Comparison of the Thorax and Head/Neck Dynamics of an Elderly Female, the HIII 50th Male and the HIII 5th Female Dummies as Front Passengers in Full-width Frontal Impacts

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Abstract Senior citizens form an age group still having one of the highest risks of suffering severe or fatal injuries during road accidents. Therefore, Humanetics is developing the Elderly Female Dummy, an Anthropomorphic Test Device which represents 70 year old female car occupants.

DEKRA conducted three full-width frontal impacts in accordance with Regulation UN R137 (except for the front passenger seat position). An early prototype version of an Elderly Female Dummy, the HIII 5th Female dummy and the HIII 50th Male dummy, were each placed on the front passenger seat. A field study and GIDAS-analysis yielded that the front passenger seat is most often placed in its longitudinal mid-position. This position was used in the crash tests.

The Elderly Female was the only Anthropomorphic Test Device tested, whose thorax was reclined at time of airbag contact. The HIII 5th Female, however, experienced only minimal torso flexion. The Elderly Female also experienced considerable upper chest deflection.

To optimise occupant protection, more research is required into the biofidelity of the Elderly Female and the development of respective Injury Assessment Reference Values and injury risk functions.

Keywords 5th and 50th percentile dummies, Elderly Female Dummy, Frontal Impacts, Hybrid III, Restraints

I. INTRODUCTION

As the world population keeps ageing, these demographic changes are increasingly noticed on the global roads too. Whereas the overall numbers of traffic fatalities continuously decline since 2010, senior citizens form the only age group with an increase in road deaths [1]. The reasons for this include a higher life expectancy and that people aged 65 and older are nowadays fitter and therefore partake more actively in road traffic. In addition to the increase in absolute numbers of senior citizens being exposed to the risks of road traffic, the elderly are also more vulnerable. For elderly patients, trauma increases with age, with injuries being more frequent in senior women than men [2-3]. Reference [4] concluded that amongst their analysed cohort the fatality risk increases by 3.11 ± 0.08 % for every year drivers or front passengers age. Female drivers and front passengers are even exposed to a fatality risk that is 17.0 ± 1.5 % higher than for equally aged male contemporaries. Regarding frontal impacts, the elderly exhibit a heightened risk of suffering thorax trauma [5-6]. Especially senior women are predisposed by having a greater relative risk of sustaining Abbreviated Injury Scale (AIS)3+ thoracic injuries compared to younger women than do senior men compared to younger men [7]. Moreover, females of all ages have a greater risk of sustaining thoracic injuries than men [8]. A study conducted by [9] concluded that the risk for the elderly of sustaining thorax injuries is 2.6 times higher than for drivers aged 24–54. The thorax is also the most critical body region for sustaining the most AIS3+ injuries [10]. Various Post Mortem Human Subject (PMHS) tests have shown that the amount of fractured ribs increases with age [11-13]. Senior drivers also tend to suffer thorax injuries in conjunction with neck injuries [9].

This increased vulnerability of the elderly is due to the ageing process being concomitant with a worsening of the mechanical properties of bone [6][14-16]. The calcification of the costal cartilage and a decline in both the overall bone mineral density and cross-section of rib cortical bone, amongst others, lead to a reduction of the

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failure strain of cortical and trabecular bone, resulting in a marked decrease in the load carrying capabilities.

To further lower the burden of motor vehicle crashes, occupant protection systems must therefore be improved to better protect females and the elderly [9][17-19]. However, the senior population is currently neither represented by crash test dummies nor considered in consumer test protocols and legislation. Therefore, Humanetics is developing the Elderly Female Dummy, an Anthropomorphic Test Device (ATD) which represents a 70 year old female car occupant with a height of 1.61 m and a mass of 73 kg [20-21], resulting in a Body Mass Index (BMI) of 28, which is representative for elderly women. To better address potential internal injuries of humans that could be life threatening, this dummy has – compared to other ATDs existing so far – a new structure: a flexible spine, a movable rib cage and floating shoulders form the supporting structure; organ sacs with organs represent the large internal organs of the human body; and a representative fat layer was added to cover the entire torso, mimicking the stratified body flesh. Additionally, new manufacturing methods such as 3D-printing are used to manufacture this ATD. This allows for using a greater freedom of design when replicating human bones, flesh, and internal organs. With the Elderly Female Dummy being a carrier of new technologies, however, further research is still required before this ATD can enter the market.

DEKRA had the chance to conduct three crash tests with an early prototype version of the Elderly Female Dummy. The aim of the tests was to compare the thorax and head/neck dynamics with the HIII 50th Male and HIII 5th Female dummies. A full-width frontal impact based on Regulation UN R137 was chosen for being the most challenging load case considering restraint kinematics. We further chose actual vehicle tests over standardised sled tests because our next step is to analyse the effects on the impact kinematics of sitting on the driver, passenger, or rear passenger seat.

