünster, Germany as shown in Figure 1. The tests were based on Regulation UN R137 except for the front passenger seat position, where the seat was adjusted to its longitudinal mid-position instead (see sub-section “seating position”). We used identical models of a popular midsize station wagon which had similar specifications and were of model years 2009 – 2013, resulting in comparable acceleration pulses (Figure 2). The Elderly Female, the HIII 50th Male and the HIII 5th Female dummies were either positioned on the driver, front passenger, or right back seat. In a previous study [14], we already focused on the front passenger seat, as we wanted to analyse the influence of both a standardised seating position and a restraint system with double pre-tensioner and load limiter. In this study, we also focused on the driver and right back seat. We have removed all four doors in order to obtain an unobstructed view.



Figure 1. Test setup [14].

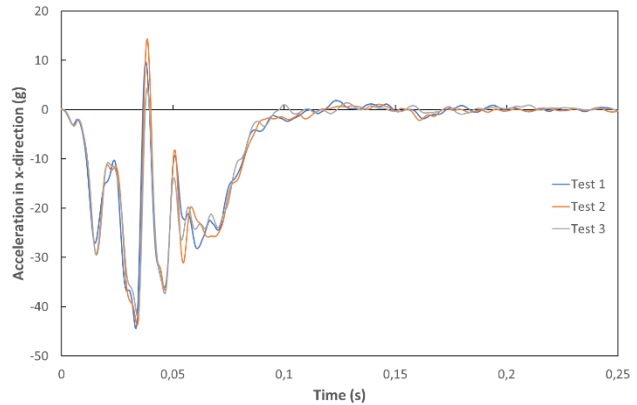


Figure 2. Acceleration pulses of the three crash tests [14].

Seating Position

Driver Seat The seat adjustments for the HIII 50th Male dummy were made according to Regulation UN R137. For the HIII 5th Female dummy, we used the European New Car Assessment Programme (Euro NCAP) frontal full-width test protocol. Thus, the driver seat was placed in its longitudinally foremost position. Currently, no regulations exist for the Elderly Female Dummy. But as its anthropometry is closer to the HIII 5th Female dummy, we have also used the Euro NCAP test protocol for the Elderly Female Dummy. However, as the Elderly Female Dummy has longer legs than the HIII 5th Female, we moved the driver seat backwards within the corridor allowed by Euro NCAP's test protocol. The seat rail overlap was 77 mm.

Front Passenger Seat While Regulation UN R137 stipulates the usage of the HIII 5th Female dummy on the front passenger seat, we wanted to use a single seating position for every ATD. Therefore, we asked ourselves what seat adjustments front passengers make. We conducted a field study and a German In-Depth Accident Study (GIDAS) analysis as previously described in [14]. These analyses yielded that the most common position was the longitudinal mid-position, which we hence chose for the crash tests.

Right Back Seat The back seats in the chosen vehicles do not allow for any adjustments. The three different ATDs were therefore simply put on the right back seat and restrained.

Measurements

While the HIII 50th Male and the HIII 5th Female dummies were equipped with a standard configuration of sensors, the prototype version of the Elderly Female Dummy had only sensors for measuring: head acceleration, thoracic spine acceleration, pelvis acceleration, and thorax compression.

Data acquisition and evaluation were performed in accordance with Regulation UN R137.

Pelvis forward displacement was determined by means of a string, while head forward displacement was determined via crash test video analysis with high-speed video software FalCon eXtra, Version 10.33.0011.

RESULTS

In order to compare the impact kinematics of the Elderly Female, the HIII 50th Male and the HIII 5th Female dummies, measurements of restraint forces; shoulder belt extractions; dummy displacements; chest deflections; and chest, pelvis, and head accelerations are presented for the different seat positions. Still images of the three crash tests and different seat positions, which visualise the dummy kinematics, are provided in the appendix.

To aid with distinguishing between the different seat positions, the individual graphs for each seat position were created with different line types. The graphs for the driver seat were created with solid lines, the ones for the front passenger seat with dashed lines, and the ones for the right back seat with lines consisting of a dash and two dots.

Driver Seat

Figures 3 and 4 show the shoulder belt and lap belt forces of the three dummies, respectively. The shoulder belt forces were measured between the D-ring anchorage and the dummy's shoulder, while the lap belt forces were measured just above the buckle. The HIII 50th Male dummy exhibited the highest values for both the shoulder belt

and lap belt forces, with around 5 kN each. Regarding the shoulder belt forces, the Elderly Female and the HIII 5th Female dummies recorded similar values at around 4 kN, though the HIII 5th Female dummy exhibited a higher peak value for lap belt forces than the Elderly Female.

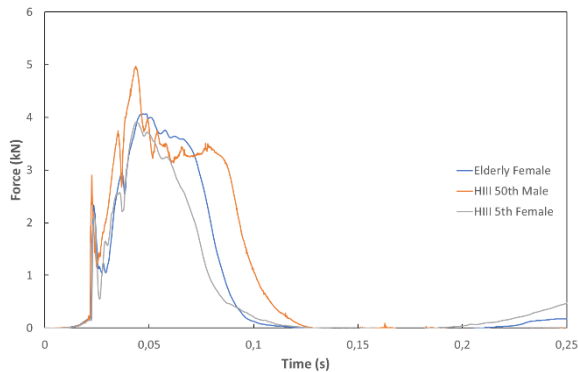


Figure 3. Shoulder belt forces driver seat.

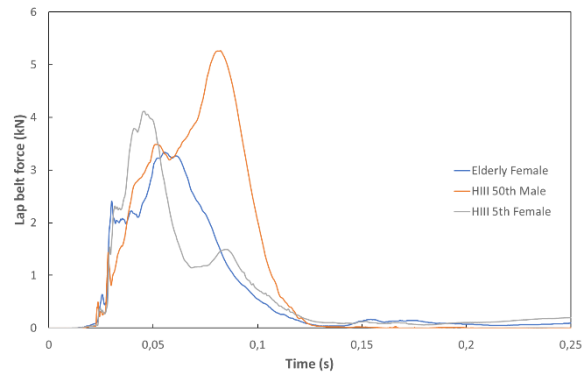


Figure 4. Lap belt forces driver seat.

The shoulder belt extractions, which are indicative of thorax forward displacement, are shown in Figure 5. Peak extraction for the HIII 50th Male occurred around 88 ms after impact and is the largest with 139 mm, with shoulder belt forces being around 3 kN at that time. The Elderly Female and HIII 5th Female dummies recorded negative peak values, meaning that the seatbelt extractions were less than the winding up of the seatbelts by the pre-tensioners.

Head forward displacements are shown in Figure 6. Like shoulder belt extractions, the HIII 50th Male dummy recorded the largest head forward displacement, which occurred around 90 ms after impact. The Elderly Female and the HIII 5th Female dummies exhibited their peak head forward displacements around 70 ms after impact.

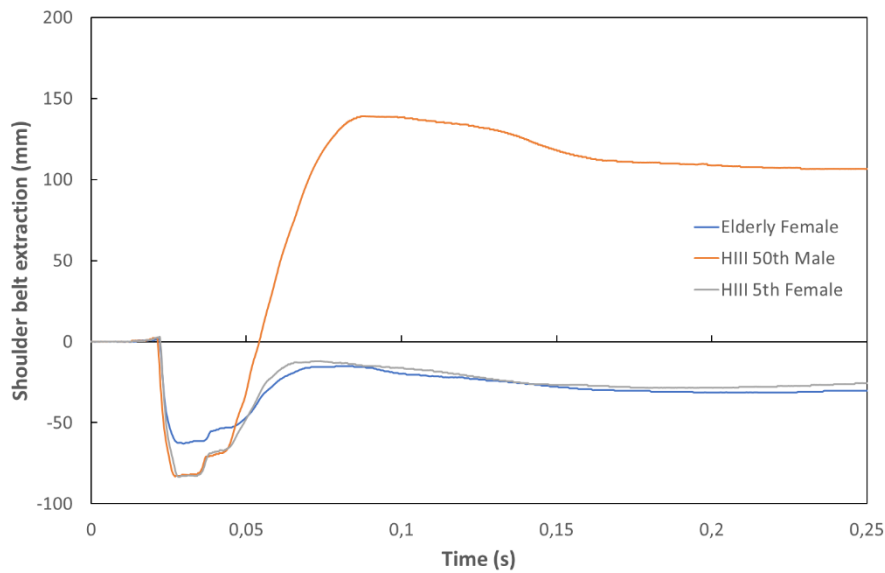


Figure 5. Shoulder belt extractions driver seat.

