Repositioning an Off-Shoulder Seatbelt Using Seatbelt Pretensioners

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Abstract Front-seat passengers have been reported to occasionally wear the seatbelt off-shoulder. Whether pretensioners can restore the belt's correct position (and optimize its protective ability in a crash) has not yet been studied; nor has its effect on the occupant's head kinematics. This study sought to address these gaps. Volunteer tests examined seatbelt repositioning possibilities and the influence of seatbelt-to-seat geometry and body shape. ATD sled tests compared electrical pre-pretensioners and pyrotechnical pretensioners and assessed the effect of a crash pulse on seatbelt repositioning. Mathematical simulations analysed in-crash occupant kinematics with a fully and partially repositioned shoulder belt. The results show that, while the seatbelt could be fully repositioned in most situations tested, the electrical pre-pretensioner achieved full repositioning more often than the pyrotechnical pretensioner. In a sled test with a full-frontal crash pulse of 40 km/h, the repositioning ability was not affected, and the occupant kinematics with a fully repositioned belt were comparable to those with a belt that was correctly positioned originally (reference test). This study concludes that the seatbelt-to-seat geometry is the most important factor for seatbelt repositioning and that a fully repositioned seatbelt maintains occupant head kinematics similar to those observed with a nominal seatbelt fit.

Keywords HBM simulation, Seatbelt fit, Seatbelt pretensioner, Sled testing, Volunteer testing.

I. INTRODUCTION

The three-point seatbelt is the primary restraint system in modern cars, having proven its efficiency for many decades. It helps protect the occupants by restraining them to the vehicle and reducing their motion in the event of a crash and distributing the load to the strong, load-bearing parts of the body. The shoulder portion of the belt should be located on the centre of the clavicle, inboard of the acromion—and the lap portion of the seatbelt should be placed low on the hips, enabling engagement of the bony pelvis [1]. It is under these circumstances, with a so-called nominal seatbelt fit, that most testing is performed to evaluate the restraint systems.

Overall, seatbelt use has increased over the years, although improper use remains an issue [2-6]. Improper use of the seatbelt can be attributed to several factors such as vehicle geometry, BMI and overall body shape [3–4], [7]. Seatbelt fit is also affected by users' behaviour: how they put the seatbelt on, how they use it while travelling, and their posture throughout the car ride. In a naturalistic driving study comprising 2733 trips made by 306 different front-seat passengers, it was shown that the shoulder portion of the seatbelt was being misused 28.5% of the time [5]. The most common type of misuse, which was seen 21.5% of the time, was wearing the seatbelt lateral to the clavicle, on the outboard side.

However, the extent to which these different types of seatbelt misuse affect occupant safety in the case of a crash has not been established. A recent study by Östling *et al.* [8] states that in low-severity crashes, which have a low per-crash injury risk, occupants who sustained AIS2+ injuries were relatively average in terms of height and weight and got injured in similar crash configurations when compared to all exposed occupants [8]. Although several studies have investigated what causes injuries in low to moderate-severity crashes [9–11], it is not well known why some occupants sustain injuries while others do not. The authors hypothesise that the difference between nominal and non-nominal seatbelt positioning is part of the explanation [8].

Several efforts have been made to improve the seatbelt fit for car occupants. For example, two studies investigated the effect of educating the occupants [1][12]; there have also been studies investigating the feasibility of using in-cabin cameras to detect seatbelt fit [13–14]. One possible use of real-time monitoring could be to alert the occupants when the seatbelt fit is sub-optimal and instruct them to adjust it [13]. In fact, from 2026 onwards, Euro NCAP will assess reminders of seatbelt misuse when the seatbelt is located under the arm or behind

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the back [15]. However, annoyance and distraction are potential problems with warning systems [16]; user acceptance and compliance can be negatively affected if the warning system is activated too frequently [17]. Therefore, it could be argued that warning systems should not be used when they are not needed. For milder types of seatbelt misuse, such as wearing the seatbelt lateral to the clavicle, other technology-based interventions could play an important role.