II. METHODS

Elderly Female Dummy

The anthropometry of the Elderly Female Dummy is based on clinical data of 80 women aged 67–73 having a mean height of 1.61 m and a mean mass of 72.8 kg. The shape of the Elderly Female Dummy was determined by means of the Statistical Body Shape Models of the University of Michigan Transportation Research Institute, while rib cage shape, flesh thickness as well as organ size and placement were determined based on Magnetic Resonance Imaging (MRI) scans. The head and neck of the Elderly Female Dummy stem from the WorldSID Small Female, while the lower arms, hands, knees, and feet are those of the HIII 5th Female [20]. The remaining body parts were newly designed for this ATD. The liver and spleen are the organs represented. The latest prototype version of the Elderly Female Dummy is equipped with a Multi-Directional Measurement Thorax (MDMT). The MDMT comprises four infra-red telescoping rods for the assessment of chest compression (IR-TRACCs), which enable the measurement of chest deflection in the x- and y-direction. This ATD can therefore be used in both frontal and side impact tests.

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.

Test Setup

Three crash tests were conducted with a midsize station wagon based on Regulation UN R137 (except for the front passenger seat position), i.e., a full-width frontal impact against a rigid barrier at 50 km/h as shown in Figure 1. The used vehicles were identical models with similar specifications and of model years 2009–2013, resulting in comparable acceleration pulses (Figure 2). The three different ATDs were either positioned on the driver, front passenger, or right back seat. In this study, however, we solely focused on the front passenger seat to analyse the influence of both a standardised seating position and a restraint system with double pre-tensioner and load limiter. All four doors were removed to obtain an unobstructed view.

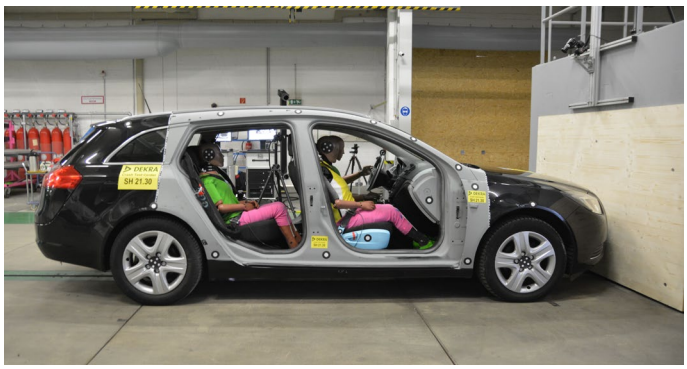


Fig. 1. Test setup.

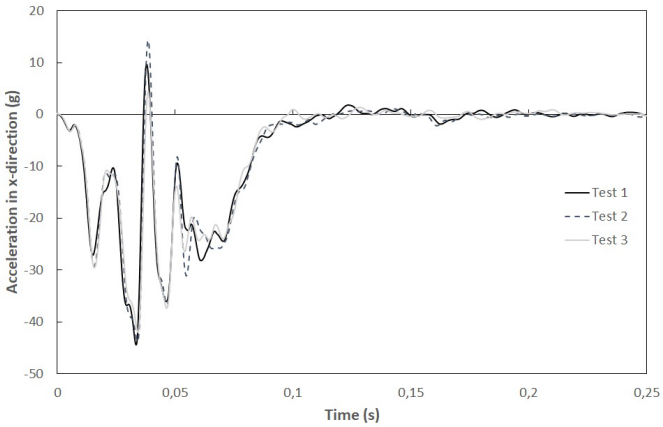


Fig. 2. Acceleration pulses of the three crash tests.

Seating Position

Regulation UN R137 stipulates the usage of the HIII 5th Female dummy on the front passenger seat in its foremost position. However, as we wanted to use the same seating position for every dummy to better compare the results, we asked ourselves what seat adjustments front passengers make. Therefore, we conducted a field study around Stuttgart, Germany, in which we focused on the seat adjustments of elderly front passengers aged 65 and older (irrespective of their sex). Figure 3 displays the dimensions measured. We also asked for their body heights.

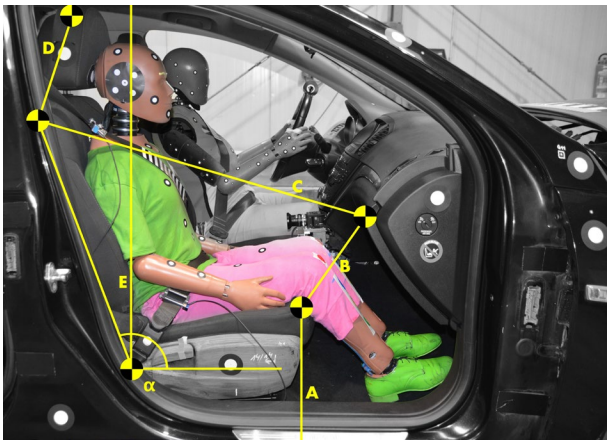


Fig. 3. Dimensions measured on front passenger seats.