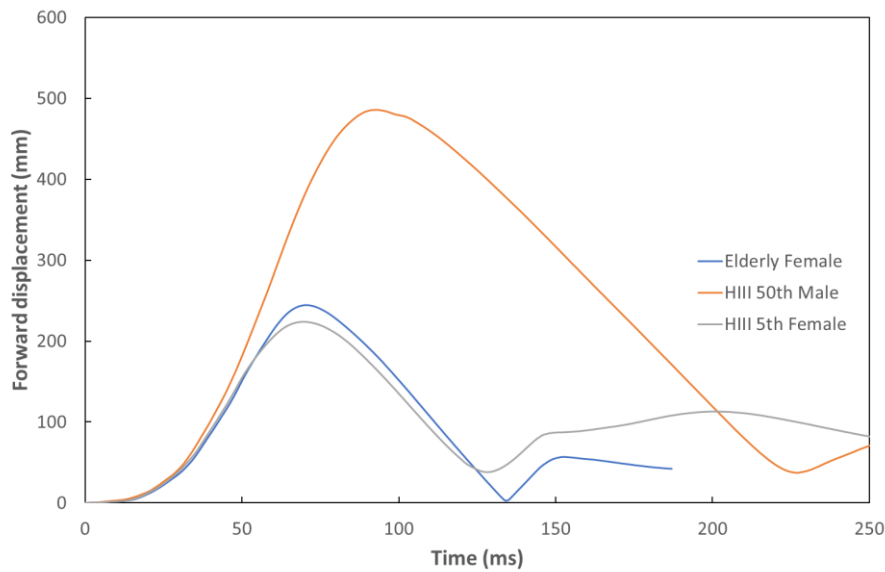


Figure 6. Head forward displacements driver seat.

Table 1 shows the peak pelvis forward displacements. Again, the HIII 50th Male dummy recorded the biggest peak value. However, the Elderly Female exhibited a larger peak pelvis forward displacement than the HIII 5th Female dummy, while both female dummies exhibited similar shoulder belt extractions.

Table 1.
Measured peak pelvis forward displacements (mm) driver seat.

Elderly Female	90
HIII 50 th Male	96
HIII 5 th Female	74

These differences in peak shoulder belt extraction and peak pelvis forward displacement led to different forward leaning angles at the time of airbag contact as shown in Figure 7. Both the Elderly Female and the HIII 5th Female dummies exhibited a forward leaning angle greater than 90° as measured between the thorax and the horizontal, though the torso of the HIII 5th Female dummy is nearly upright. The HIII 50th Male dummy experienced a forward leaning angle of less than 90°.



Figure 7. Images of the driver seats taken 80 ms post-impact.

Pelvis accelerations are shown in Figure 8. The Elderly Female Dummy recorded the largest peak value, while both the HIII 50th Male and the HIII 5th Female dummies exhibited a similar peak value. The Elderly Female Dummy's peak value also occurred later than the ones for the HIII dummies.

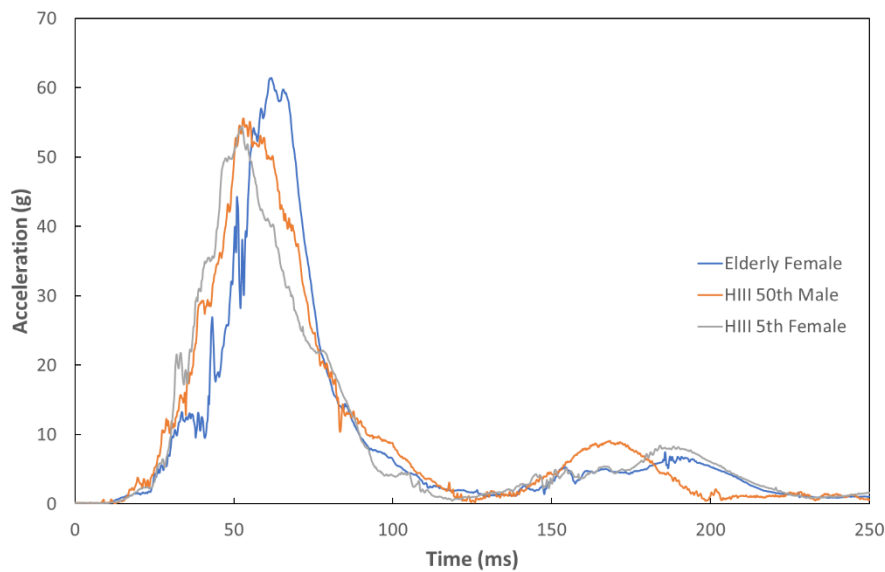


Figure 8. Pelvis accelerations driver seat.

Figures 9 and 10 show the chest accelerations and chest deflections, respectively. In contrast to the HIII dummies, the Elderly Female is equipped with two accelerometers, which are placed on vertebral bodies T1 and T12. These are also only biaxial and not triaxial as those of the HIII dummies. This is why we only evaluated the chest accelerations in the x-direction. Influences in the y- and z-direction are negligible because we conducted full-width frontal impacts. Moreover, the Elderly Female is also equipped with two chest deflection potentiometers, while the HIII dummies are only equipped with one chest deflection potentiometer each. The chest acceleration recordings in the x-direction for all three dummies are very similar. The chest deflection readings for the Elderly Female's upper measurement, the HIII 50th Male and the HIII 5th Female are very similar with 32 mm, 31 mm, and 32 mm, respectively. The Elderly Female also recorded a lower measurement reading of 42 mm. The Elderly Female Dummy's lower deflection measurement had an earlier onset than the upper deflection measurement and was at a greater rate.

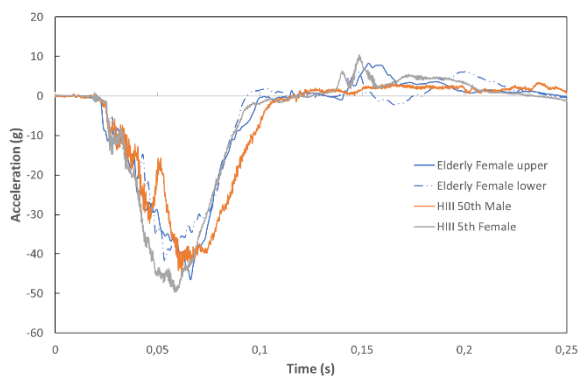


Figure 9. Chest accelerations in x-direction driver seat.

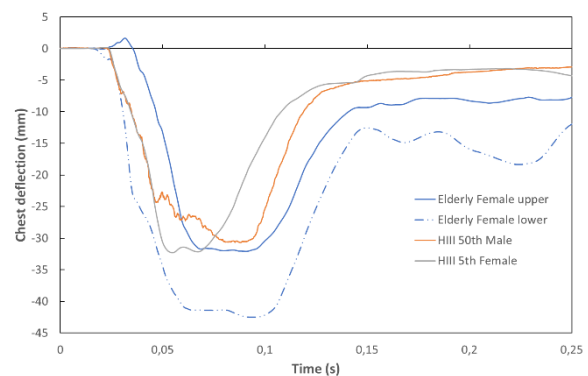


Figure 10. Chest deflections driver seat.

Figure 11 displays the head accelerations. Two distinct peaks are distinguishable. The first occurred at around 70 ms, with the second occurring around 150 ms post-impact for the female dummies, and around 230 ms for the HIII 50th Male. Regarding the first peak, the Elderly Female Dummy recorded its overall peak value of 71 g, while the HIII 50th Male dummy recorded its overall peak value of 49 g. Maximum head acceleration of the HIII 5th Female dummy is 63 g. This is lower than its overall peak value of 78 g, which occurred during the second peak at around 150 ms post-impact. This is also the largest acceleration among all three dummies.

