Impact Kinematics and Dynamics of an Obese ATD in Comparison with an Elderly Female, the HIII 50th Male and the HIII 5th Female ATDs as Drivers and Front Passengers in Full-width Frontal Impacts

Andreas Schäuble, Florian Zippel, Peter Rücker, Thomas Kinsky

Abstract The aim of this project is to analyse the impact kinematics and dynamics of an Obese anthropomorphic test device (ATD) and to compare these findings with those of an Elderly Female, the HIII 50th Male and the HIII 5th Female ATDs as drivers and front passengers in full-width frontal impacts.

DEKRA conducted five crash tests with a midsize station wagon based on Regulation UN R137 – except for the front passenger seat, which was adjusted in its longitudinal mid-position. The ATDs were either positioned on the driver seat or the front passenger seat.

On both seats, the Obese ATD exhibited by far the largest pelvis excursions, which were concomitant with minimal torso pitch. Its knees and lower limbs impacted hard against the dashboard. The additional soft tissue material limited the engagement of the lap belt with the pelvis, which resulted in submarining.

With their additional sensors, both the Obese and Elderly Female ATDs can better capture the complex loading of the thorax than the HIII ATDs.

Both the HIII 50th Male and the HIII 5th Female do not sufficiently represent obese, elderly, and female vehicle occupants, and do thus not interact with restraint systems in a manner to properly replicate the challenges posed by these groups. By developing both the Obese and the Elderly Female ATDs, manufacturers will be provided with tools that represent these vulnerable groups to assess and validate their restraint systems to improve occupant safety. However, more research into the biofidelity of the Obese and the Elderly Female ATDs is required to improve ATD design and to develop injury assessment reference values and injury risk functions.

Keywords 5th and 50th percentile ATDs, Elderly Female ATD, frontal Impacts, Hybrid III, Obese ATD

I. INTRODUCTION

Obesity, which is defined by the World Health Organization as a Body Mass Index (BMI) (the individual's mass divided by the height squared) of 30 kg/m² or higher, has nearly tripled since 1975 worldwide [1]. In Europe, nearly 60% of the adult population is affected by overweight and obesity, whilst this figure is almost 30% amongst children [2]. In addition to being detrimental to overall health, epidemiological studies have shown that obesity also results in an increased risk of death in motor vehicle accidents [3-5]. Reference [6], however, found that moderately to morbidly obese drivers had an increased risk in fatality, while overweight and mildly obese drivers had, in fact, a lower fatality risk than normal or underweight drivers. Reference [7] concluded that next to a heightened risk of mortality, obese occupants are also exposed to a higher risk of suffering lower extremity injuries. It was also observed by [8] that the risk of suffering Abbreviated Injury Scale (AIS)2+ and AIS3+ thoracic injuries is 26% and 33% higher, respectively, for obese occupants compared to lean occupants. Reference [9], however, observed that the adjusted odds ratio for crash fatality only increased significantly with an increase of BMI amongst male drivers, but not amongst female drivers. Likewise, [10] found that obese male drivers have a higher risk of sustaining injuries, particularly upper body injuries, than normal-weight men and females, likely attributing the sex differences to differing body shapes, adipose tissue distributions and centres of gravity.

To investigate potential injury mechanisms, [11-12] performed impact tests with obese Post-Mortem Human Subjects (PMHS) and non-obese PHMS. The obese PMHS experienced greater maximum forward excursions. The larger pelvis excursion in the obese PMHS was concomitant with a torso backwards rotation – leading to a

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different load distribution to the torso by the seat belt – and a larger forward excursion of the lower extremities. This increases the risk of a hard contact against the lower dashboard and possible lower extremity injuries. An increase in BMI also reduces the ability of the lap belt to interact with and restrain the pelvis properly in frontal impacts, as the lap belt is being placed further forward and higher relative to the pelvis [13]. In addition, an increase in BMI is further associated with a larger kinetic energy that the restraint system must handle, which is why obese occupants pose a challenge for current restraint systems.

To address these challenges and to provide manufacturers with a tool to assess their restraint systems, Humanetics is currently developing the Obese ATD. This ATD, which is based on the THOR 50th Male ATD, represents an obese male vehicle occupant with a mass of 124 kg and a BMI of 40.

DEKRA had the chance to conduct two frontal impact tests with a prototype version of the Obese ATD. In previous studies [14-15], we already investigated the impact kinematics and dynamics of a prototype version of the Elderly Female – an ATD representing a 70-year-old female vehicle occupant – the HIII 50th Male and the HIII 5th Female ATDs as drivers, front passengers and rear passengers in full-width frontal impacts. This study continues and extends the previous research by analysing the impact kinematics and dynamics of the Obese ATD as a driver and front passenger. These findings are then compared with those of the Elderly Female, the HIII 50th Male, and the HIII 5th Female ATDs from the previous studies. The Obese ATD was not tested as a rear occupant.

II. METHODS

Obese ATD

The Obese ATD used in this study is still a prototype version and represents an obese male vehicle occupant with a mass of 124 kg and a BMI of 40 [16-18]. This ATD is based on the skeletal structure of the THOR 50th Male ATD. The conversion is made by adding unique flesh and additional mass to the THOR 50th Male. This is done by means of a flesh jacket – which represents the superficial tissue at the chest, pelvis, and upper legs – and increasing the mass of the legs and arms. The design of the flesh jacket is based on the anthropometry of an obese PMHS with a BMI of 35 previously tested at the University of Virginia's Center for Applied Biomechanics. Research into the biofidelity of the Obese ATD is ongoing to improve ATD design.

Elderly Female ATD

The Elderly Female ATD, which is still a prototype version, represents a 70-year-old female vehicle occupant [14][19-20]. This ATD is based on clinical data of 80 women aged 67–73 years and has a height of 1.61 m, a mass of 73 kg, and a BMI of 28. The body shape of average elderly females is much better represented by the Elderly Female ATD than by the HIII 5th Female ATD or other ATDs due to its mass distribution over height. The head and neck of the Elderly Female stem from the WorldSID Small Female. The lower arms, hands, knees, and feet are those of the HIII 5th Female. The remainder, which comprises a new and unique structure, was specifically designed for the Elderly Female ATD. The Elderly Female comprises a flexible spine, a movable rib cage and floating shoulders, which form the supporting structure. The liver and spleen are represented by organ sacs placed in the abdomen. New manufacturing technologies such as 3D-printing are used to make certain components like the ribs and shoulder assembly. The ribs are designed to be more flexible to account for the worsening of the mechanical properties of bone that is concomitant with ageing. Research into the biofidelity of the Elderly Female ATD is ongoing to improve ATD design.

Test Setup

Two full-width frontal impact tests against a rigid barrier at 50 km/h were conducted with the Obese ATD and the HIII 50th Male ATD either positioned on the driver or front passenger seat, as shown in Fig. 1. The tests were identical to those in our previous studies [14-15], where the Elderly Female, the HIII 50th Male and the HIII 5th Female ATDs were either positioned on the driver, or front passenger seat. The test vehicles were identical models of a popular midsize station wagon of model years 2009–2013. The tests were conducted in accordance with Regulation UN R137 apart from the front passenger seat position (see section "seating position"). Though the vehicles were only loaded with two ATDs in this test series, as compared to the three ATDs in our previous test series, the vehicles had similar testing masses and hence comparable crash pulses (see Fig. 2). Both front doors have been removed to obtain an unobstructed view. The HIII 50th Male ATD of the previous test series will be referred to as #1, while that of the current test series will be referred to as #2.

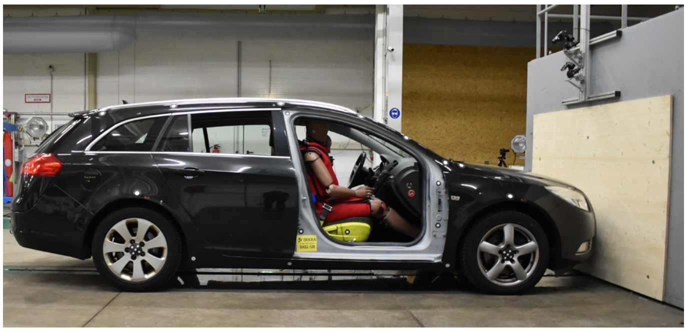

Fig. 1. Test setup.