Subsequently, we also performed a German In-Depth Accident Study (GIDAS) analysis comprising 366 females aged 65 or older, who have been front passengers in cars that have been involved in an accident. As the front passenger seats in the chosen test vehicles were only adjustable in the longitudinal direction, we solely analysed the respective variable “seating position (SITZST)”. The body height was also analysed.

Based on these analyses, the front passenger seats were adjusted in their longitudinal mid-position.

Measurements

The HIII 5th Female and HIII 50th Male dummies were equipped with a standard configuration of sensors, while the provided 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.

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.

III. RESULTS

Seating Position

Regarding the field study, the front passenger seat adjustments of 27 seniors (26 women, 1 man) have been gathered. See Table I.

TABLE I
FRONT PASSENGER SEAT ADJUSTMENTS AS MEASURED IN FIELD STUDY.

Person ID	Gender	Body height (cm)	A (cm)	B (cm)	C (cm)	D (cm)	E (cm)	α (°)
1	f	165	19	45	98	29	101	95.50
2	f	150	30	37	95	24	101	96.00
3	f	179	27	40	100	26	95	107.75
4	f	160	29	36	109	23	102	106.25
5	f	170	23	40	107	27	103	100.25
6	f	165	26	35	96	25	98	99.25
7	f	169	20	37	97	24	99	94.50
8	f	170	28	34	93	26	95	95.25
9	f	153	34	33	94	27	97	101.50
10	f	169	24	31	97	25	92	103.50
11	f	168	32	36	99	28	97	99.25
12	f	160	31	36	95	25	94	89.50
13	f	160	24	35	101	24	90	99.00
14	f	155	34	37	103	30	98	100.75
15	f	176	30	45	109	22	99	95.00
16	f	170	28	45	103	24	100	92.50
17	f	170	34	39	103	26	102	97.75
18	f	163	29	32	94	25	96	98.00
19	f	158	25	36	90	25	100	93.00
20	f	170	41	30	89	25	100	95.00
21	f	167	24	36	86	28	102	89.25
22	f	165	33	31	85	27	100	92.00
23	f	160	32	40	106	26	100	103.00
24	f	165	32	50	100	24	104	94.00
25	m	176	31	36	93	27	92	93.00
26	f	175	30	30	101	30	95	97.25
27	f	150	33	36	90	25	96	98.00
Average value		165.00	29.00	36.96	97.52	25.81	98.07	97.26

The average values in Table I correspond approximately to the longitudinal mid-position in the test vehicles.

Regarding the GIDAS analysis, Figure 4 shows the number of passengers, who adjusted their seats in the front, mid, or back position depending on their body height. The dashed line represents the body height of the Elderly Female Dummy. Most female seniors, irrespective of their body height, had their seats adjusted in its longitudinal mid-position.

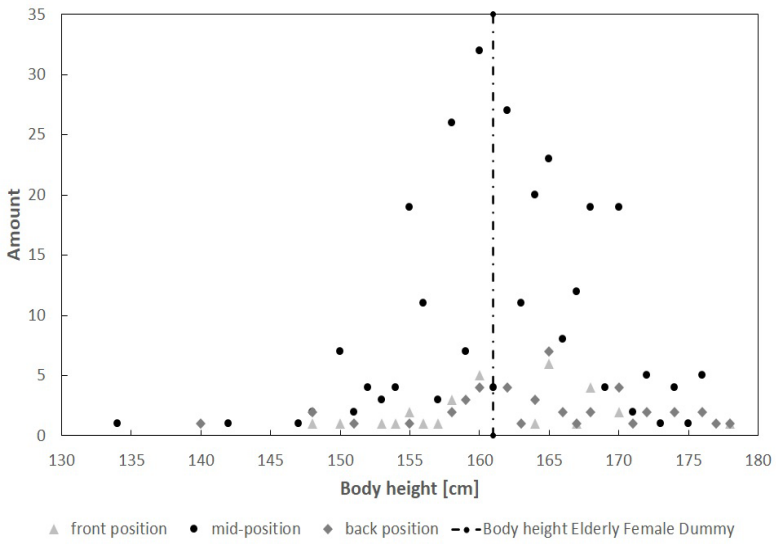


Fig. 4. Seat adjustment based on body height.

Crash Tests

To compare the thorax and head/neck dynamics of the Elderly Female, the HIII 50th Male and the HIII 5th Female dummies, as front passengers in full-width frontal impacts, measurements of restraint forces, shoulder belt extractions, dummy displacements, chest deflections, and chest and head accelerations are presented. Still images of the three crash tests are provided in the Appendix to visualise the dummy dynamics.

Figure 5 shows the shoulder belt forces of the three dummies as measured between the D-ring anchorage and the dummy's shoulder. Though the peak values are very close, the HIII 50th Male dummy exhibited the highest value.

The shoulder belt extractions, which allow conclusions to be drawn about the forward displacement of the thorax, are shown in Figure 6, with peak extraction for the HIII 50th Male being more than six-times as large as the one for the Elderly Female. Peak extraction occurred around 100 ms after impact. The shoulder belt forces were around 1 kN at this time except for the HIII 50th Male dummy, which recorded a shoulder belt force of around 2 kN.