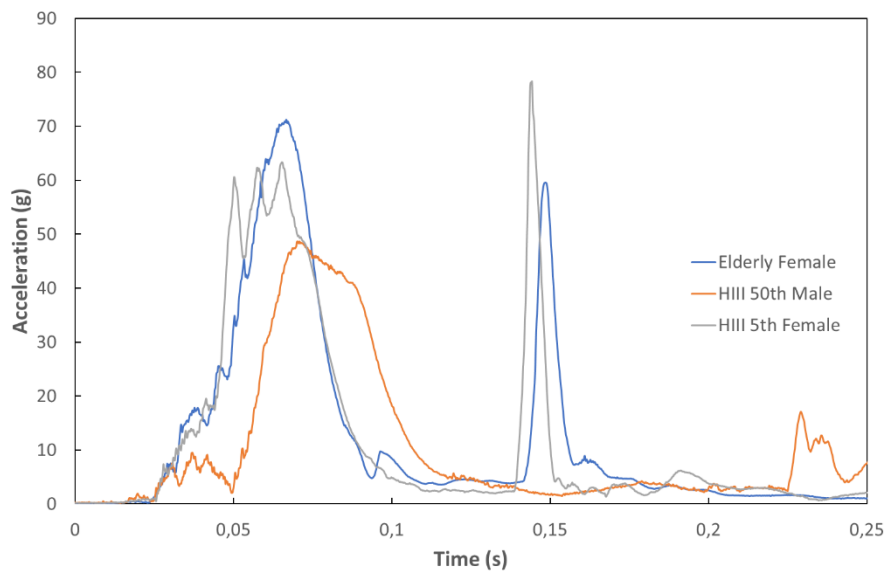


Figure 11. Head accelerations driver seat.

Table 2 shows the measured peak values to aid with comparing the results.

Table 2.
Measured peak values driver seat.

	Shoulder belt force (kN)	Lap belt force (kN)	Shoulder belt extraction (mm)	Head forward displacement (mm)	Pelvis forward displacement (mm)	Pelvis acceleration (g)	Chest acceleration (g)	Chest deflection (mm)	Head acceleration (g)
Elderly Female	4.06	3.34	-15 [^]	244	90	61.44	46.49/42.03 [°]	32/42 [°]	71.22
HIII 50 th Male	4.97	5.23	139	486	96	55.60	45.03	31	48.67
HIII 5 th Female	3.90	4.11	-12 [^]	224	74	54.42	49.63	32	78.34

[°] Upper/lower chest acceleration and deflection measurements.

[^] The negative sign indicates that the seatbelt extraction was less than the winding up by the pre-tensioner.

Front Passenger Seat

The thorax and head/neck dynamics of the Elderly Female, the HIII 50th Male and the HIII 5th Female dummies were previously analysed by us in [14]. We therefore refrain from showing the individual graphs here again, but only present the measured peak values in table 3.

Figures 12 and 13, however, show the lap belt forces and pelvis accelerations, respectively, as these were not considered in our previous research. The HIII 50th Male dummy exhibited the largest peak lap belt force, while the Elderly Female Dummy exhibited the lowest. The Elderly Female, however, recorded the largest peak pelvis acceleration, while the HIII 5th Female dummy recorded the lowest peak value. Peak acceleration for the Elderly Female Dummy also occurred later than for the HIII dummies as did peak lap belt force.

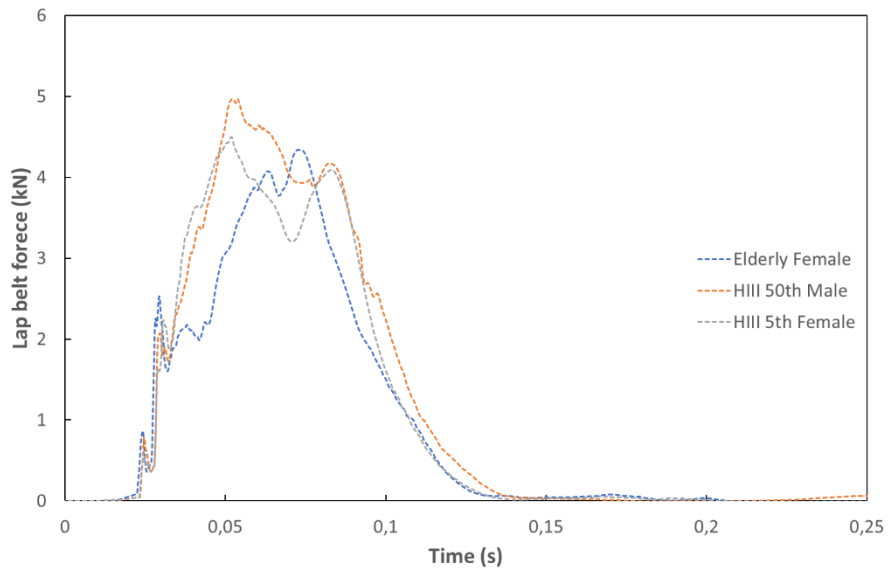


Figure 12. Lap belt forces front passenger seat.

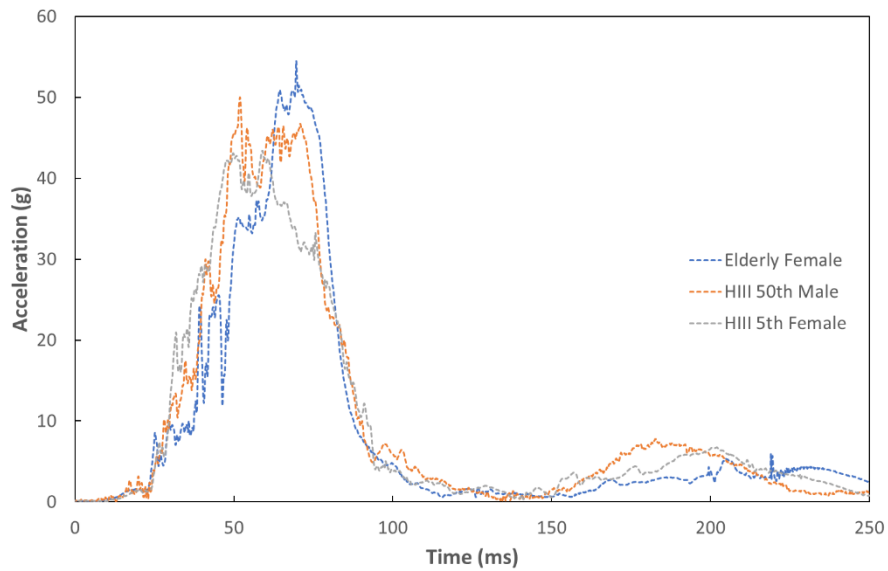
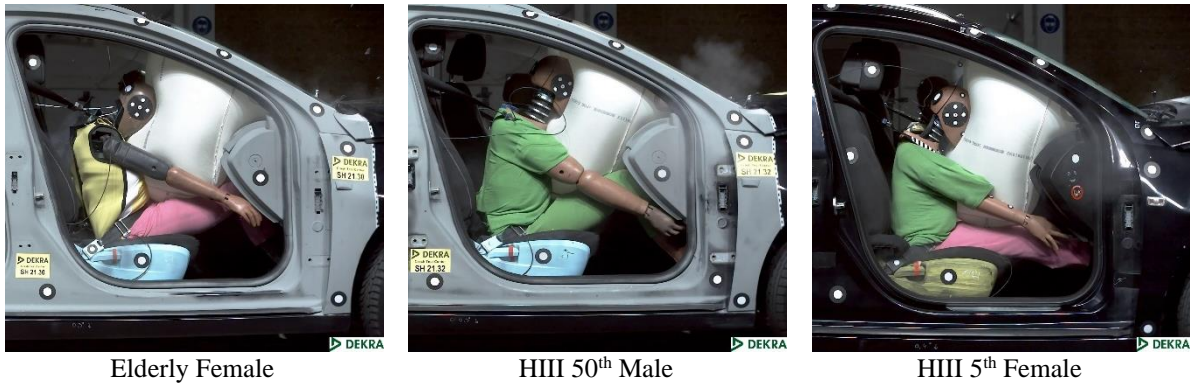


Figure 13. Pelvis accelerations front passenger seat.

Figure 14 displays the different forward leaning angles caused by the different impact kinematics of the three dummies on the front passenger seat. The Elderly Female Dummy is the only ATD with a forward leaning angle greater than 90° as measured between the thorax and the horizontal.



Elderly Female HIII 50th Male HIII 5th Female
Figure 14. Images of the front passenger seats taken 80 ms post-impact [14].

Table 3.
Measured peak values front passenger seat.