One such complementary approach to warnings is to use existing seatbelt pretensioning technology, such as electrical pre-pretensioners (PPT) or pyrotechnical retractor pretensioners (RPT), to actively correct the belt position just before or at the onset of a crash. While PPTs retract the seatbelt and minimize slack just before the crash, RPTs can engage milliseconds after the crash onset. If the seatbelt pretensioners could reposition an off-shoulder seatbelt onto the shoulder before a crash or early on in a crash, the occupant kinematics may be improved. Otherwise, the non-optimal routing could result in severe consequences in the event of a crash. Despite the widespread use of pretensioners, particularly RPTs, there is no evidence that they can reposition an off-shoulder seatbelt, or that this repositioning would affect the crash outcomes. Addressing these unknowns is essential for guiding future seatbelt design and improving safety for front seat passengers.
Thus, the aim of this study was, first, to determine the ability of a seatbelt pretensioner to move an off-shoulder seatbelt to an on-shoulder position for front seat passengers with varying upper body geometry and seatbelt-to-seat geometry. Secondly, to study the ability of PPT and RPT to move an off-shoulder seatbelt to an on-shoulder position on crash test dummies with and without a frontal crash pulse. Thirdly, to evaluate the head kinematics for a Human Body Model (HBM) in a full-frontal crash pulse with a partly and fully repositioned shoulder belt.

II. METHODS

To address these aims, this study was conducted in five steps. First, a volunteer study was performed to investigate the possibility of moving an off-shoulder seatbelt to an on-shoulder position using a PPT. The seatbelt-to-seat geometry was varied and occupants with diverse upper body shapes were recruited. Secondly, three different Anthropomorphic Test Devices (ATDs) were placed in the same test rig and exposed to the same test procedure as the volunteers, to investigate whether those results were reproducible for ATDs. Thirdly, one ATD (selected based on the outcome of the previous step) was moved to a sled environment to investigate the difference in repositioning ability of an RPT and a PPT. Fourthly, seatbelt repositioning was evaluated with an ATD in a sled with a full-frontal crash pulse, to investigate if the repositioning still occurred. Lastly, finite element (FE) simulations using the SAFER Human Body Model (SAFER HBM) were performed to evaluate the occupant head kinematics, both with and without a repositioned shoulder belt. Each step is explained in detail below.

1. Volunteer study

After ethics approval was reviewed and approved by the Swedish Ethical Review Authority (Application 2023-01920-01), 37 volunteers were recruited, 17 males and 18 females. All gave informed consent before testing. No restrictions for volunteer recruitment were set. The recruited volunteers had an average age of 42 (±13) years, an average weight of 80 (±14) kg and an average stature of 175 (±8) cm.

The test rig (Fig. 1) consisted of the front car seat from a mid-sized European vehicle mounted on an aluminium frame. It was equipped with a three-point seatbelt with a 47 mm wide Rukaflex webbing, a manually

(a) (b) (c)

Fig. 1. Images of the test rig illustrating (a) the test rig with coordinate system, (b) fore-aft adjustment of the seat, and (c) the B-pillar installation with height adjustment of the D-ring.

activated PPT and a wire buckle. The seatbelt was guided via a traditional D-ring to the PPT, mounted in the lower part of the B-post and retracting the belt with a force of 250 N. The seatbelt-to-seat geometry could be changed by means of fore-aft translation of the seat (Fig. 1(b)) and height adjustment of the D-ring (Fig.1(c)).

Inclination and height adjustment of the seat were also possible, but those parameters would affect the occupant-to-seatbelt geometry in the same way as the fore-aft and D-ring adjustments, so they were not changed. The seat inclination was kept at a torso angle of 25° and the seat height was kept at the lowest possible level.

To avoid the effect of variations in friction due to different clothing on the seatbelt repositioning, all volunteers were provided with a plain cotton long-sleeve T-shirt during testing. The shirt was selected to match the ATD clothing in terms of material and structure. Key anthropometric measurements were taken of each volunteer in all three dimensions: the seated height from sitting area to acromion, shoulder breadth (biacromial and bideltoid), and upper body depth (measured at the chest and the abdomen). These measurements were recorded according to the standard SS-EN ISO 7250-1:2017 from the Swedish Standards Institute [18]. For more details on recorded anthropometric measurements; see [19].