The forward displacement of the head, as measured by crash test video analysis, is shown in Figure 7. Peak excursion for the HIII 50th Male dummy's head occurred around 100 ms after impact and is the largest, while peak excursions for the Elderly Female and the HIII 5th Female dummies' heads occurred around 80 ms after impact.

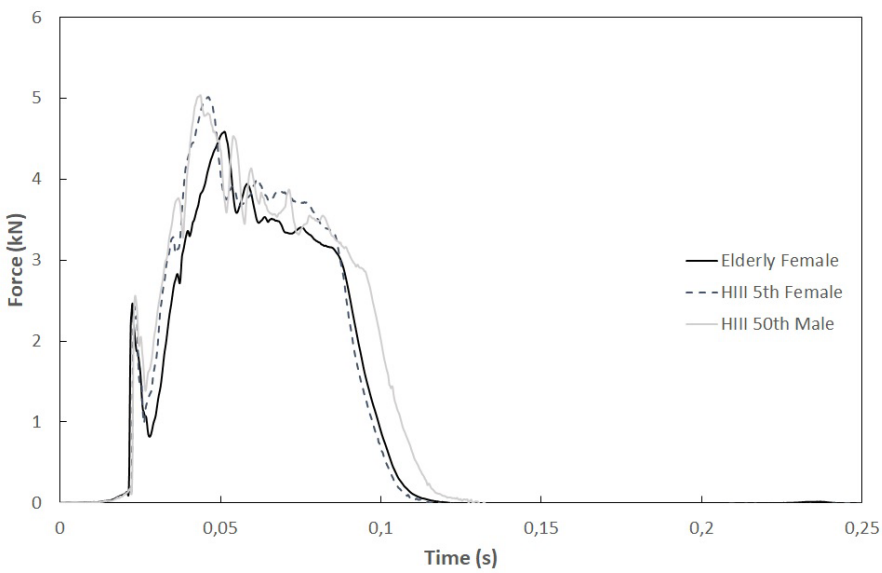


Fig. 5. Shoulder belt forces.

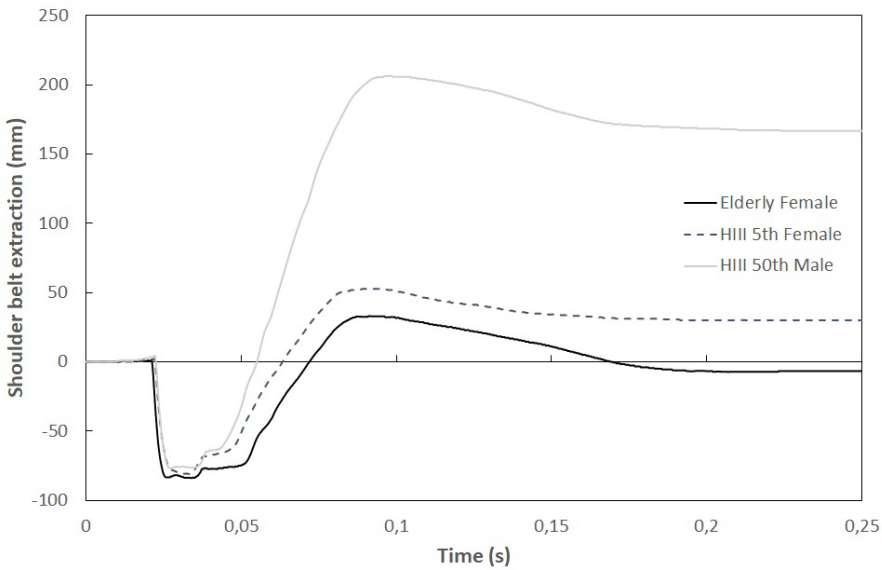


Fig. 6. Shoulder belt extractions.

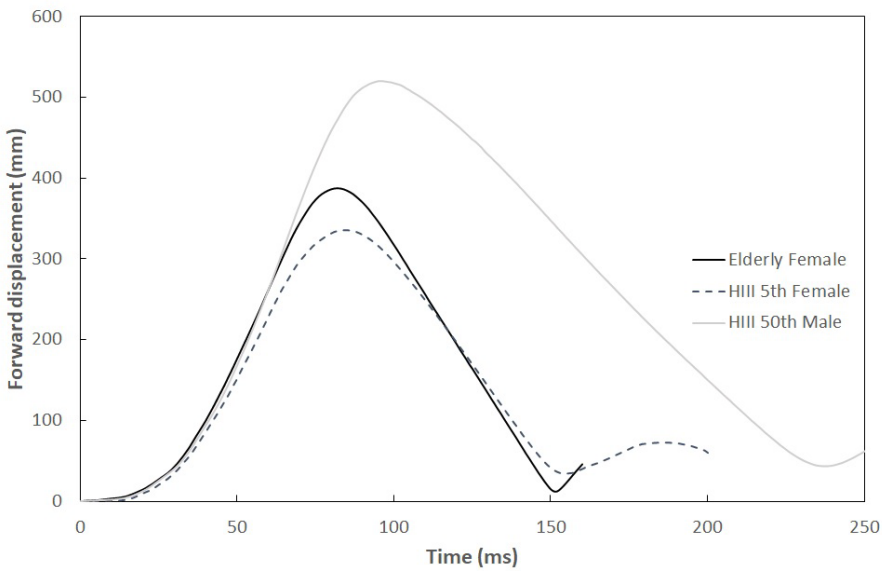


Fig. 7. Head forward displacements.