	Shoulder belt force (kN)	Lap belt force (kN)	Shoulder belt extraction (mm)	Head forward displacement (mm)	Pelvis forward displacement (mm)	Pelvis acceleration (g)	Chest acceleration (g)	Chest deflection (mm)	Head acceleration (g)
Elderly Female	4.59	4.34	33	387	53	54.50	40.54/33.18°	41/33°	248.49*
HIII 50 th Male	5.04	4.96	206	520	91	49.99	42.97	33	54.55
HIII 5 th Female	5.02	4.50	53	336	48	43.42	39.36	24	68.89

° Upper/lower chest acceleration and deflection measurements.

* The head acceleration reading for the Elderly Female is erroneous due to a cable breakage.

Right Back Seat

Figures 15 and 16 show the shoulder belt and lap belt forces, respectively. While the peak lap belt forces are very similar for all three dummies, the HIII 50th Male dummy recorded the largest peak shoulder belt force with 9.51 kN, followed by the HIII 5th Female dummy with 7.59 kN, and the Elderly Female Dummy with 5.83 kN. However, the Elderly Female's thorax and shoulder assembly were severely damaged by the seatbelt during the impact (see Figure 17). The seatbelts in the rear were not equipped with a pre-tensioner and load limiter. We assume that the shoulder belt force readings might have been affected by the collapse of the rib cage and are therefore erroneous.

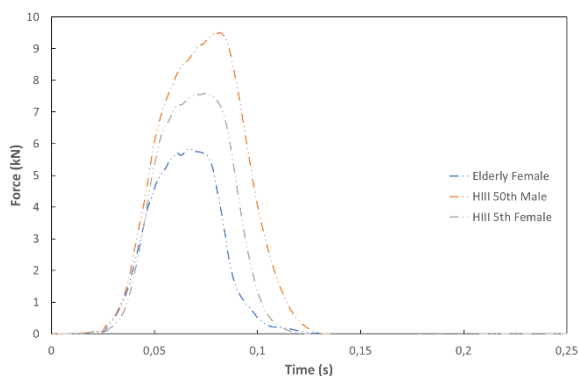


Figure 15. Shoulder belt forces right back seat.

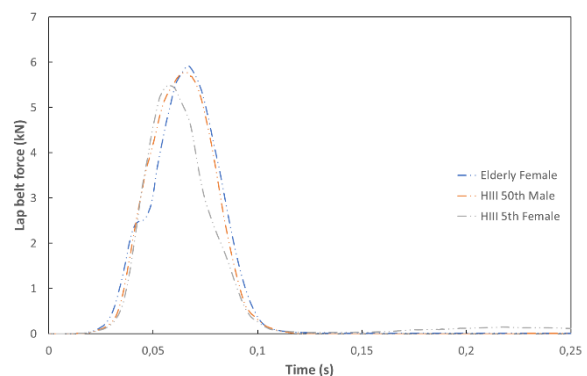


Figure 16. Lap belt forces right back seat.

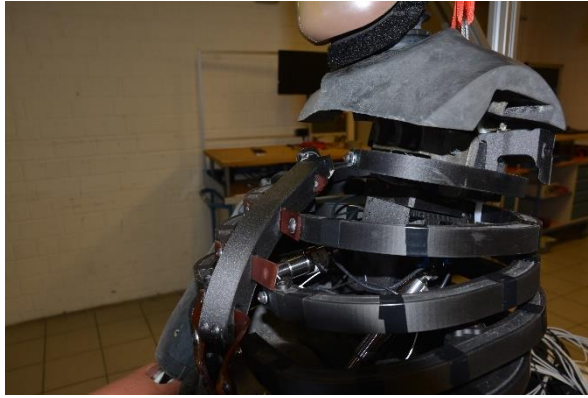


Figure 17. Damage to the thorax and shoulder assembly of the Elderly Female Dummy.

The shoulder belt extractions were not measured in the rear.

Figure 18 displays the head forward displacements as measured by crash test video analysis. Upon reaching its maximum forward displacement, the target on the Elderly Female Dummy's head, which is required to track the head's movement, became covered by the dummy's right arm and the measurement thus broke off. Peak excursion for the Elderly Female Dummy occurred around 100 ms post-impact and was the smallest. Peak excursion for the HIII 50th Male dummy occurred around the same time but was, however, the largest. The HIII 5th Female dummy recorded its peak excursion around 90 ms after impact.

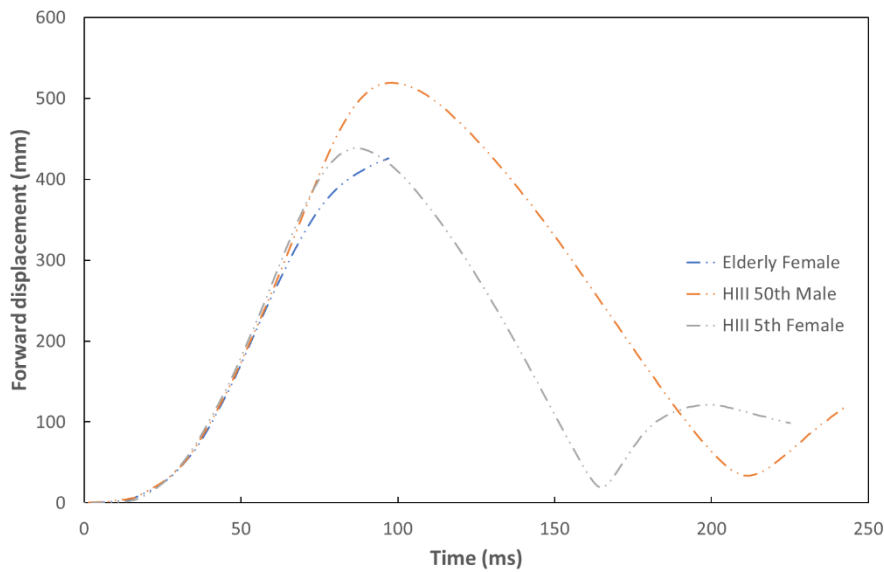


Figure 18. Head forward displacements right back seat.

The peak pelvis forward displacements, as measured by a string, are shown in Table 4. However, the measurement for the Elderly Female Dummy's pelvis forward displacement malfunctioned, which is why there is no value. The HIII dummies recorded similar forward displacements.

Table 4.
Measured peak pelvis forward displacements (mm) right back seat.

Elderly Female	-
HIII 50 th Male	190
HIII 5 th Female	194

These large forward displacements are shown in Figure 19. Graphical observations also indicate that the torsos of the HIII dummies' are nearly upright, while the Elderly Female Dummy exhibited a forward leaning angle greater than 90° as measured between the thorax and the horizontal.

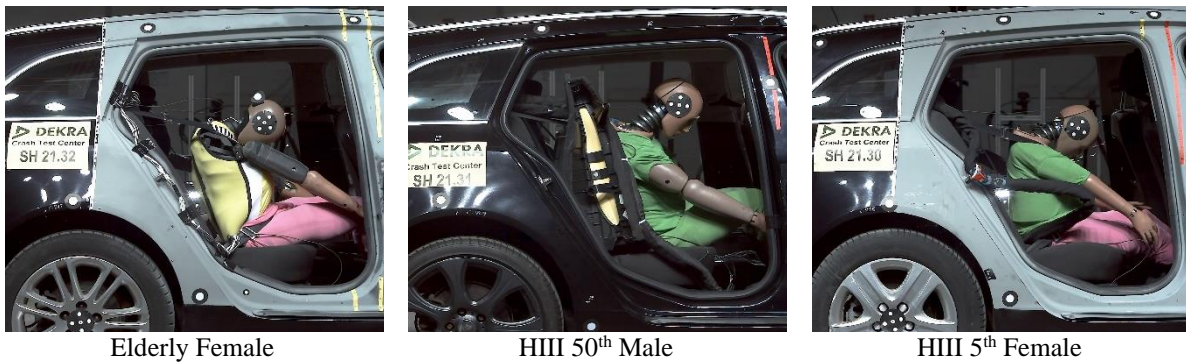


Figure 19. Images of the right back seats taken 80 ms post-impact.

The pelvis accelerations are shown in Figure 20. The Elderly Female Dummy recorded the largest peak value with 57.80 g, while the HIII 50th Male dummy recorded the lowest peak value with 53.51 g. Though acceleration onset is similar, the pelvis accelerations of the HIII dummies increase at a greater rate than the one of the Elderly Female Dummy.