The volunteers were asked to sit upright and in the mid sagittal plane on the seat, with their hands in their lap. Each volunteer was tested in four different fore-aft seat positions. Based on the findings of Reed *et al.* [5], who reported that the median seat position is 22% forward of the full rear position, this position was selected as a baseline. As it was hypothesised that a more forward position would make repositioning more difficult, three additional seat positions were chosen: 50%, 75% and 100% forward of full rear in the mid-sized European vehicle. However, due to limitations of the test rig, the most forward position could not be achieved. As a result, the actual tested positions were 22%, 50%, 75%, and 93% forward of the most rearward seat track position. These seat positions will be referred to as the rear, mid, forward, and foremost seat positions, respectively. Two different D-ring heights, corresponding to the highest and lowest possible in the same mid-sized European car (with a difference of 69 mm), were tested, Fig. 1c. Several different off-shoulder seatbelt positions were tested for each seat configuration to investigate how it affected the repositioning of the seatbelt. The seatbelt position for each retraction was selected according to the flowchart in Fig. 2. The distances 5, 10, 15 and 20 cm below acromion was selected to be spread out over the upper arm and to be achievable for all volunteers, without placing the belt below the elbow or in contact with the forearm [20].

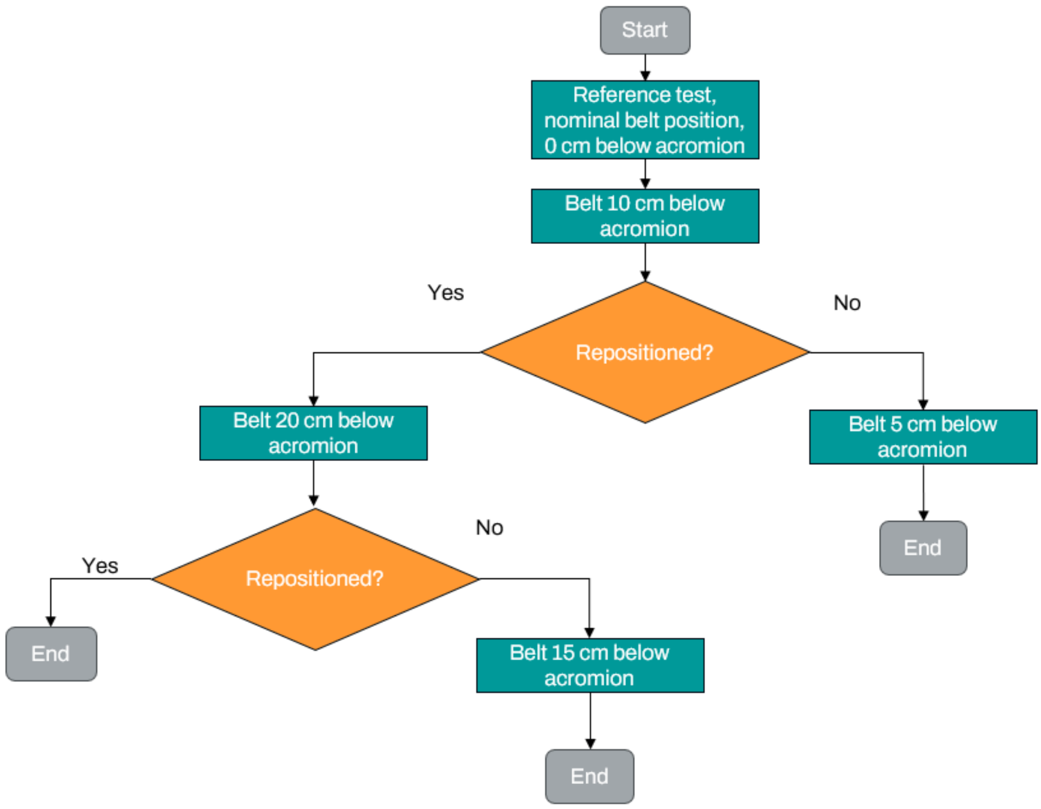


Fig. 2. Flowchart describing the test sequence for how the different seat belt positions were selected for each test.