Table II shows the peak pelvis forward displacements as measured by a string. Like shoulder belt extraction, the HIII 50th Male recorded the biggest peak value. In contrast, the Elderly Female Dummy's peak pelvis forward displacement is larger than the HIII 5th Female dummy's, while peak shoulder belt extraction is smaller.

TABLE II
MEASURED PEAK PELVIS FORWARD DISPLACEMENT (MM).

Elderly Female	53
HIII 5th Female	48
HIII 50th Male	91

These different forward excursions led to varying forward leaning angles at the time of airbag contact (see Figure 8). While both the HIII 5th Female and the HIII 50th Male dummies exhibited a forward leaning angle of less than 90° (as measured between the thorax and the horizontal), the Elderly Female exhibited a forward leaning angle greater than 90°. However, the torso of the HIII 5th Female is nearly upright. It can also be observed that the Elderly Female Dummy's head rotated the furthest towards the thorax.

Elderly Female HIII 5th Female HIII 50th Male

Fig. 8. Images taken 80 ms post-impact showing the different forward leaning angles.

Chest accelerations and chest deflections are shown in Figures 9 and 10, respectively. The Elderly Female is equipped with two accelerometers, which are placed on vertebral bodies T1 and T12. In contrast to the HIII ATDs, which are only equipped with one chest accelerometer, the Elderly Female Dummy's accelerometers were biaxial and not triaxial. Therefore, we decided to only evaluate chest acceleration in the x-direction. As we conducted full-width frontal impacts, influences in the y- and z-directions are also limited. The Elderly Female also has two chest deflection potentiometers, whilst the HIII ATDs are solely equipped with a single chest deflection potentiometer. While all three dummies recorded similar accelerations in the x-direction, chest deflections varied. Peak chest deflection for the Elderly Female Dummy was 41/33 mm (upper and lower measurement) compared to 24 mm and 33 mm for the HIII 5th Female and HIII 50th Male dummies, respectively. Deflection onset for the Elderly Female Dummy's upper measurement occurred earlier and was at a greater rate than for the two Hybrid dummies, while the Elderly Female Dummy's lower deflection measurement had the latest onset.

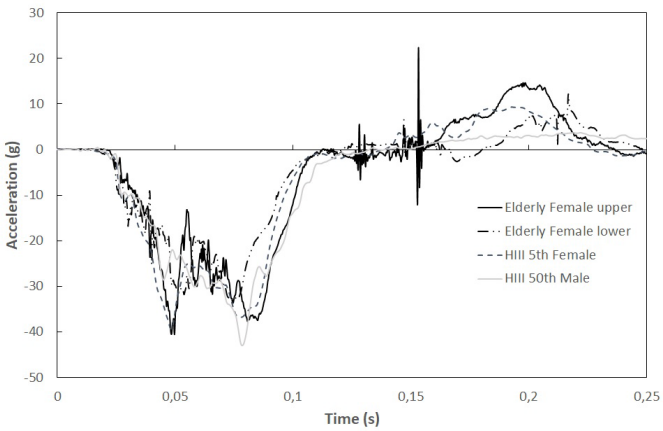


Fig. 9. Chest accelerations in x-direction.

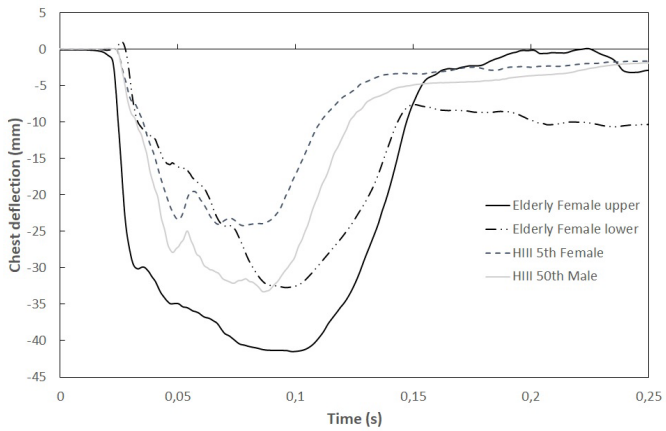


Fig. 10. Chest deflections.