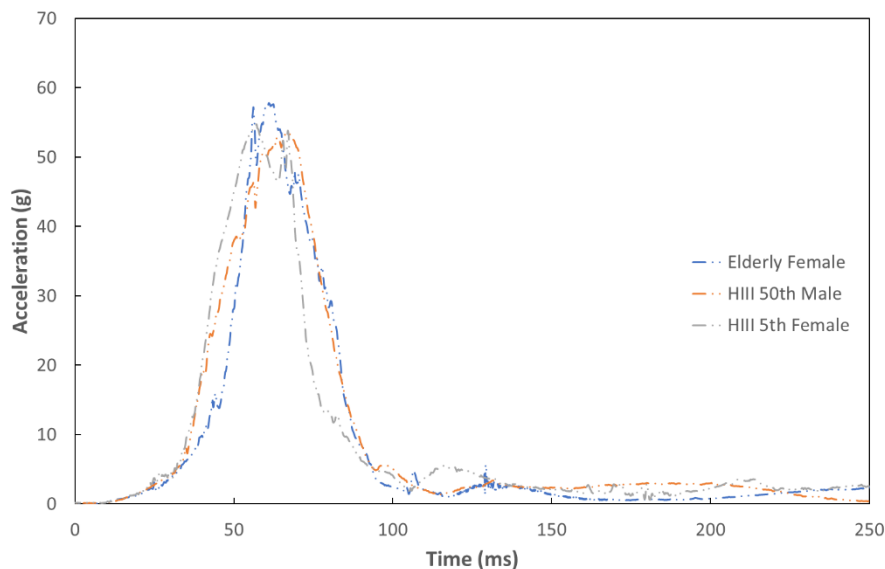


Figure 20. Pelvis accelerations right back seat.

Figures 21 and 22 display the chest accelerations and chest deflections, respectively. While the Elderly Female Dummy's lower acceleration measurement is very similar to those of the HIII dummies, its upper measurement shows an unusual peak value of 756.78 g, which we deem unrealistic. We assume that this measurement was caused by the collapse of the Elderly Female Dummy's thorax due to the high seatbelt forces. Likewise, we assume that the Elderly Female Dummy's chest deflection measurements were detrimentally affected by the dummy's damage. The HIII 50th Male dummy recorded a peak deflection of 48 mm compared to 36 mm for the HIII 5th Female dummy.

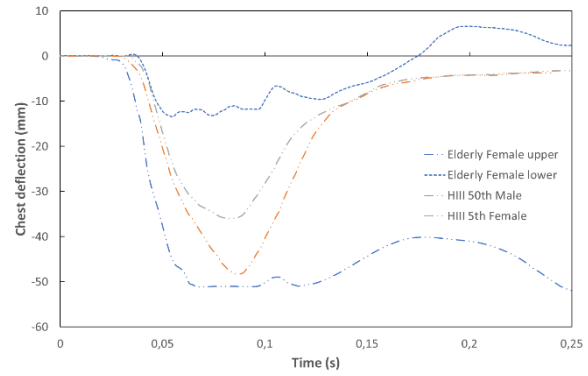
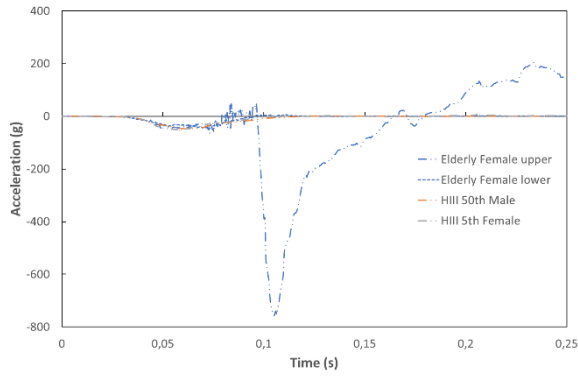


Figure 21. Chest accelerations in x-direction right back seat. Figure 22. Chest deflections right back seat.

Head accelerations are shown in Figure 23. The HIII 5th Female dummy recorded the highest peak value of 71.45 g, as well as a significant second peak. The HIII 50th Male dummy recorded the lowest accelerations. Regarding the Elderly Female Dummy, we assume that the head acceleration was also influenced by the substantive damages to the dummy's thorax and shoulder assembly.

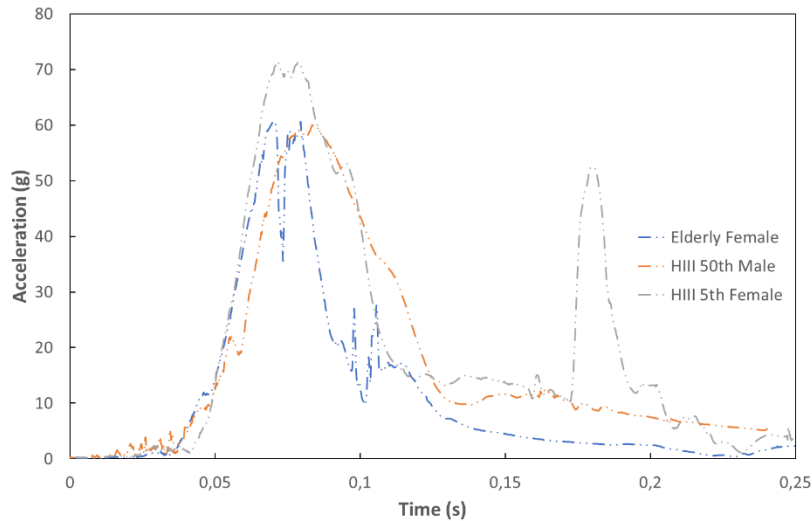


Figure 23. Head accelerations right back seat.

Table 5 shows the measured peak values.

**Table 5.
Measured peak values right back seat.**

	Shoulder belt force (kN)	Lap belt force (kN)	Shoulder belt extraction (mm)	Head forward displacement (mm)	Pelvis forward displacement (mm)	Pelvis acceleration (g)	Chest acceleration (g)	Chest deflection (mm)	Head acceleration (g)
Elderly Female	5.83 [#]	5.92	-	426	-	57.80	756.78 [#] /43.87 ^o	53 [#] /13 ^o	60.74 [#]
HIII 50 th Male	9.51	5.78	-	519	190	53.51	47.54	48	59.96
HIII 5 th Female	7.59	5.50	-	439	194	54.75	52.36	36	71.45

^o Upper/lower chest acceleration and deflection measurements.

[#] We assume that this value is erroneous due to significant damage to the thorax and shoulder assembly.

Anthropomorphic Test Device

Tables 6–8 display the measured peak values for the different seat positions of each ATD. The peak value per measurement is indicated in bold, irrespective of being erroneous or not.

Table 6.
Measured peak values Elderly Female Dummy.

	Shoulder belt force (kN)	Lap belt force (kN)	Shoulder belt extraction (mm)	Head forward displacement (mm)	Pelvis forward displacement (mm)	Pelvis acceleration (g)	Chest acceleration (g)	Chest deflection (mm)	Head acceleration (g)
Driver Seat	4.06	3.34	-15 [^]	244	90	61.44	46.49/42.03 [°]	32/ 42 [°]	71.22
Front Passenger Seat	4.59	4.34	33	387	53	54.50	40.54/33.18 [°]	41/33 [°]	248.49 *
Right Back Seat	5.83 [#]	5.92	-	426	-	57.80	756.78 [#] / 43.87 [°]	53 [#] / 13 ^{#°}	60.74 [#]

[°] Upper/lower chest acceleration and deflection measurements.

* The head acceleration reading is erroneous due to a cable breakage.

[^] The negative sign indicates that the seatbelt extraction was less than the winding up by the pre-tensioner.

[#] We assume that this value is erroneous due to significant damage to the thorax and shoulder assembly.

Table 7.
Measured peak values HIII 50th Male dummy.

	Shoulder belt force (kN)	Lap belt force (kN)	Shoulder belt extraction (mm)	Head forward displacement (mm)	Pelvis forward displacement (mm)	Pelvis acceleration (g)	Chest acceleration (g)	Chest deflection (mm)	Head acceleration (g)
Driver Seat	4.97	5.23	139	486	96	55.60	45.03	31	48.67
Front Passenger Seat	5.04	4.96	206	520	91	49.99	42.97	33	54.55
Right Back Seat	9.51	5.78	-	519	190	53.51	47.54	48	59.96

Table 8.
Measured peak values HIII 5th Female dummy.