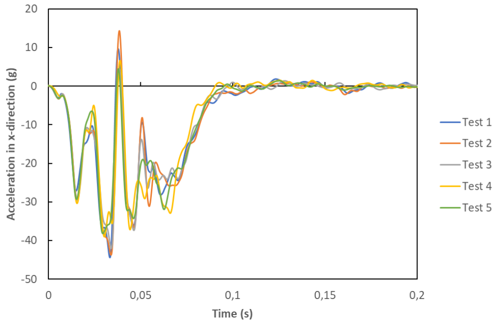

Fig. 2. Acceleration pulses of the five crash tests.

Seating Position

Driver Seat: the seat adjustments for the HIII 50th Male ATD were made in accordance with Regulation UN R137. The seat rail overlap was thus 35 mm. The European New Car Assessment Programme (Euro NCAP) frontal full-width test protocol was used for the HIII 5th Female ATD, yielding a seat rail overlap of 118 mm. Currently, no regulations exist neither for the Obese ATD nor the Elderly Female ATD. As the anthropometry of the Elderly Female ATD is closest to the HIII 5th Female, the same protocol was used as a basis. Due to the longer legs of the Elderly Female, the driver seat was moved backwards until the Elderly Female took a realistic seating position. The seat rail overlap was 77 mm. As the structure of the Obese ATD is based on the THOR 50th Male ATD, we took the seat adjustments for the HIII 50th Male as stipulated by Regulation UN R137 as a basis and then adapted the longitudinal adjustment until the ATD took a realistic seating position. The seat rail overlap was 18 mm. The seat was also in its vertical lowermost position. The larger the seat rail overlap, the further forward is the driver seat.

Front Passenger Seat: we wanted to use a single seating position for all four ATDs on the front passenger seat, which is why we considered what seat adjustments are made by front passengers. A field study and a German In-Depth Accident Study (GIDAS) analysis were conducted, as previously described in [14], which yielded that the most common position was the longitudinal mid-position. The front passenger seats of the test vehicles did not allow for a height adjustment.

Measurements

Restraint forces, shoulder belt extractions, ATD displacements, femur forces, chest deflections and chest, pelvis and head accelerations were measured. To visualise the ATD kinematics, still images of the five crash tests and different seat positions are provided in the Appendix. However, due to their similar kinematics, only the still images of the HIII 50th Male ATD #1 are shown.

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

As the Obese ATD is based on the THOR 50th Male, it was equipped with the same standard configuration of sensors, as were the HIII 50th Male and HIII 5th Female. The Elderly Female ATD, however, was only equipped with sensors for measuring: head acceleration, thoracic spine acceleration, pelvis acceleration, and thorax compression.

The shoulder belt forces were measured between the D-ring anchorage and the ATD's shoulder. The lap belt forces were measured just above the buckle.

Shoulder belt extractions are measured by means of a displacement transducer. The transducer measures the linear movement of the seat belt via an adhesive measurement tape placed on the seat belt.

Head forward displacement was determined by means of crash test video analysis using high-speed video software FalCon eXtra, Version 10.33.0011. Pelvis forward displacement was determined by means of a string in accordance with a test protocol by the Insurance Institute for Highway Safety (IIHS) [21]. A string is hereby attached to the pelvis of the ATD, threaded through the gap in between the backrest and the seat cushion, and finally fixated onto the seat in a way that the remainder of the string can be pulled out. The string is marked at the fixation site. During impact, the forward movement of the ATD's pelvis will pull out the string. The string is marked again at the fixation site post-crash and the difference between both marks equals to the maximum pelvis forward displacement.

III. RESULTS

Figures 3 and 4 display the shoulder belt forces for the driver and front passenger seat, respectively. On the driver seat, both the Obese ATD and the HIII 50th Male ATD #1 recorded maximum values of around 5 kN, while the Elderly Female ATD exhibited the lowest value. The force lasted the longest with the Obese ATD and sort of plateaued after reaching its peak, whereas the force levels dropped much quicker for the other ATDs. On the front passenger seat, the HIII ATDs recorded the highest peak values, followed by the Obese and the Elderly Female ATD.

The lap belt forces are shown in Figs. 5 and 6. As the driver, the HIII 50th Male #2 exhibited the highest peak value, followed by the Obese and the HIII 50th Male #1. The Elderly Female ATD recorded the lowest value, which is less than half of the HIII 50th Male #2's value. On the front passenger seat, however, the Obese ATD exhibited the lowest value, and the HIII 50th Male the highest.

Figures 7 and 8 show the shoulder belt extractions, which are indicative of thorax excursion. Peak extraction was the largest for the Obese ATD on both seat positions – 210 mm on the driver seat at around 85 ms post-impact, and 238 mm on the front passenger seat at around 90 ms post-impact. The shoulder belt forces were around 5 kN at that time on the driver seat and around 4 kN on the front passenger seat, respectively. The Elderly Female and the HIII 5th Female recorded negative peak values on the driver seat, indicating that the seatbelt extractions were less than the winding up of the seat belts by the pre-tensioners. While the shoulder belt extractions were similar for both female ATDs as drivers, the Elderly Female ATD recorded the lowest value as a front passenger – less than a seventh of the Obese ATD's shoulder belt extraction.

Figures 9 and 10 display the head forward displacements. The Obese ATD exhibited the largest head forward displacement on both seats. The measurements of both the Obese and the HIII 50th Male #2 ATDs broke off because the heads were either completely immersed in the airbags or turned away so that the targets, which are required to track the heads' movements, were no longer visible.

The peak pelvis forward displacements are shown in Tables I and II. The Obese ATD exhibited the largest pelvis excursions on both seats, while the HIII 5th Female exhibited the smallest forward displacements. Pelvis forward displacement was larger on the driver seat for every ATD.

TABLE I
MEASURED PEAK PELVIS FORWARD DISPLACEMENT (MM)
DRIVER SEAT

Obese	169
Elderly Female	90
HIII 50th Male #1	96
HIII 50th Male #2	103
HIII 5th Female	74

TABLE II
MEASURED PEAK PELVIS FORWARD DISPLACEMENT (MM)
FRONT PASSENGER SEAT

Obese	139
Elderly Female	53
HIII 50th Male #1	91
HIII 50th Male #2	94
HIII 5th Female	48

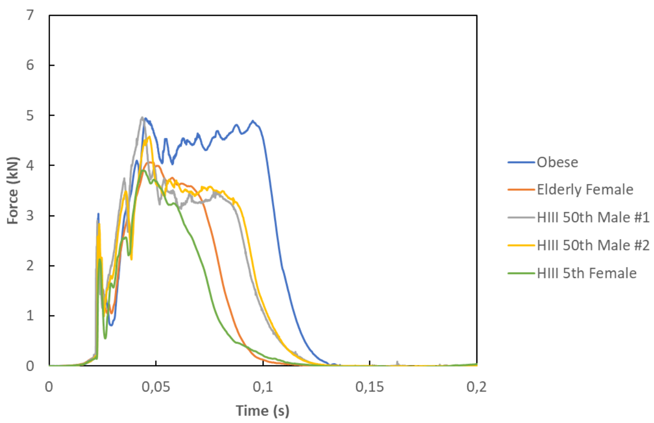

Fig. 3. Shoulder belt forces driver seat.