Head accelerations are shown in Figure 11. The Elderly Female recorded a peak value nearly five-times as high as the one for the HIII 50th Male. However, we noticed upon removing the dummy post-crash that the respective sensor cable was broken. This damage explains the unusual reading that is therefore erroneous. The HIII 5th Female recorded its peak head acceleration after 66 ms, while the HIII 50th Male recorded its peak head acceleration 83 ms post-impact. The HIII 5th Female dummy's peak head acceleration also surmounts the HIII 50th Male dummy's peak head acceleration by 14.34 g.

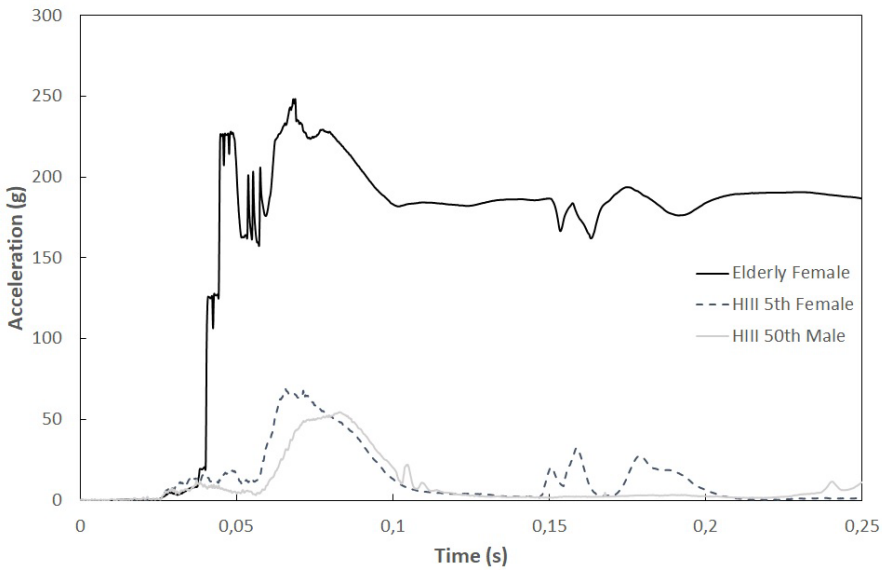


Fig. 11. Head accelerations.

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

TABLE III
MEASURED PEAK VALUES.

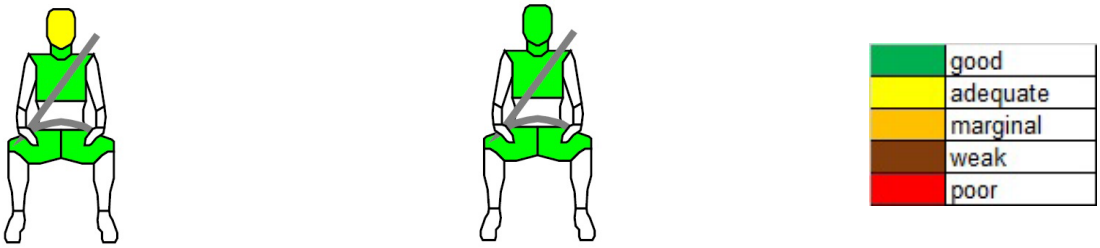
	Shoulder belt force (kN)	Shoulder belt extraction (mm)	Head forward displacement (mm)	Pelvis forward displacement (mm)	Chest acceleration (g)	Chest deflection (mm)	Head acceleration (g)
Elderly Female	4.59	33	387	53	40.54/33.18°	41/33°	248.49*
HIII 5th Female	5.02	53	336	48	39.36	24	68.89
HIII 50th Male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

° Upper/lower chest acceleration and deflection measurements.
* The head acceleration reading for the Elderly Female is erroneous due to a cable breakage.

IV. DISCUSSION

Aim of this project was to compare the thorax and head/neck dynamics of the Elderly Female, HIII 5th Female and HIII 50th Male dummies as front passengers in full-width frontal impacts.

Research has shown that the biofidelity of the HIII dummy is restraint system dependent [22]. The HIII 5th Female dummy's biofidelic requirements were scaled down from the HIII 50th Male dummy [23]. In this study, we used another front passenger seating position as stipulated by Regulation UN R137. Previous studies have shown that positioning the front passenger seat in its longitudinal mid-position, as we did in our crash tests, increased chest deflection for the HIII 5th Female. This was explained by the missing knee contact with the front bolsters [24]. Based on the regulation limits of Regulation UN R137, however, the HIII 50th Male recorded measurements all below the respective thresholds, while head acceleration for the HIII 5th Female was adequate. Neither injury assessment reference values (IARVs) nor regulation limits have been developed for the Elderly Female yet. See Figure 12.



(a) (b)

Fig. 12. Injury risk assessment for (a) the HIII 5th Female and (b) the HIII 50th Male.