	Shoulder belt force (kN)	Lap belt force (kN)	Shoulder belt extraction (mm)	Head forward displacement (mm)	Pelvis forward displacement (mm)	Pelvis acceleration (g)	Chest acceleration (g)	Chest deflection (mm)	Head acceleration (g)
Driver Seat	3.90	4.11	-12 [^]	224	74	54.42	49.63	32	78.34
Front Passenger Seat	5.02	4.50	53	336	48	43.42	39.36	24	54.55
Right Back Seat	7.59	5.50	-	439	194	54.75	52.36	36	71.45

[^] The negative sign indicates that the seatbelt extraction was less than the winding up by the pre-tensioner.

DISCUSSION

Aim of this study was to compare the impact kinematics of the Elderly Female, the HIII 50th Male and the HIII 5th Female dummies as drivers, front passengers, and rear passengers in full-width frontal impacts.

It is known that the HIII dummy exhibits a restraint-system-dependent biofidelity [15]. Chest deflection of the HIII 5th Female, for example, was shown to increase when placing the front passenger seat in its longitudinal mid-position [16-17]. In our study – contrary to Regulation UN R137 – we also placed the front passenger seat in its longitudinal mid-position. Generally, ATD excursion is influenced by airbag and knee bolster contact on the front seats, while ATD excursion is primarily controlled by the seatbelt in the rear. The biofidelic requirements of the HIII 5th Female dummy were scaled down from the HIII 50th Male dummy [18], while neither injury assessment reference values (IARVs) nor regulation limits exist for the Elderly Female Dummy yet.

Figure 24 displays the injury assessments according to Regulation UN R137 for the two HIII dummies and their different seat positions. On the front seats, the HIII 50th Male dummy recorded measurements all below the respective thresholds, while chest protection was poor in the rear. For the HIII 5th Female dummy, chest protection was adequate on the driver seat with all other measurements being good. On the front passenger seat, the HIII 5th Female recorded adequate head acceleration, while head acceleration and chest protection were poor in the rear. These findings proof epidemiological data that rear seat occupants are worse protected than occupants in the front.

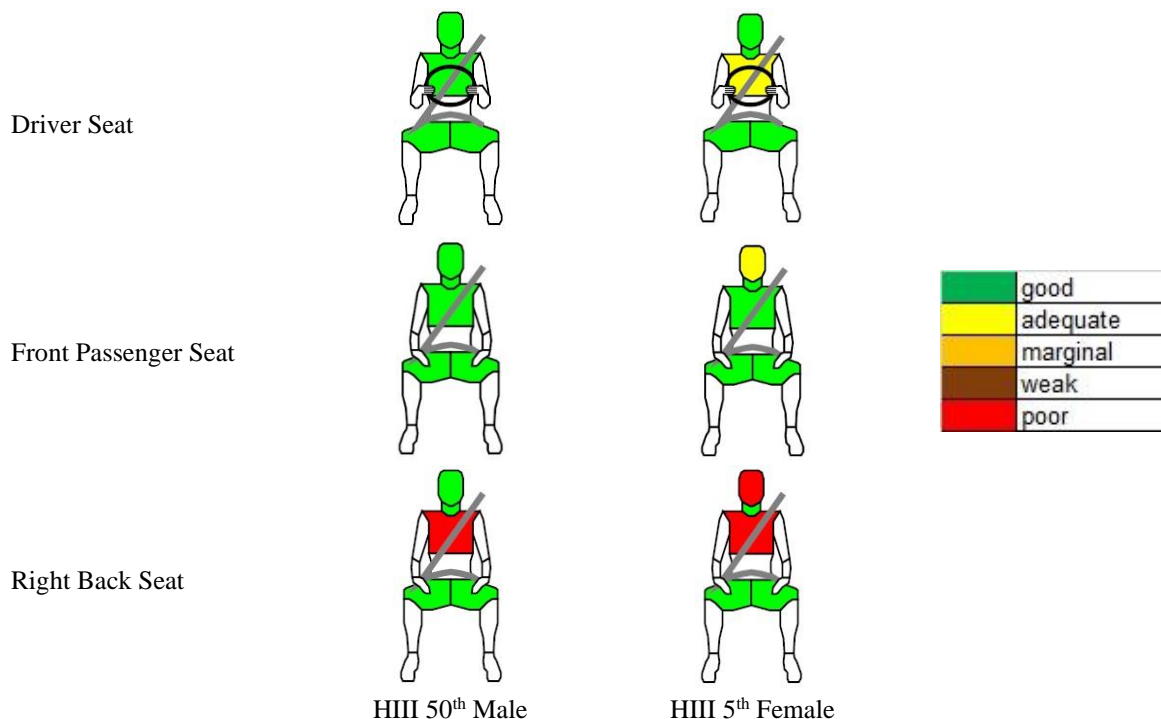


Figure 24. Injury risk assessments according to Regulation UN R137.

As previously observed on the front passenger seat [14], kinematic observations have also shown differences in ATD dynamics for the driver and rear seats. While the front seats were equipped with double pre-tensioners and load limiters, the back seats were fitted with neither.

In the front, the HIII 50th Male experienced the largest pelvis excursions and shoulder belt extractions. As we observed in our previous study for the front passenger seat, the Elderly Female Dummy also experienced a bigger pelvis displacement than the HIII 5th Female on the driver seat, while, to the contrary, shoulder belt extractions were quite similar on the driver seat. For both female dummies, the peak shoulder belt extraction value was negative, meaning that the shoulder belt was extracted less by the dummies than wound up by the respective pre-tensioner. This implies, similar to the front passenger seat, different forward leaning angles on the driver seat. These are not corroborated quantitatively, but graphic observations show that on the driver seat only the HIII 50th Male dummy experienced a forward leaning angle of less than 90° as measured between the thorax and the horizontal, while on the front passenger seat both HIII dummies experienced a forward leaning angle of less than 90° (see Figures 7 and 14). The Elderly Female Dummy, however, experienced a forward leaning angle of greater than 90° on both front seats.

The HIII 50th Male dummy experienced the biggest torso forward rotations on both front seats, while the HIII 5th Female dummy's torsos rotated minimally being nearly upright on both front seats. On the front passenger seat, such a behaviour was observed before by [19] for the HIII 5th Female when the seat was positioned in its longitudinal mid-position.

Interestingly, pelvis excursion was larger on the driver seat than on the front passenger seat for all three ATDs. Graphic observations of the Elderly Female Dummy on the driver seat show that the ATD is susceptible to submarining. Figure 25 shows still images beginning at 25 ms post-impact – the time at which the driver airbag started to deploy – and then at intervals of 10 ms. The red horizontal bar is placed at the same height in each frame. At 35 ms after impact, it can clearly be seen how the deploying driver airbag hit the Elderly Female Dummy's chest, while the head did not yet contact the airbag. Starting at roughly 45 ms post-impact, it can be seen how the thorax slid down the backrest – this can be visualised by looking at the targets placed on the ATD's upper arm and how they move below the red horizontal bar – while the pelvis continued to move forward. Simultaneously, the seat base and the backrest tilted forward. Upon inspection of the seat post-crash, we noticed that metal parts in the seat base had deformed. Regarding the HIII 5th Female on the driver seat, we observed a similar pattern, i.e., the thorax slid down the backrest, and the seat base and the backrest tilted forward, though to a lesser extent. The seat base was adjusted to its vertical uppermost position for both female dummies, while to its lowest for the HIII 50th Male. Therefore, we did not observe the seat base to tilt forward when the HIII 50th Male dummy was placed on the driver seat. We do not know in how far this is a problem with the seat design of the chosen test vehicle, or whether this is something of a general concern when the seat is adjusted to its vertical uppermost position. The fact that the driver seat tilted more when the Elderly Female Dummy was seated on it might be explained by the fact that the pelvis accounts for 18.5 % of total mass for the Elderly Female compared to only 14.5 % for the HIII 5th Female.

Like what happened on the front passenger seat, we assume that the Elderly Female Dummy experienced compression in its thoracolumbar spine on the driver seat too, caused by the torso sliding down the backrest. However, as the ATD is not equipped with respective sensors, we cannot quantify this. In sled tests with reclined occupants, [20] observed a combination of flexion and compression in the thoracolumbar spines of all five Post Mortem Human Subjects (PMHSs). Three PMHSs suffered fractures at vertebral body L1. Therefore, it needs to be investigated in how far this kinematic behaviour of the Elderly Female Dummy correlates with elderly women, as a forward leaning angle of greater than 90° seems to be potentially injurious.