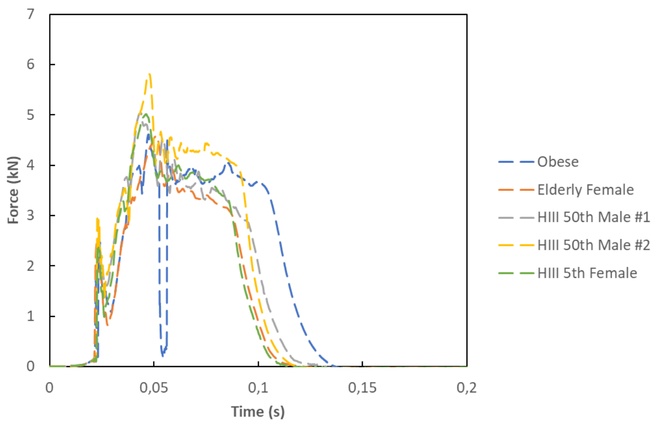

Fig. 4. Shoulder belt forces front passenger seat.

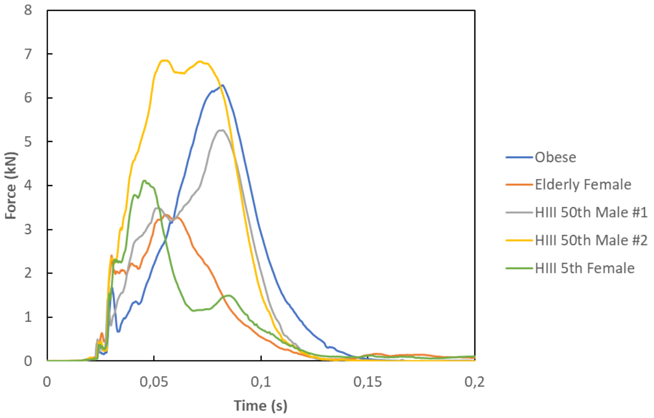

Fig. 5. Lap belt forces driver seat.

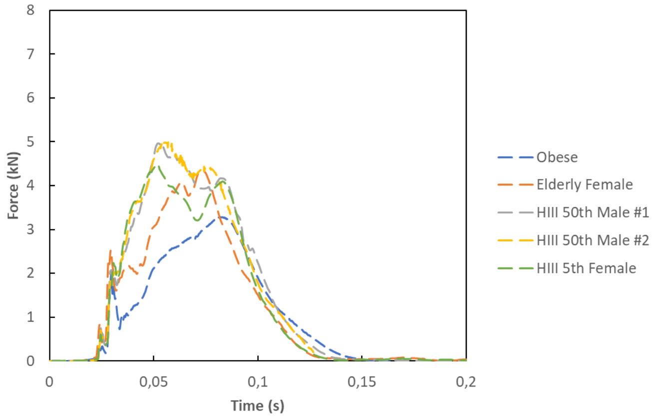

Fig. 6. Lap belt forces front passenger seat.

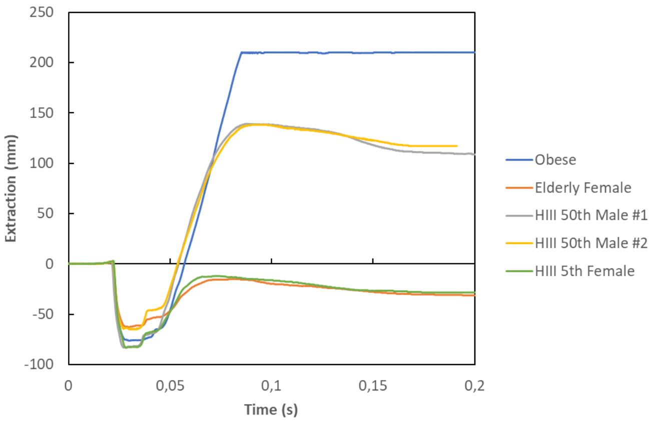

Fig. 7. Shoulder belt extractions driver seat.

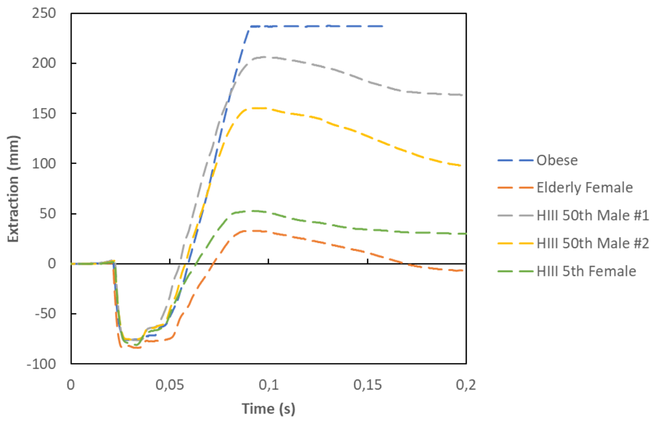

Fig. 8. Shoulder belt extractions front passenger seat.

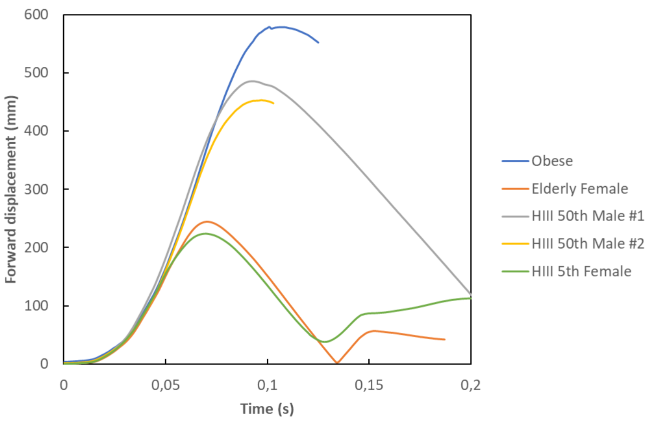

Fig. 9. Head forward displacements driver seat.

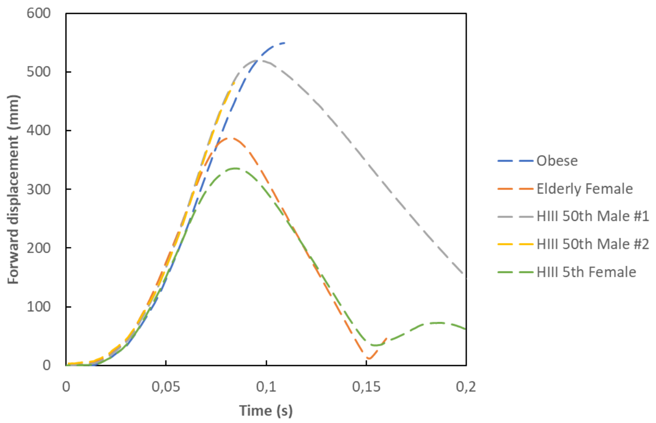

Fig. 10. Head forward displacements front passenger seat.

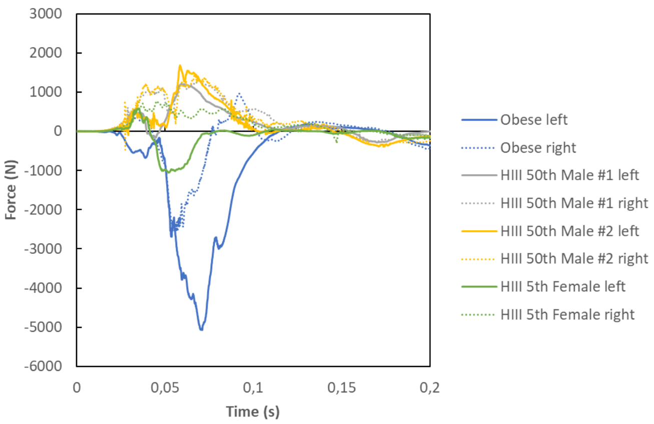

Fig. 11. Femur forces driver seat.