The seatbelt was positioned down on the volunteers' shoulder (see Fig. A-1). A piece of narrow masking tape kept it in place until just before the seatbelt was retracted, when it was torn to ensure it did not hinder the repositioning. All tests were first performed with the low D-ring. If the seatbelt was not fully repositioned, the D-ring was moved to its highest position, and an additional series of tests was performed, as described in Fig. 2. The order of the different fore-aft seat positions was randomized.

All tested combinations are presented in Table I. The corresponding measurements from the D-ring to a target H-point in the seat were estimated using the SAE H-point mannikin. The PPT was manually activated, and the force was held constant for 2 s to ensure the retraction time was long enough to not affect the repositioning outcome. The seatbelt was deemed fully repositioned if it returned to the nominal position. If it did not, it was considered to be partially repositioned. Each test was recorded using a GoPro Hero 11 camera with a frame rate of 240 frames per second.

The results were analysed using two-sample T-tests comparing volunteers with partial seatbelt repositioning to those with full repositioning, based on the anthropometric measurements collected. A confidence level of 95% was selected; after Bonferroni correction, a corrected significance level of 0.005 was used for the analysis.

TABLE I
ABSOLUTE RELATIVE MEASUREMENTS BETWEEN THE D-RING LOCATION AND THE ESTIMATED H-POINT OF THE SEAT.

D-ring height	Seat position			
	Rear [mm]	Mid [mm]	Forward [mm]	Foremost [mm]
High	x: 219 y: 280 z: 702	x: 284 y: 280 z: 702	x: 346 y: 280 z: 702	x: 387 y: 280 z: 702
Low	x: 219 y: 280 z: 632	x: 284 y: 280 z: 632	x: 346 y: 280 z: 632	x: 387 y: 280 z: 632

2. *ATD tests in the volunteer test rig*

Three different ATDs, a Hybrid III 50% male, Hybrid III 5% female and THOR 50% male, were used. Before testing, the anthropometric body measurements recorded for the volunteers were also recorded for the ATDs. The ATDs were positioned in the test rig using the SAE H-point mannikin. The same test procedure, rig set-up and pretensioning force (250N) was used for the ATDs as for the volunteers.

3. *Pretensioner test with ATD in sled environment*

The results from testing with the three ATDs in the volunteer test rig showed that the Hybrid III 50% male best matched the volunteer results. Therefore, an instrumented Hybrid III 50% male ATD was placed in the sled environment to investigate the difference in repositioning possibilities using an PPT compared to an RPT. The environment included a simplified semi-rigid seat [21], seatback to support the occupant, a generic floor geometry, and foot support. The environment was set-up to mimic the sitting posture in the volunteer test rig (Fig. 3).

The seatbelts were equipped with a PPT with a target retraction force of 400 N, an RPT with a maximum pretensioning force of 2.5 kN at the retractor, and a pyrotechnical lap belt pretensioner (LPT) with a maximum pretensioning force of 2 kN. All pretensioners were manually activated: the PPT was activated 710 ms before the RPT and 715 ms before the LPT. These timings were chosen to simulate the PPT's activation 700 ms before the crash and the activations of the RPT and LPT 10 and 15 ms, respectively, after the crash onset. The tests were recorded using high speed cameras with a frequency of 1000 frames per second. The ATD was tested in four different set-ups: foremost seat position with low and high D-ring and mid seat position with low and high D-ring. The resulting distances from the seat H-point are presented in Table A-I. The seatbelt was positioned 10 cm below acromion and retracted with three different pretensioner combinations: PPT only; PPT, RPT and LPT; and RPT and LPT only.

Fig. 3. The Hybrid III 50% male ATD positioned on the semi-rigid seat on the sled.

4. *Sled testing with an ATD*

The Hybrid III 50% male ATD was positioned in the same test setup on the same sled as in the previous section, in two different configurations, foremost seat position with a low D-ring position and mid seat position with a high D-ring position. These two were chosen to obtain one situation with full repositioning and one position with partial repositioning, based on the findings in the pretensioner tests. The seatbelt was equipped with the same pre-tensioners as presented above and with a 4 kN load limiter. A generic crash pulse, representing a 40 km/h full-frontal rigid barrier (FFRB) crash was used [22]; see Fig. 4.