Kinematic observations of the three crash tests indicate differences in dummy dynamics. While the HIII 50th Male experienced both the largest pelvis forward displacement and shoulder belt extraction, pelvis displacement was bigger for the Elderly Female than for the HIII 5th Female, though shoulder belt extraction was smaller. This implies different forward leaning angles. Though not corroborated quantitatively, Figure 8 shows that the HIII 5th Female and HIII 50th Male exhibited a forward leaning angle of less than 90° at the time of airbag contact (as measured between the thorax and the horizontal direction). The Elderly Female, however, exhibited a forward leaning angle of greater than 90°. Torso forward rotation was the biggest for the HIII 50th Male, while the HIII 5th Female rotated minimally so that the torso was nearly upright. Such a behaviour for the HIII 5th Female has already been observed by [25], who also conducted full-width frontal impact tests in which the front passenger seat was placed in its longitudinal mid-position.

Comparing the two female ATDs, this might be explained by differences in Body Mass Index (BMI) and mass distribution. With a standing height of 1.51 m and a mass of 46.72 kg, the HIII 5th Female has got a BMI of approximately 20 [23]. For the Elderly Female, the values are 1.61 m, 73 kg, and 28, respectively [20]. The proportions of the Elderly Female are also such that this ATD has more relative mass at the pelvis than the HIII 5th Female – the pelvis of the Elderly Female accounts for 18.5 % of the total mass compared to 14.5 % for the HIII 5th Female – and a lowered centre of mass (CoM). Thus, the relative mass difference between pelvis and thorax is greater for the Elderly Female than for the HIII 5th Female. Therefore, the Elderly Female Dummy's pelvis moved further forward, while the thorax was restraint by the shoulder belt. Due to the lowered CoM, the Elderly Female is also more susceptible to submarining as observed in the crash test. The different pelvis kinematics hence led to different torso kinematics. The deviating forward leaning angle of the Elderly Female may also impact injury mechanisms in its torso. To what extent, however, the observed kinematics of the Elderly Female Dummy are applicable to senior women merits further research.

Reference [26] conducted five PMHS sled tests, in which the PMHSs were reclined. They observed a combination of flexion and compression of the thoracolumbar spine in all PMHSs and fractures at vertebral body L1 in three of the PMHSs. While each PMHS had their torso reclined to 50° pre-crash (as measured from the vertical), the Elderly Female Dummy's torso was reclined to a lesser extent when contacting the front airbag. Based on the PMHS tests, we hypothesise that the Elderly Female experienced more compression in the thoracolumbar spine due to the reclined thorax than the HIII 5th Female and HIII 50th Male dummies. However, we cannot quantify this, as the Elderly Female was not equipped with respective sensors. This is to be investigated in the future.

Graphic observations also indicate that the Elderly Female Dummy's neck experienced greater flexion than the ones of the two HIII dummies. While the torso is restrained by the seatbelt, the ATD's head rotates with the chin contacting the thorax shortly after the first contact with the airbag (see Figure 8). Unfortunately, the tested prototype version of the Elderly Female had not yet been equipped with neck sensors, so that we cannot relate this observed behaviour to changed injury risks. However, chin contact with the thorax implies large flexion, which may be injurious. We further hypothesise that the neck may experience compression due to the front airbag and the torso still moving forward after chin contact. However, we cannot prove this hypothesis without respective measurements, which merits further research. Regarding the HIII 50th Male, previous research shows that the ATD's neck response is stiffer than PMHS neck responses [27]. We cannot say in how far these findings correlate to the Elderly Female. It should also be noted that the Elderly Female Dummy's neck stems from the WorldSID Small Female, an ATD designed for side impact scenarios. Since the Elderly Female is designed to be omnidirectional, it was thought that this would be a good first step to be used in this prototype version of the ATD. Research is currently being conducted to investigate in how far the WorldSID's neck used in the Elderly

Female Dummy better represents neck kinematics of senior women than the HIII 5th Female's neck design.

Chest acceleration is an unsuitable discriminator for thoracic injuries, while chest deflection is the most reliable [22][28]. As shown in Figure 9, all three dummies experienced similar chest accelerations in the x-direction. On the other hand, chest deflection differed. The HIII 5th Female dummy's chest is more compliant than the HIII 50th Male dummy's chest [29]. However, the HIII 5th Female dummy's peak chest deflection corresponds to only 71.2 % of the regulation limit compared to 76.8 % for the HIII 50th Male. Given that the restraint system is identical for the three tested vehicles, one would assume that the chest deflection for the HIII 5th Female is larger than for the HIII 50th Male. One explanation might be that the HIII 50th Male experienced a greater chest loading by the front airbag due to greater forward displacement. The Elderly Female dummy's thorax is the most compliant. As neither IARVs nor regulation limits have been developed for this ATD yet, we cannot deduce any injury risk. However, as the elderly are more susceptible to rib fractures, the exhibited larger chest deflection is as expected. The difference between the upper and lower chest deflection measurements indicates that the dummy's chest was not uniformly loaded. The upper thorax experienced more loading by the shoulder belt than the lower part. If the regulation limit for the HIII 5th Female were taken as a basis (the dimensions of the Elderly Female most closely resemble those of the HIII 5th Female), the Elderly Female would have clearly exceeded the limit of 34 mm, indicating that there may be a risk for thoracic injuries. Reference [30] established a link of HIII 50th Male sternal deflections of 50 mm to a risk of suffering AIS3+ thoracic injuries of 40–50 %. To convert this injury risk relationship to the HIII 5th Female dummy, scaling factors have been established [29]. Both HIII dummies recorded values below this threshold.