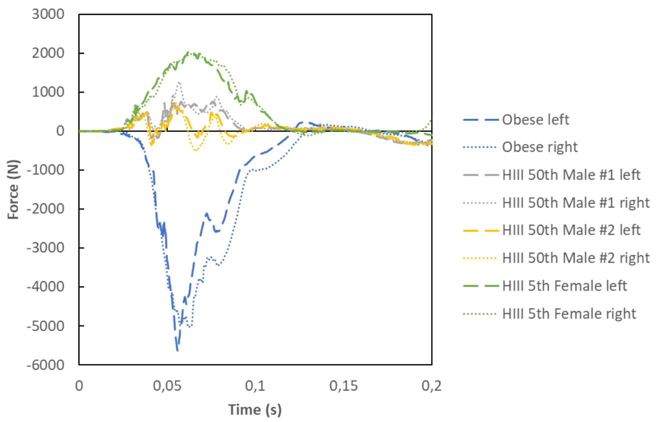

Fig. 12. Femur forces front passenger seat.

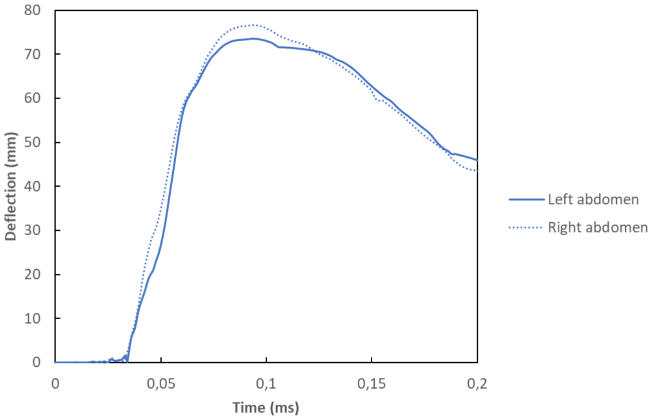

Fig. 13. Obese ATD's resultant abdominal deflections driver seat.

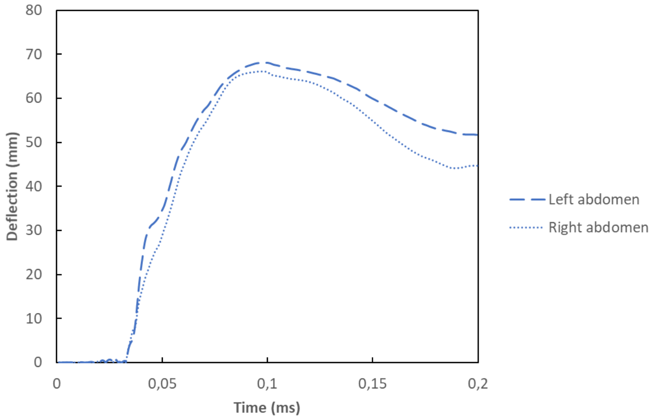

Fig. 14. Obese ATD's resultant abdominal deflections front passenger seat.

The femur forces are shown in Figs. 11 and 12. There are no measurements for the Elderly Female, as this ATD had no sensors in its femurs to measure the acting forces. The Obese ATD registered by far the largest peak forces in both femurs and on both seats. On the driver seat, only the Obese ATD and the HIII 5th Female ATD impacted against the lower dashboard. The Elderly Female ATD and the HIII 50th Male ATDs registered no knee contact. On the front passenger seat, the Obese ATD's knees and lower limbs contacted the lower dashboard hard, while the Elderly Female ATD and the HIII 50th Male ATDs registered minimal knee contact. The HIII 5th Female ATD's knees did not contact the lower dashboard.

Figures 13 and 14 show the resultant abdominal deflections of the Obese ATD on the driver seat and front passenger seat, respectively, indicating that submarining occurred. As this ATD is the only ATD being equipped with sensors to measure abdominal deflections, the maximum values are not displayed in Tables III and IV.

Figures 15 and 16 display still images of the different ATDs on the driver seat and front passenger seat, respectively, which were taken 80 ms post-impact. Due to the different peak shoulder belt extractions and peak pelvis forward displacements, the ATDs exhibited different impact kinematics in form of different pitch angles at time of airbag contact. On the driver seat, the Obese ATD's thorax virtually remained upright until the lower extremities impacted hard against the dashboard, deforming it. Only after dashboard contact did the Obese ATD's thorax begin to rotate forward to result in a pitch angle of less than 90° as measured between the thorax and the horizontal. The Elderly Female and the HIII 5th Female ATDs both exhibited a pitch angle greater than 90° as measured between the thorax and the horizontal. However, the HIII 5th Female's thorax was nearly upright. The HIII 50th Male exhibited a pitch angle of less than 90°. On the front passenger seat, the Obese ATD exhibited similar impact kinematics, with virtually no thorax rotation until the lower extremities impacted hard against the dashboard. While the HIII 50th Male exhibited a pitch angle of less than 90° again, the HIII 5th Female's thorax rotated more than on the driver seat as to exhibit a pitch angle of less than 90° too. The Elderly Female exhibited a pitch angle greater than 90°, as on the driver seat. Moreover, its head rotated the furthest towards the thorax, resulting in chin contact.

Obese | Elderly Female | HIII 50th Male #1 | HIII 5th Female

Fig. 15. Images of the driver seats taken 80 ms post-impact.

Obese Elderly Female HIII 50th Male #1 HIII 5th Female

Fig. 16. Images of the front passenger seats taken 80 ms post-impact.

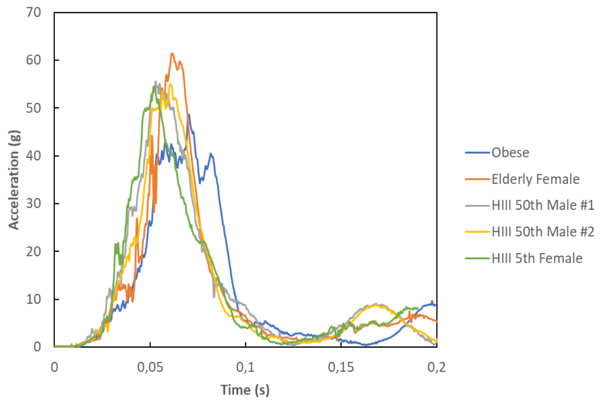

Fig. 17. Pelvis accelerations driver seat.

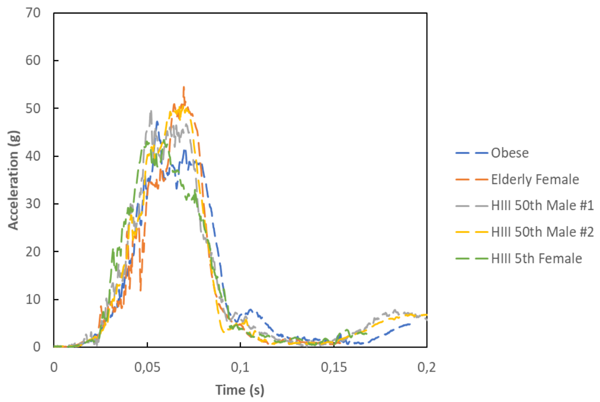

Fig. 18. Pelvis accelerations front passenger seat.

Pelvis accelerations are shown in Figs. 17 and 18. On the driver seat, the Elderly Female recorded the largest peak value, the Obese ATD the lowest, and the three HIII ATDs similar values sitting in between. The Obese ATD's peak value, however, occurred the latest. On the front passenger seat, the Elderly Female also exhibited the largest peak pelvis acceleration, though the HIII 5th Female recorded the lowest peak acceleration. The Obese ATD reached its peak acceleration earlier on the front passenger seat than on the driver seat.

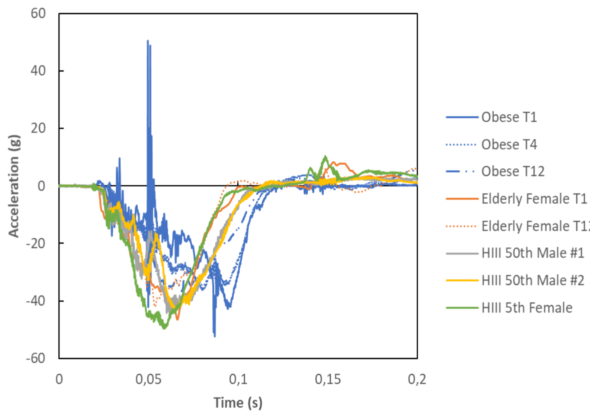

Fig. 19. Chest accelerations in x-direction driver seat.