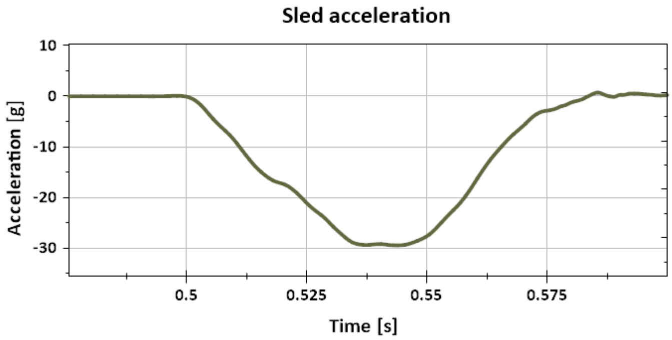


Fig**.** 4. Time vs sled acceleration of the 40 km/h pulse used for the dynamic sled test.

Due to limitations for test recording, the PPT was activated 500 ms before the crash, 200 ms later than in the static tests; it was triggered 510 ms before the RPT and 515 ms before the LPT. Based on the results from the static sled test, this change was not expected to affect the outcome of the seatbelt repositioning. As before, the tests were recorded using high speed cameras with a frequency of 1000 frames per second. Seatbelt pay-out at the retractor was measured using an optic sensor and seatbelt force at retractor was measured using a load cell placed between the retractor and the D-ring. For each of the two test configurations, a reference test with the seatbelt in a nominal position and seatbelt pretensioning with PPT, RPT and LPT was performed. Thereafter, each test configuration was tested with a non-nominal seatbelt position, with both PPT, RPT and LPT and with only RPT and LPT. The non-nominal seatbelt position tested was set to 10 cm as this was the highest seatbelt location where all volunteers and ATDs experiencing partial repositioning All test conditions were repeated twice, resulting in a total of 12 tests (2 test configurations x 3 pretensioner combinations x 2 repetitions).

5. *HBM simulation*

The explicit solver LS-DYNA single-precision version R12.2 (ANSYS/LSTC, Livermore, CA, USA) was used to run FE simulations of a frontal sled model with a full-frontal crash pulse to investigate how in-crash occupant head kinematics are affected by a fully or partially repositioned shoulder belt. The sled model represented the same sled used in the testing with the ATD, described above. The sled model has been validated previously through mechanical sled tests [23].

The restraint system model included a B-pillar integrated seatbelt, a shoulder belt retractor with a 2 kN pretensioner and 4 kN load limiter, a wire buckle, crash-locking tongue, and a 2 kN lap belt pretensioner. The RPT and LPT were activated 10 ms and 15 ms into the crash, respectively, consistent with the sled testing conditions. Since the PPT did not affect the seatbelt force and seatbelt pay-out in the sled tests, it was not included in the simulation study in the sled testing. Two seat and D-ring configurations were applied. The first matched the conditions used to achieve full seatbelt repositioning in the sled tests, with the seat at mid position and the D-ring at the high position. The second configuration was intended to achieve partial repositioning of the seatbelt, with the seat in a forward position and the D-ring in the low position. For each configuration, simulations were run with a nominally positioned seatbelt (on the shoulder) and a seatbelt positioned 10 cm down from the acromion (as in the sled tests), resulting in a total of four simulations.

The SAFER HBM v11.0.1, representing a mid-sized male of height 175.3 cm and mass 77.3 kg, was used to virtually simulate a passenger seated upright in the front passenger seat [24].

The same crash pulse used in the sled tests was used in the simulations, albeit scaled down by a factor of 0.7—resulting in an FFRB pulse with a Delta-V of 33 km/h (21 g). This change simulated a low-severity frontal crash and prevented head and chest contact with the femur in the absence of a frontal airbag. Head kinematics were extracted from the head centre of gravity (CoG) to compare the occupant's head CoG trajectories when the seatbelt was fully repositioned from an off-shoulder position to when it was only partially repositioned.

III. RESULTS

1. Volunteer testing

After removal of data from two male volunteers, excluded from the analysis due to failure to maintain the initial sitting posture and incomplete testing arising from discomfort, 35 complete data sets were analyzed. The volunteer sample did not align with the general distribution of body measurements observed in the broader population. Specifically, the recorded measurements did not encompass the extreme values (high and low tails) of the population for neither height and weight [20][25], nor seated shoulder height, chest depth, abdominal depth, bideltoid breadth and biacromial breadth [20]. A summary of volunteer data can be found in Table A-II.