Considering seatbelt loading, however, research has shown that human thoraces are more compliant than HIII dummy thoraces [31]. The Elderly Female Dummy's thorax design is not based on the HIII dummy but is a new development. Therefore, more research is necessary to correlate the chest deflection characteristics of the Elderly Female Dummy to the injury risk of elderly car occupants under seatbelt loading.

Benchmarking of ATDs is primarily based on elderly PMHSs due to their availability over younger cadavers. However, anthropometric data for elderly women stemming from the International Center of Automotive Medicine (ICAM) and the University of Michigan Transportation Research Institute (UMTRI) show that this demographic group is anthropometrically not properly represented by the HIII 5th Female. The HIII 5th Female is rather representative of adolescent girls, while the Elderly Female is specifically based on the anthropometry of senior women. However, there are little kinematic response differences between the Elderly Female and the HIII 5th Female. Though the Elderly Female represents the weight and height of an elderly 50th percentile female, the differences to the 5th percentile are relatively small. With this, we hypothesise that the kinematic responses just compensate the differences in weight and height in comparison to age and stature, underlining that the more fragile Elderly Female is behaving similarly as the smaller and lighter HIII 5th Female. However, to determine whether the Elderly Female represents senior women better than the HIII 5th Female, further research is necessary, especially PMHS tests as the Elderly Female has not yet been validated against PMHSs.

V. LIMITATIONS

The Elderly Female Dummy used in these three crash tests is still an early prototype version. This ATD is continuously being developed further, and the results presented in this paper should therefore not be construed as the final performance of the dummy. The findings of this project will help to further improve the dummy design to better represent elderly females as car occupants.

VI. CONCLUSIONS

The Elderly Female was the only ATD tested, whose thorax was reclined at time of airbag contact. As shown by previous studies, impact dynamics of the HIII 5th Female were influenced by the changed seating position. Therefore, to optimise protection for elderly car occupants and for seating positions outside of regulatory protocols, more research will be necessary into: 1) the susceptibility of the Elderly Female Dummy's biofidelity to varying seating positions; 2) the current capabilities and limitations of the Elderly Female Dummy's design; 3) the development of IARVs and injury risk functions for the Elderly Female; 4) the capabilities and limitations of current ATD designs under varying seating positions; and 5) the improvement of adaptive restraint systems to

account for passengers of different sexes, sizes, ages, BMI, and postures.

VII. Acknowledgement

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

VIII. References

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IX. APPENDIX

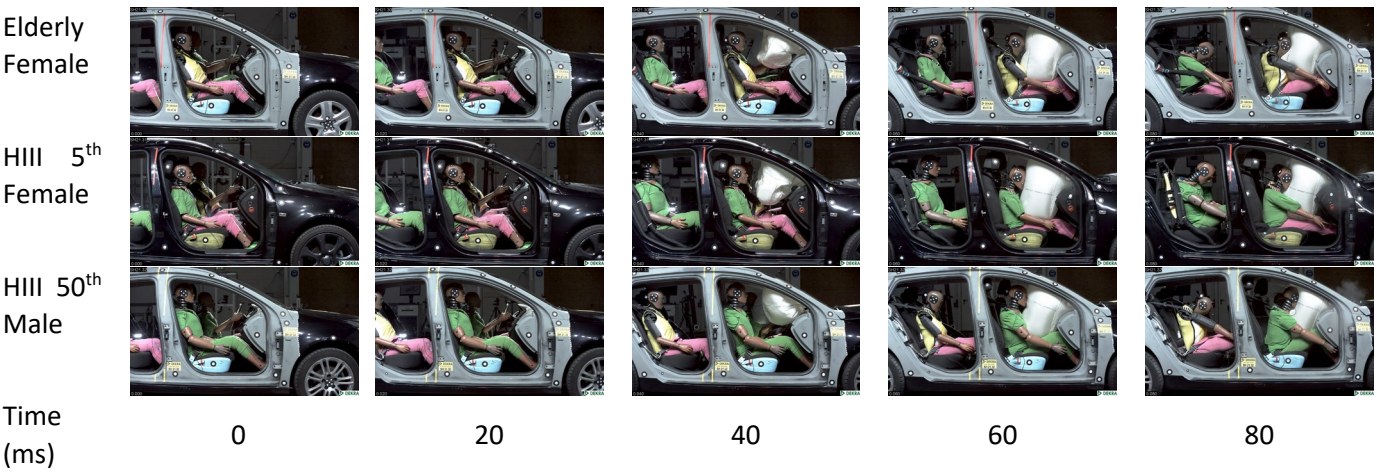

Fig. AI. Still images of the three crash tests.