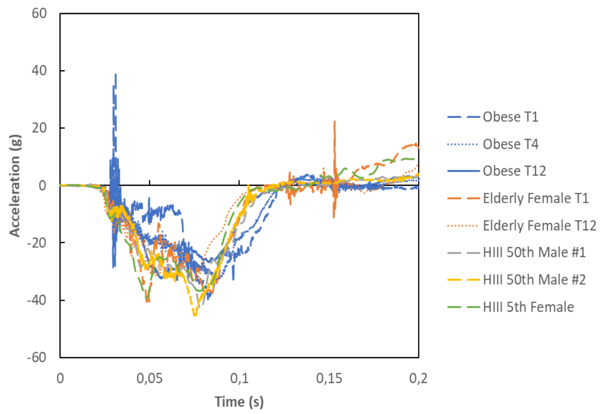

Fig. 20. Chest accelerations in x-direction front passenger seat.

Figures 19 and 20 display the chest accelerations for the driver and front passenger seat, respectively. The Obese ATD is equipped with three accelerometers, which are placed on vertebral bodies T1, T4 and T12, while the Elderly Female is equipped with two accelerometers placed at vertebral bodies T1 and T12. The HIII ATDs are equipped with only one accelerometer. However, the Elderly Female ATD's accelerometers were only biaxial, not triaxial like those of the other ATDs. Therefore, only the chest accelerations in the x-direction were evaluated. Moreover, influences in the y- and z-direction are negligible because we conducted full-width frontal impact tests. The largest recorded value amongst all five ATDs on the driver seat was for the Obese ATD's vertebral body T1, with vertebral bodies T4 and T12 recording considerably lower values. On the front passenger seat, however, all three accelerometers of the Obese ATD recorded quite similar values, while the largest overall peak value was recorded by the HIII 50th Male #2.

The chest deflections are shown in Figs. 21 and 22. While the HIII ATDs are solely equipped with a single chest deflection potentiometer, the Elderly Female ATD has two, and the Obese ATD is equipped with four chest deflection potentiometers: upper left, lower left, upper right, and lower right. On the driver seat, the right deflection potentiometers of the Obese ATD recorded larger values than on the left side of the thorax, while it was the opposite on the front passenger seat. Moreover, the upper potentiometers recorded larger deflections than the lower potentiometers for both seat positions. As drivers, the chest deflection readings for the Elderly Female's upper measurement, the HIII 50th Male #1 and #2, and the HIII 5th Female are very similar. The Elderly Female's lower measurement reading is larger than the upper measurement reading – 42 mm compared to 32 mm. The largest peak deflection overall on the driver seat, with 51 mm, was the Obese ATD's upper right measurement reading. On the front passenger seat, the Elderly Female's upper peak chest deflection was larger than the lower one. Regarding both seat positions, the Elderly Female recorded the earliest deflection onset. On the driver seat, the lower deflection measurement had an earlier onset than the upper deflection measurement and was at a greater rate. On the front passenger seat, however, deflection onset for the upper measurement occurred earlier than for the lower measurement and was at a greater rate. The largest peak deflection overall on the front passenger seat, with 52 mm, was the Obese ATD's upper left measurement reading.

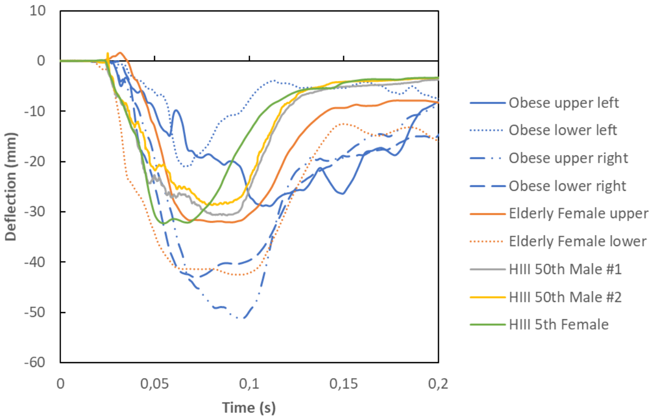

Fig. 21. Chest deflections driver seat.

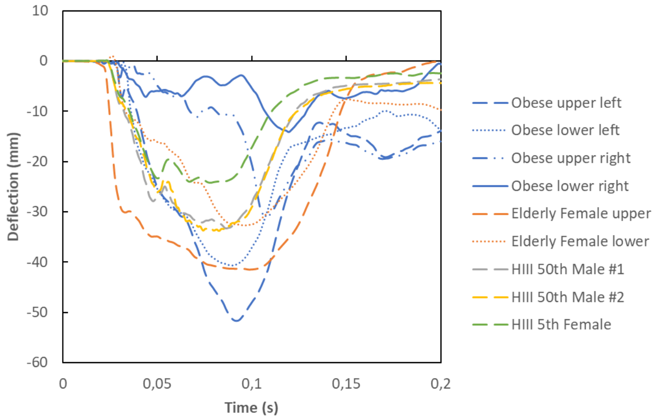

Fig. 22. Chest deflections front passenger seat.

Figures 23 and 24 display the head accelerations. For the driver seat, two distinct peaks are distinguishable for the Elderly Female and the HIII 5th Female. The second peak results from the contact with the headrest during rebound. As the headrest contact of the other ATDs occurred later than the timeframe shown, their second peaks are not visible in Fig. 23. The second peak value of the HIII 5th Female is larger than the first one, and the largest overall. The Obese ATD exhibited the lowest head acceleration. On the front passenger seat, the Elderly Female recorded a peak value six times as high as that for the Obese ATD, which recorded the lowest acceleration – 248 g compared to 41 g. However, we noticed upon removing the Elderly Female post-crash that the respective sensor cable was broken. This damage explains the unusual reading, which is therefore erroneous. This is also why the respective acceleration curve is cut off in Fig. 24.

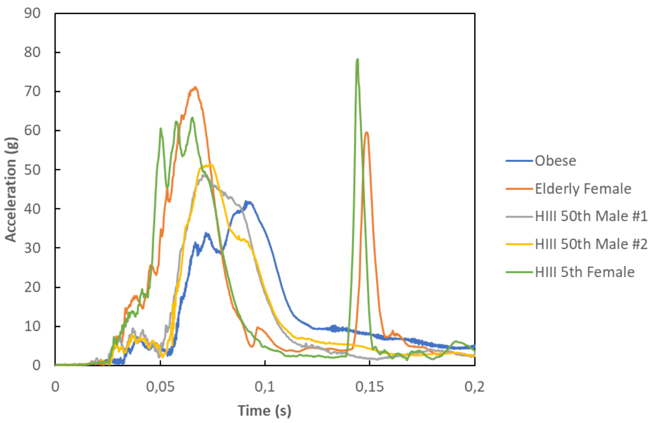

Fig. 23. Head accelerations driver seat.

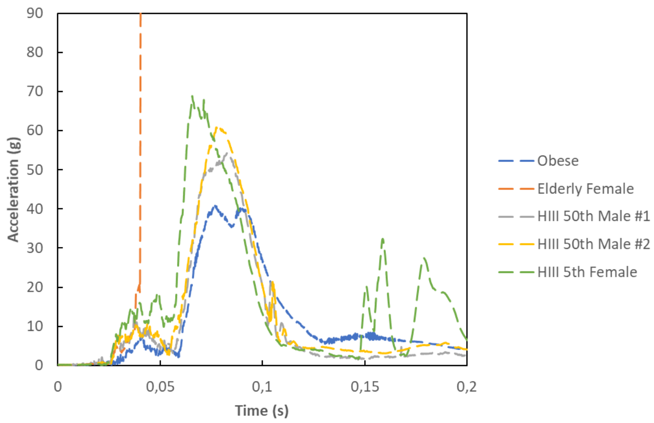

Fig. 24. Head accelerations front passenger seat.