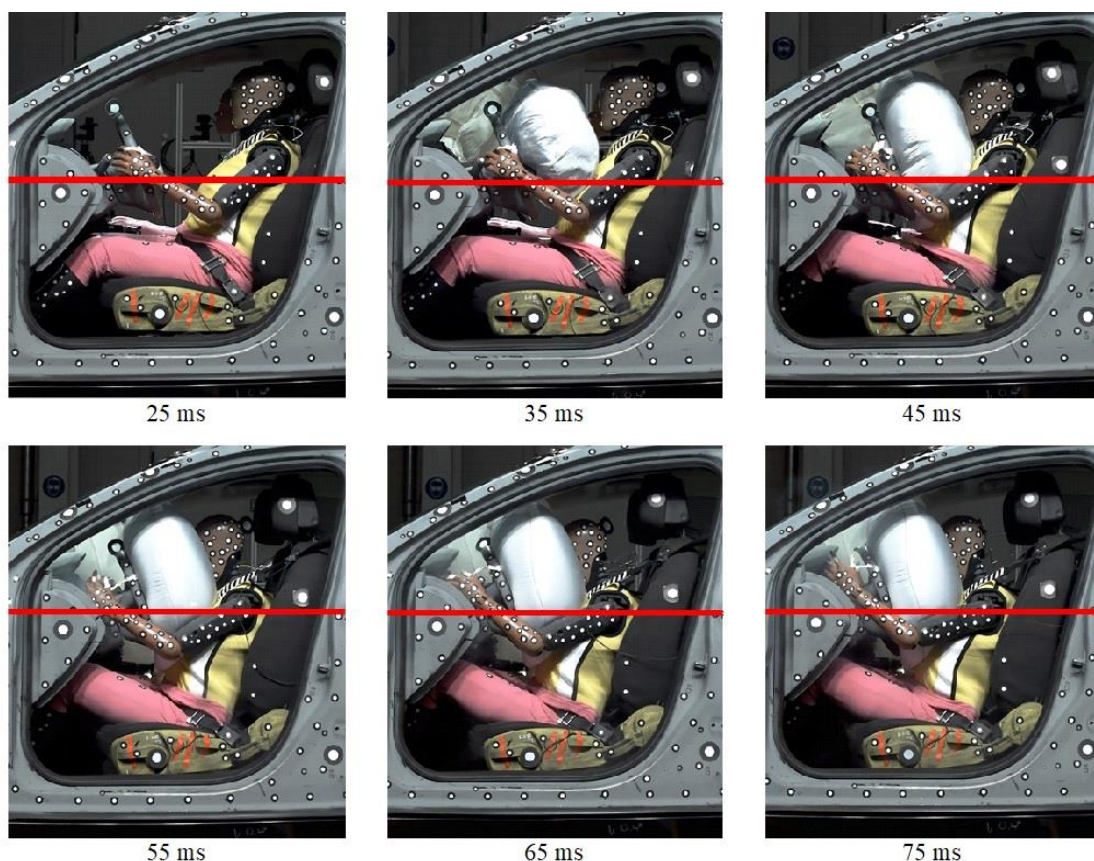


Figure 25. Still images of the Elderly Female Dummy on the driver seat.

In the rear, the HIII 5th Female exhibited a greater pelvis forward displacement than the HIII 50th Male, which is more than double as large as on the driver seat and more than threefold as on the front passenger seat. For the HIII 50th Male dummy, pelvis excursion in the rear is double that on the front seats. Unfortunately, the equipment for measuring the pelvis displacement of the Elderly Female malfunctioned in the rear. However, graphic observations show that the ATD contacted the front passenger seat with its knees, indicating substantive pelvis excursion. The torsos of the HIII dummies hardly rotated forwards with them being nearly upright, while the Elderly Female Dummy experienced – as on the front seats – again a forward leaning angle of greater than 90° as measured between the thorax and the horizontal. These observations indicate that dummy kinematics are primarily controlled by the seatbelt in the rear, whereas airbag and knee bolster contact control dummy kinematics in the front. Missing airbag and knee bolster contact may also explain why each ATD recorded both its highest shoulder belt and lap belt forces in the rear.

Considering the HIII dummies, shoulder belt forces in the rear were nearly double as large as in the front. The HIII 50th Male dummy recorded similar shoulder belt forces in the front seats, while the HIII 5th Female dummy's shoulder belt force was larger on the front passenger seat than on the driver seat. Considering the Elderly Female Dummy, we assume that the shoulder belt force recorded in the rear is erroneous due to severe damage to the ATD's thorax and shoulder assembly caused by the seatbelt. This highlights the effectiveness of pre-tensioners and load limiters to reduce chest loading. Shoulder belt extractions were not measured in the rear.

Chest deflection is the most suitable discriminator for thoracic injuries, with chest acceleration being unreliable [15][21]. On the front passenger seat, the HIII 5th Female experienced a lower peak chest deflection than on the driver seat. The HIII 50th Male, however, experienced a larger peak chest deflection on the front passenger seat than on the driver seat. For both HIII dummies, peak chest deflection was the largest in the rear. Computing the injury likelihoods according to Regulation UN R137, this translates into a peak chest deflection for the HIII 5th Female dummy of 71.2 % of the regulation limit on the front passenger seat compared to 95.5 % on the driver seat and 107.0 % in the rear, while the HIII 50th Male dummy recorded a peak chest deflection of 76.8 % of the regulation limit on the front passenger seat compared to 70.4 % on the driver seat and 112.4 % in the rear. Considering that the HIII 5th Female features a more compliant chest than the HIII 50th Male [22], and that both dummies were subjected to identical restraint systems, one would, however, assume that the HIII 5th Female generally experiences a larger chest deflection than the HIII 50th Male. On the front passenger seat, one explanation might be that the greater chest excursion of the HIII 50th Male translated into greater loading by the front passenger airbag. On the driver seat, though, the HIII 5th Female experienced greater chest loading by the front airbag as the seat was adjusted further forward. In the rear, where the seatbelts were neither equipped with a pre-tensioner and load limiter, the greater chest deflection of the HIII 50th Male might be explained by the greater mass of the ATD's thorax. Moreover, the HIII 5th Female experienced a greater pelvis forward displacement than the HIII 50th Male, which could also contribute to less chest loading. The Elderly Female Dummy features the most compliant thorax, which is also equipped with two chest deflection potentiometers. As no IARVS nor regulation limits exist yet, no injury risks can be computed. The chests were not uniformly loaded on all three seat positions, which is indicated by the differences between the upper and lower measurements. On the front passenger and right back seat, the upper chest deflection measurements were greater than the lower ones, while the lower chest deflection potentiometer recorded the larger deflection on the driver seat. These non-uniform load distributions are explained by shoulder belt loading, as the belt is routed over the sternum. On the driver seat, however, the lower chest deflection potentiometer is loaded by the deploying airbag; see Figure 25. This indicates that the driver front airbag can potentially be injurious when the driver sits close to the steering wheel. Were the regulation limit of 34 mm of the HIII 5th Female used for the Elderly Female Dummy – the Elderly Female is anthropometrically closer to the HIII 5th Female than the HIII 50th Male – the limit would have been exceeded for the lower measurement on the driver seat and for the upper measurement on the front passenger seat, indicating a potential risk of thoracic injuries. On the right back seat, the Elderly Female Dummy's thorax was severely damaged by the seatbelt, which is why we do not know in how far the chest deflection measurements are correct. Nonetheless, the damage by its own does already highlight that the chest has been subjected to potentially injurious loads. A 40 – 50 % risk of suffering Abbreviated Injury Scale (AIS) 3+ thoracic injuries is linked to HIII 50th Male sternal deflections of 50 mm [23]. Respective scaling factors have been established for the HIII 5th Female [22]. The measured peak values of both HIII dummies were below these thresholds on any seat position. In the rear, however, the recorded peak deflection values were not far below these thresholds. Were the same scaling factors as for the HIII 5th Female used for the Elderly Female Dummy, the lower chest deflection on the driver seat and the upper deflections on the front passenger and right back seat would exceed the threshold.

Given that the mechanical properties of bone get worse due to ageing, the elderly are more susceptible to trauma [24-27]. Moreover, human thoraces are more compliant than HIII dummy thoraces under seatbelt loading [28]. As the Elderly Female Dummy's thorax is a new design, more research is required to correlate ATD chest deflection to injury risk for senior women under seatbelt loading.