The measured peak values for the driver and front passenger seat are shown in Tables III and IV, respectively, to aid with comparison of results.

TABLE III
MEASURED PEAK VALUES DRIVER SEAT

	Shoulder belt force (kN)	Lap belt force (kN)	Shoulder belt extraction (mm)	Head forward displacem. (mm)	Pelvis forward displacem. (mm)	Pelvis acceleration (g)	Femur force (N)	Chest acceleration (g)	Chest deflection (mm)	Head acceleration (g)
Obese	4.94	6.29	210	579+	169	48.69	-5071$ -2562$	52.34~ 36.44~ 36.69~	29/51# 21/43#	42.00
Elderly Female	4.06	3.34	-15^	244	90	61.44	-	46.49~ 42.03~	32# 42#	71.22
HIII 50th Male #1	4.97	5.23	139	486	96	55.60	-286$ -259$	45.03	31	48.67
HIII 50th Male #2	4.58	6.85	138	453+	103	55.00	-390$ -469$	43.59	29	51.37
HIII 5th Female	3.90	4.11	-12^	224	74	54.42	-1053$ -299$	49.63	32	78.34

^The negative sign indicates that the seat belt extraction was less than the winding up by the pre-tensioner.
+ The measurements broke off early.
$ Left and right femurs, respectively.
~ Obese ATD: accelerations at T1, T4 and T12; Elderly Female ATD: accelerations at T1 and T12.
# Obese ATD: upper left/right and lower left/right deflections; Elderly Female ATD: upper and lower deflections.

TABLE IV
MEASURED PEAK VALUES FRONT PASSENGER SEAT

	Shoulder belt force (kN)	Lap belt force (kN)	Shoulder belt extraction (mm)	Head forward displacem. (mm)	Pelvis forward displacem. (mm)	Pelvis acceleration (g)	Femur force (N)	Chest acceleration (g)	Chest deflection (mm)	Head acceleration (g)
Obese	4.61	3.28	238	549+	139	47.26	-5631$ -5031$	39.71~ 33.04~ 32.98~	52/31# 41/20#	40.84
Elderly Female	4.59	4.34	33	387	53	54.50	-	40.54~ 33.18~	41# 33#	248.49*
HIII 50th Male #1	5.04	4.96	206	520	91	49.99	-324$ -374$	42.97	33	54.55
HIII 50th Male #2	5.82	4.99	155	482+	94	50.83	-360$ -490$	45.86	34	61.00
HIII 5th Female	5.02	4.50	53	336	48	43.42	-100$ -112$	39.36	24	68.89

+ The measurements broke off early.
$ Left and right femurs, respectively.
~ Obese ATD: accelerations at T1, T4 and T12; Elderly Female ATD: accelerations at T1 and T12.
# Obese ATD: upper left/right and lower left/right deflections; Elderly Female ATD: upper and lower deflections.
* The head acceleration reading for the Elderly Female ATD is erroneous due to a cable breakage.

IV. DISCUSSION

The aim of this project was to compare the impact kinematics and dynamics of an Obese, an Elderly Female, the HIII 50th Male and the HIII 5th Female ATDs as drivers and front passengers in full-width frontal impacts.

Studies have shown that the biofidelity of the HIII ATDs is restraint system dependent [22]. The HIII 5th Female's biofidelity requirements were scaled down from the HIII 50th Male [23]. It was shown in previous studies that chest deflection of the HIII 5th Female increases when the front passenger seat is positioned in its longitudinal mid-position instead of its foremost position, as stipulated by Regulation UN R137 [24-25]. In our study, we also positioned the front passenger seat in its longitudinal mid-position. Regarding the Obese and the Elderly Female ATDs, neither injury assessment reference values (IARVs) nor regulation limits have been developed yet.

Kinematic observations highlight differences in impact kinematics between the ATDs. Though not corroborated quantitatively, the ATDs experienced different pitch angles at time of airbag contact (see Figs. 15

and 16). The Obese ATD experienced the largest shoulder belt extractions and pelvis excursions on both seat positions. We observed similar kinematics as previously reported by [11] and [12], who investigated the kinematic differences between obese PMHS and mid-sized PMHS, and [16-18], who conducted crash tests with the very first prototype of the Obese ATD. The Obese ATD experienced excessive pelvis excursion with hardly any torso forward rotation at time of airbag contact. The increased pelvis excursion as compared to the other ATDs can be explained, amongst others, by the flesh jacket of the Obese ATD, which represents, amongst others, the adipose tissue at the pelvis. This additional soft tissue material limited the engagement of the lap belt with the pelvis, which resulted in submarining. Due to the additional soft tissue material, lap belt positioning was elevated above the anterior superior iliac spine (ASIS) point on the pelvic bone. Thus, the lap belt did not interact with the iliac wings during the impact. Submarining can increase the risk of suffering abdominal injuries [26]. Figures 25 and 26 display the Obese ATD's femur forces, lap belt forces, and resultant abdominal deflections on the driver seat and front passenger seat, respectively. Maximum resultant abdominal deflections occurred close in time to maximum lap belt forces. Maximum femur forces, however, occurred earlier. Graphic observations show that the Obese ATD is still moving forward at time of maximum femur forces, which explains this time offset.

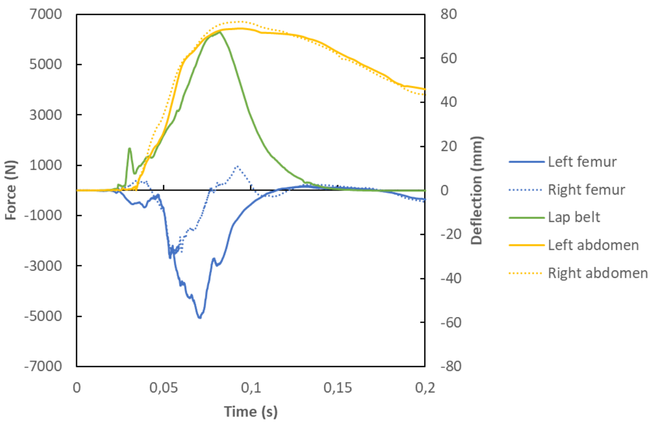

Fig. 25. Obese ATD's femur forces, lap belt forces, and resultant abdominal deflections driver seat.

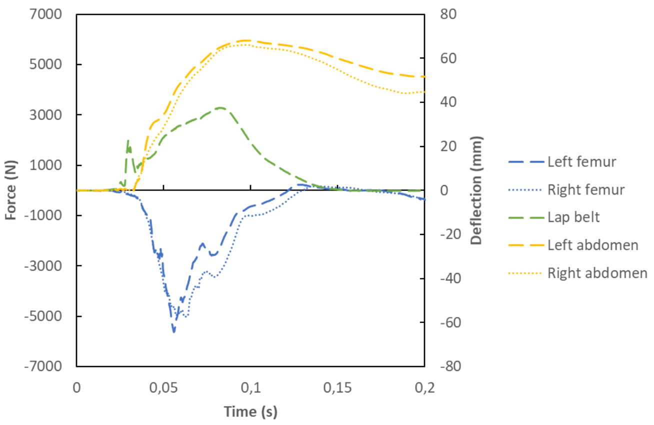

Fig. 26. Obese ATD's femur forces, lap belt forces, and resultant abdominal deflections front passenger seat.

The knees and lower limbs of the Obese ATD also impacted hard against the dashboard and deformed it on both the driver seat and front passenger seat. This may contribute to an elevated injury risk of lower extremity trauma [7]. The torso of the Obese ATD only began to rotate forward after the legs impacted against the dashboard and thus prevented any further forward excursion of the pelvis. On the driver seat, the HIII 5th Female was the only other ATD registering knee contact, however, this ATD was seated the furthest forward. On the front passenger seat, the Elderly Female and the HIII 50th Male registered minimal knee contact. The HIII 50th Male dummy experienced the second largest shoulder belt extractions and pelvis excursions on both seat positions. This led to a pitch angle of less than 90° as measured between the thorax and the horizontal. On the driver seat, the Elderly Female experienced a greater pelvis excursion than the HIII 5th Female, while shoulder belt extractions were similar. The peak shoulder belt extraction values of both female ATDs were negative, indicating that the shoulder belt was extracted less by the forward moving thorax than wound up by the respective pre-tensioner. Thus, the Elderly Female experienced a pitch angle greater than 90° on both seat positions, while the HIII 5th Female also experienced a pitch angle greater than 90° on the driver seat, but a pitch angle of less than 90° on the front passenger seat.

The different seating positions on the driver side, in conjunction with the kinematic differences, lead to different driver front airbag interactions. Figure 27 displays still images of the different ATDs on the driver seat at time of first head contact with the driver front airbag. While the driver front airbags had enough time and space to fully deploy in the case of both HIII 50th Male ATDs, the driver airbags were still in their deployment phases when both Female ATDs contacted them first with their heads. Considering that the Female ATDs were seated further forward than both the HIII 50th Male and the Obese ATD, the Female ATDs contacted the driver front airbag earlier with their heads than their male counterparts – the HIII 5th Female at around 34 ms post-impact and the Elderly Female at around 42 ms post-impact, compared to around 50 ms, 53 ms, and 56 ms for the HIII 50th Male #1, the HIII 50th Male #2, and the Obese ATD, respectively. Regarding the Obese ATD, the driver front airbag had enough time and space to fully deploy but was already contacted by the torso before first head contact. This might result in different injury likelihoods with regard to the head, chest and abdomen.

Obese	Elderly Female	HIII 50th Male #1	HIII 50th Male #2	HIII 5th Female
56 ms	42 ms	50 ms	53 ms	34 ms

Fig. 27. Still images of the driver seats at time of first head contact with the driver front airbag.

While the HIII ATDs are equipped with only one chest deflection potentiometer, both the Obese ATD and the Elderly Female ATD are equipped with upper and lower chest deflection potentiometers. The chest deflection readings of the latter two ATDs highlight that the chests were not uniformly loaded. Non-uniform load distribution is generally expected due to shoulder belt loading, as the shoulder belt is routed over the sternum. On the driver seat, the Elderly Female's lower chest deflection potentiometer recorded the larger value. On the front passenger seat, however, the upper chest deflection potentiometer recorded the larger reading. In the case of the Obese ATD on the driver seat, the upper right chest deflection potentiometer recorded the largest reading, with the lower right reading being the second largest. On the front passenger seat, however, the left readings were the larger. This can be explained by the respective seat belt routing on the driver seat and front passenger seat. The large lower chest deflection readings on both seat positions also indicate that the lower chest was loaded by the respective airbags and/or seat belts. With their single chest deflection potentiometers, the HIII ATDs can thus not capture the complex loading of the thorax as can both the Obese and Elderly Female ATDs with their four and two chest deflection potentiometers, respectively. In comparison to the HIII ATDs, the Obese ATD experienced much larger chest deflections, which is explained by the excessive pelvis forward excursions and larger shoulder belt extractions. Thus, the airbags are loaded more by the heavier Obese ATD, which conversely leads to increased chest deflection caused by the airbags. These findings corroborate the increased risk for obese occupants of suffering thoracic injuries, as observed by [8]. However, the Obese ATD is based on the THOR 50th Male ATD, which has a different thorax design that is softer than the thoraces of HIII ATDs. These design differences may also contribute to the differences in chest deflections. More research is necessary to quantify this. The Elderly Female's thorax is the most compliant as the mechanical properties of bone get worse with age, and the elderly are therefore more susceptible to trauma [27-30]. Despite recoding the largest chest deflections, the Obese ATD recorded the lowest chest acceleration values on both seats. This can be explained by the larger forward excursion, but chest acceleration is an unreliable discriminator for thoracic injuries [31-32].

The Obese ATD also recorded the lowest head accelerations on both seats. This might also be explained by the larger general forward displacement.

As both the Obese ATD and Elderly Female ATD are still in the prototype phase, there are not yet many results from crash tests. To further improve the ATD designs to better represent the obese and elderly females as vehicle occupants, the findings of this project can be compared by the ATD developer with epidemiological data and PMHS tests to evaluate to what extend the behaviour of these ATDs is already biofidelic to derive possible improvements. Furthermore, since new manufacturing technologies such as 3D-printing are used, the performance of these ATDs during the crash tests can by analysed to further assess the usability of these manufacturing technologies to guarantee the repeatability and reproducibility of the Obese and Elderly Female ATDs.

Despite Human Body Models (HBMs), which can be morphed to represent various vehicle occupants including the obese and elderly, ATDs are still widely used by vehicle manufacturers and suppliers in designing and validating restraint systems. Moreover, "[…] the use of ATDs in research and regulatory tests will continue to be required" [33]. "ATD testing has the benefit of providing empirically defined data outputs in a controlled and observable setting" [33]. Current ATDs such as the HIII 50th Male and the HIII 5th Female, however, do not sufficiently represent obese, elderly, and female vehicle occupants. To improve occupant safety for these vulnerable populations, there is the necessity for a tool that interacts similarly with restraint systems to replicate the challenges posed by these groups. By developing both the Obese and Elderly Female ATDs, manufacturers will be provided with such tools that represent these vulnerable populations to assess their restraint systems.

V. LIMITATIONS

The Obese and Elderly Female ATDs used in the crash tests are still early prototype versions. The ATDs are continuously being developed, therefore the results presented in this paper should not be construed as the final performances of the ATDs. Moreover, the anthropometry of both ATDs is solely based on US data and might hence not be representative globally.

VI. CONCLUSIONS

The analysis of the impact kinematics and dynamics of the Obese ATD and the comparison of these findings with those of an Elderly Female, the HIII 50th Male, and the HIII 5th Female ATDs shows that these four ATDs behave differently.

On both seats, the Obese ATD exhibited by far the largest pelvis excursions, which were concomitant with minimal torso pitch. Its knees and lower limbs impacted hard against the dashboard. The additional soft tissue material limited the engagement of the lap belt with the pelvis, which resulted in submarining.

With their additional sensors, both the Obese and Elderly Female ATDs can better capture the complex loading of the thorax than the HIII ATDs.

Both the HIII 50th Male and the HIII 5th Female do not sufficiently represent obese, elderly, and female vehicle occupants, and do thus not interact with restraint systems in a manner to properly replicate the challenges posed by these groups. By developing both the Obese and the Elderly Female ATDs, manufacturers will be provided with tools that represent these vulnerable groups to assess and validate their restraint systems to improve occupant safety. However, more research into the biofidelity of the Obese and the Elderly Female ATDs is required to improve ATD design and to develop IARVs and injury risk functions.

VII. ACKNOWLEDGEMENTS

We would like to acknowledge Humanetics for supporting this research project by providing the prototype versions of the Obese and Elderly Female ATDs. We would also like to thank all personnel at DEKRA Crash Test Center in Neumünster, Germany, involved in designing and executing the crash tests.