The damages to the Elderly Female Dummy also highlight challenges in using new advanced manufacturing technologies such as 3D-printing. Certain components of the Elderly Female Dummy failed due to delamination,

as the fibres have been aligned perpendicularly to the load direction. Changing the printing direction by 90° – so that fibre alignment would be along the load direction in frontal impacts – would, however, complicate the printing process by requiring more support material.

All three ATDs recorded two head acceleration peaks, the first one caused by airbag contact during impact and the second one caused by headrest contact during rebound. The HIII 5th Female dummy was the only ATD, whose second peak was larger than the first one. This phenomenon, however, was only observed on the driver seat. We assume that these differences between the ATDs are explained by the different masses of the heads, with the lighter head being decelerated more by the headrest. The HIII 5th Female dummy's head is lighter than the HIII 50th Male dummy's head. The Elderly Female Dummy's head is the lightest, but stems, as its neck, from the WorldSID Small Female, a side impact ATD. Using the WorldSID Small Female's head in this early prototype version of the Elderly Female Dummy was considered to be a good first step in the development process, since the Elderly Female is designed to be omnidirectional. Research is currently being conducted to investigate whether the WorldSID Small Female's head and neck assembly is more representative of the neck kinematics of elderly women than the HIII 5th Female's design. The Elderly Female Dummy's head acceleration measurements on the front passenger seat are erroneous due to a cable breakage, and we also assume that the measurements on the right back seat were affected by the severe damage to the ATD's thorax and shoulder assembly.

Graphic observations also show that, on the front passenger seat, the Elderly Female Dummy's chin contacted its thorax shortly after airbag contact. Such a behaviour was not observed on the driver seat. Neither HIII dummy experienced chin contact in the front seats. In the right back seat, all ATDs experienced chin contact, indicating large neck flexion, which might be injurious. While the front airbags cushion the head and counteract neck flexion, such a safety device is not installed in the rear. Research shows that HIII 50th Male neck response is stiffer than PMHS neck responses [29].

The HIII 5th Female Dummy does not properly represent senior women anthropometrically based on anthropometric data from the International Center of Automotive Medicine (ICAM) and the University of Michigan Transportation Research Institute (UMTRI). Pelvis design, for example, is simply scaled down from the HIII 50th Male dummy [30]. The Elderly Female Dummy, on the other hand, is being designed based specifically on the anthropometry of elderly women. However, more research is necessary to determine whether the Elderly Female Dummy's biofidelity is more representative of senior women than the HIII 5th Female.

CONCLUSIONS

The three full-width frontal impact tests have shown that second-row seats offer less protection than first-row seats. Moreover, restraint systems should be adaptive to account for passengers of different sexes, sizes, ages, weight distributions, and postures. Using another seating position on the front passenger side than stipulated by Regulation UN R137, led to changes in impact dynamics of the HIII 5th Female dummy. This was already observed in previous studies. The HIII 50th Male dummy experienced the greatest torso forward rotation on all seats, with changes in the forward leaning angle of both the Elderly Female and HIII 5th Female dummies dependent on their respective seat positions. More research into the biofidelity of the Elderly Female Dummy is necessary to improve ATD design and to develop IARVs and injury risk functions.

The damages to the Elderly Female Dummy highlight the challenges in using new advanced manufacturing technologies such as 3D-printing.

DISCLAIMER

The Elderly Female Dummy is still in its early prototype stage and continuously being developed further, which is why the presented results should not be construed as the final performance of this ATD.

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APPENDIX

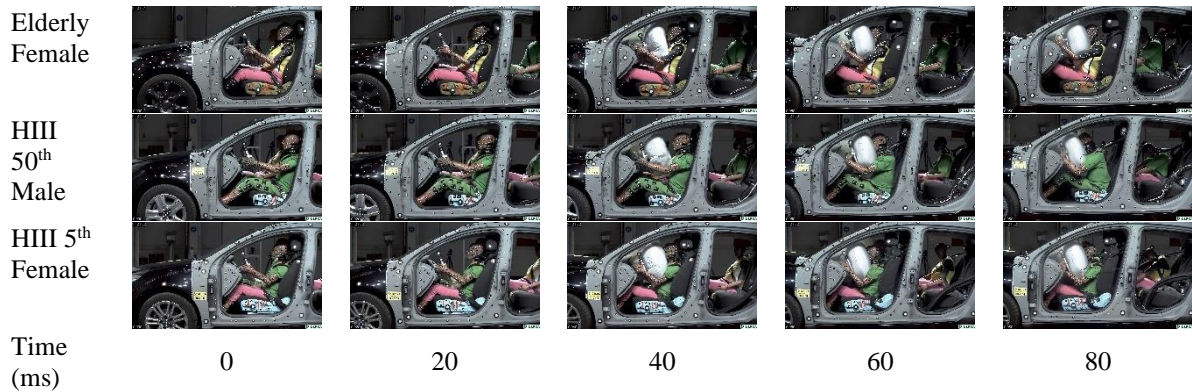


Figure AI. Still images of the driver seats in the three crash tests.

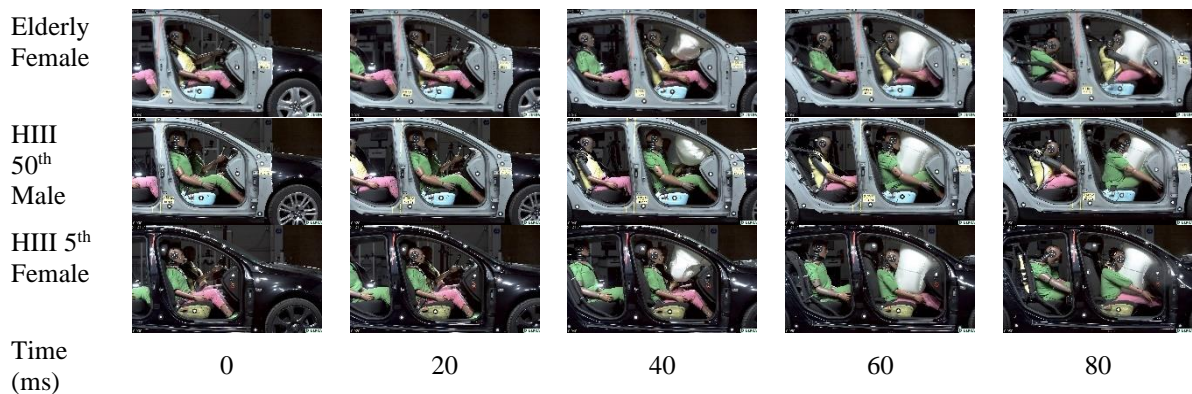


Figure AII. Still images of the front passenger seats in the three crash tests [14].

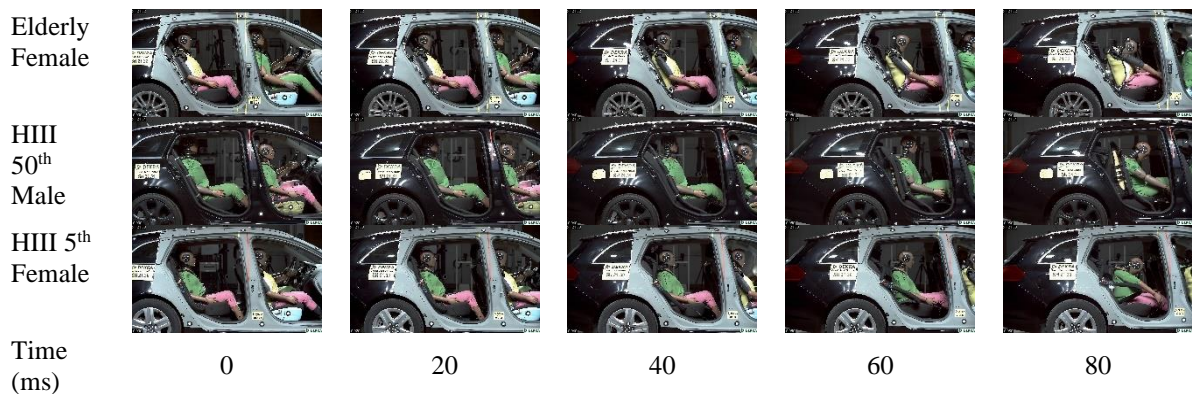


Figure AIII. Still images of the right back seats in the three crash tests.