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IX. APPENDIX

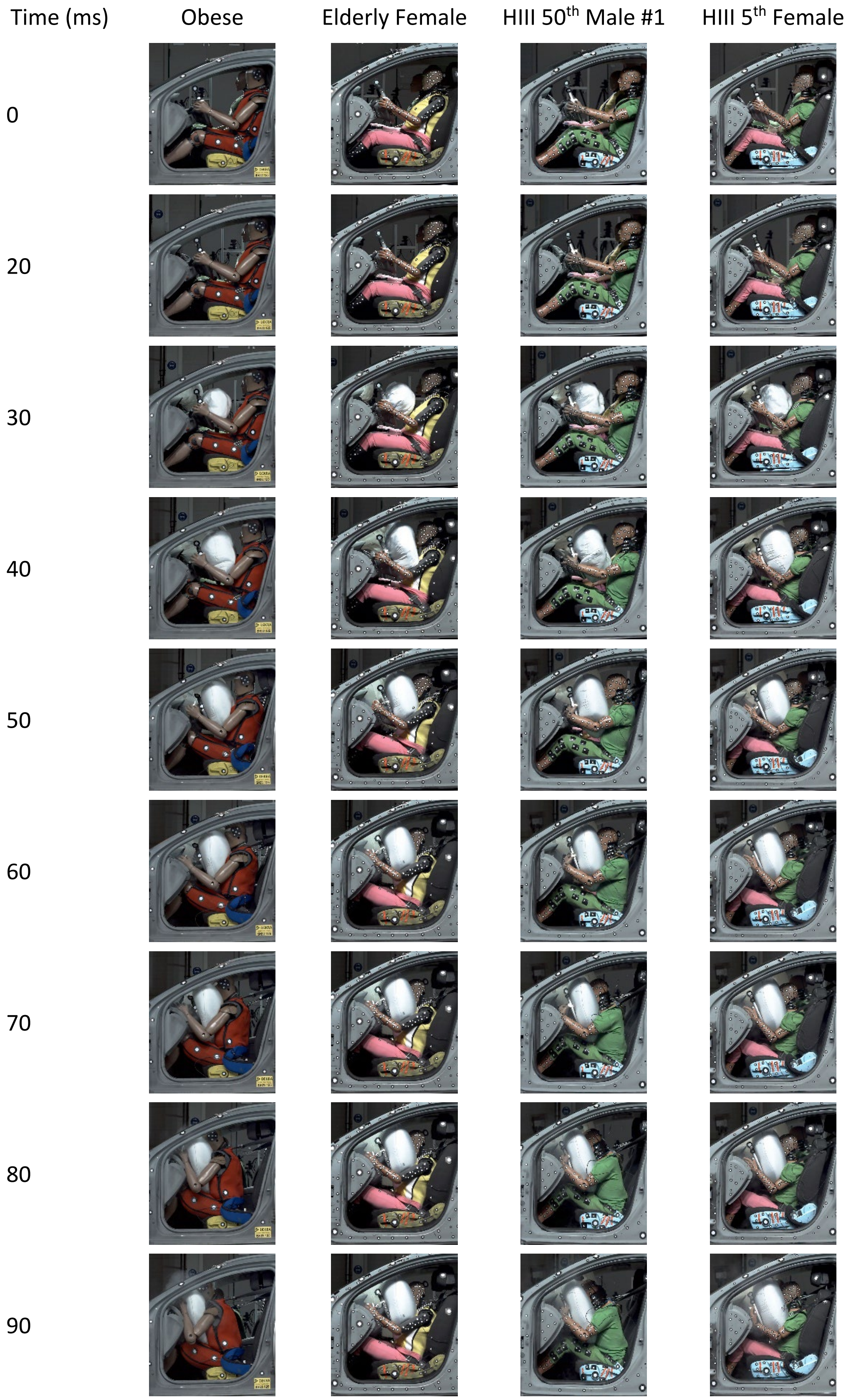
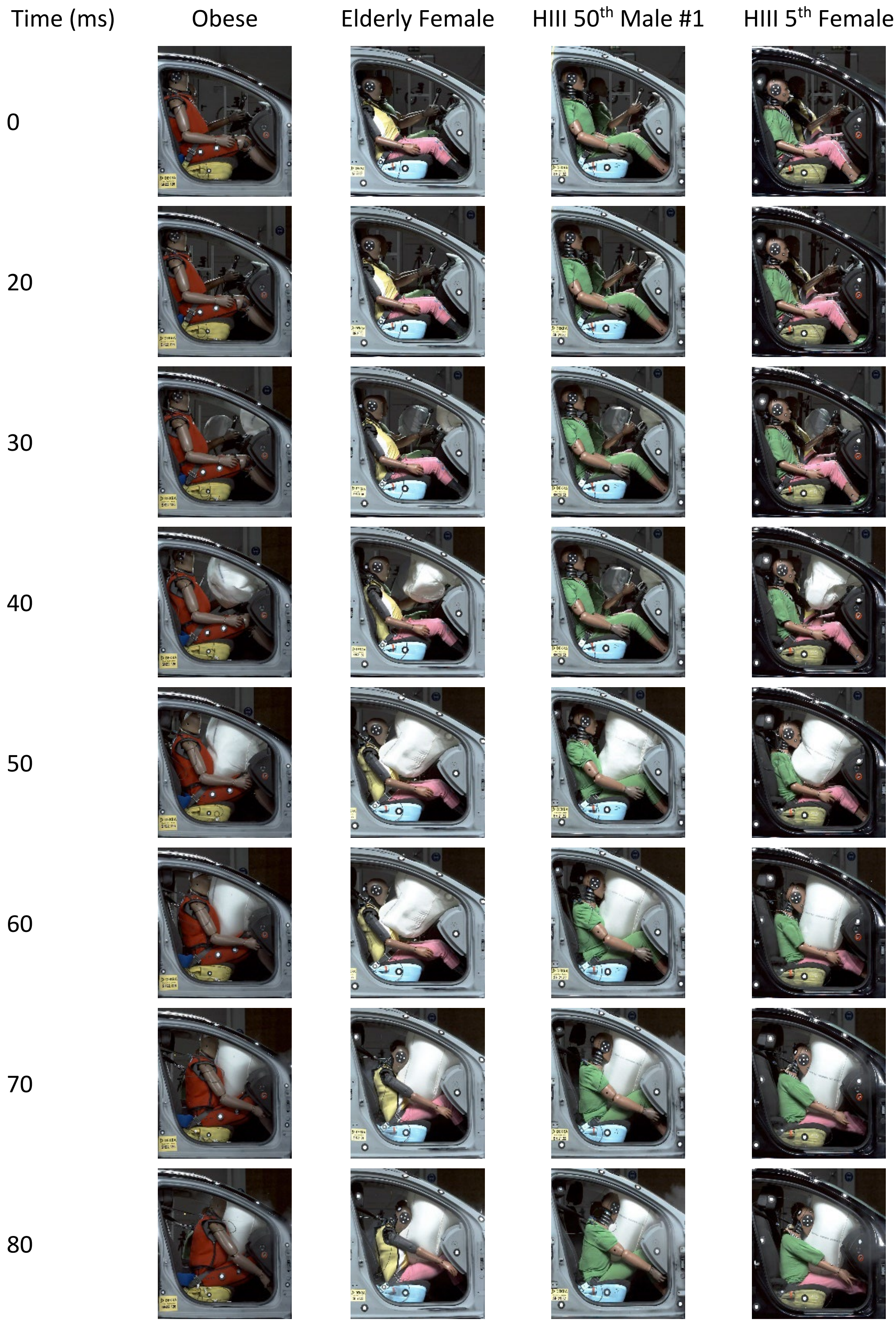


Fig. A1. Still images of the driver seats.



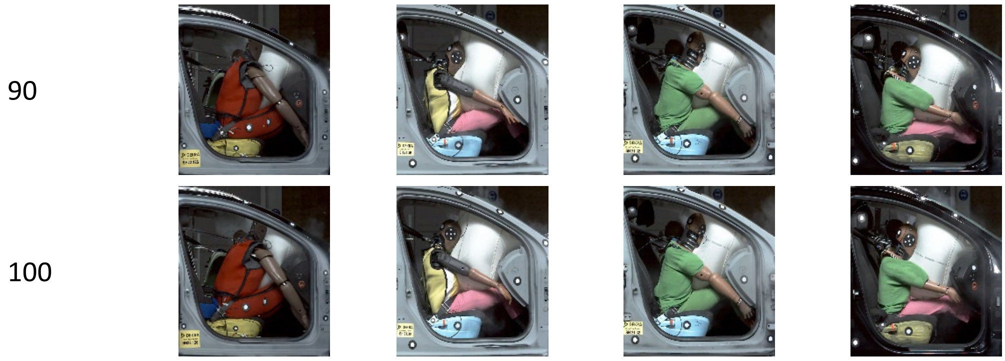


Fig. A2. Still images of the front passenger seats.