In the tests with the high D-ring position, the seatbelt was fully repositioned for all volunteers regardless of seat for-aft position and initial seatbelt location. In the test with the low D-ring position, the seatbelt repositioned in all cases in the rear and mid seat positions. For the forward seat position with low D-ring, the belt repositioned only partially for two volunteers, one male and one female. For both of these volunteers, the belt repositioned partly if it was placed 10 cm below acromion or further down. In the foremost seat position with low D-ring, seven volunteers (four males and three females) experienced partial repositioning. For three of these seven, the seatbelt was only partly repositioned already when placed 5 cm below the acromion; for the other four, the seatbelt stuck if it was placed 10 cm below the acromion. Pictures from before and after activation of the PPT can be seen in Fig. A-2.

The anthropometric measurements of the volunteers, divided in groups of full and partial repositioning are presented in Table II. In both the forward and foremost seat track position, the average shoulder height appeared to be lower in the full repositioning group than in the partial repositioning group. Similarly, the average abdominal depth and the average bideltoid breadth appeared higher in the full repositioning group. For chest depth and biacromial breadth, there was no consistency in differences between the used seat track positions. According to the p-values, also presented in Table II, none of the differences in mean anthropometric measurements were statistically significant. The lowest p-values, however, were observed for abdominal depth and seated shoulder height.

2. ATD testing in the rig

The anthropometric measurements of the ATDs were similar to that of the volunteers in terms of abdominal depth and chest depth. The Hybrid III and THOR 50% male dummies also correlated well with the volunteers in terms of seated height and bideltoid breadth, both with respect to all volunteers and with respect to male volunteers only. The Hybrid III 5% female was significantly smaller than the volunteers in terms of seated height and shoulder breadth. A complete list of the measurements can be found in Table A-II. In terms of repositioning, the results differed between the different ATDs. The THOR 50% male repositioned fully in all tested configurations. The Hybrid III ATDs both repositioned fully in all tests with the D-ring in the high location. In the tests with a low D-ring position, the seatbelt was fully repositioned in the rear and mid seat track position. In the forward seat track position, the Hybrid III 5% female experienced partial seatbelt repositioning if the belt was placed 20 cm below acromion and the Hybrid III 50% male experienced partial repositioning if the belt was placed 15 cm below acromion or further down. In the foremost seat position the Hybrd III 5% female experienced partial repositioning if the belt was placed 10 cm below acromion or further down and for the Hybrid III 50% male

TABLE II
MEAN VALUES AND P-VALUES FOR THE ANTHROPOMETRIC MEASUREMENTS FOR THE GROUPS OF FULL AND PARTIAL REPOSITIONING OF THE SEATBELT.

		Full repositioning [mm]				Partial repositioning [mm]				p-value
		Min	Max	Mean	SD	Min	Max	Mean	SD	
Forward seat			n=33				n=2			
	Seated shoulder height	549	677	607	30	644	665	654	15	0.085
	Biacromial breadth	308	417	355	26	347	351	349	3	0.209
	Bideltoid breadth	397	548	470	38	436	473	455	26	0.545
	Chest depth	166	287	219	32	169	241	205	51	0.762
	Abdominal depth	181	338	258	38	215	227	221	8	0.010
Foremost seat			n=28				n=7			
	Seated shoulder height	549	677	605	38	584	673	629	34	0.117
	Biacromial breadth	308	417	355	25	322	403	356	27	0.942
	Bideltoid breadth	402	548	470	35	397	539	463	48	0.705
	Chest depth	166	287	218	32	169	268	217	38	0.927
	Abdominal depth	181	338	263	38	195	282	229	27	0.019

the seatbelt repositioned partly already at 5 cm below acromion. As the THOR 50% male did not demonstrate partial repositioning it was not chosen for testing in the sled environment. The Hybrid III 50% male was more similar to the volunteers' abdominal depth and seated height than the Hybrid III 5% female was. Since these dimensions most affected the repositioning in the volunteer testing, the former was chosen for testing on the sled.

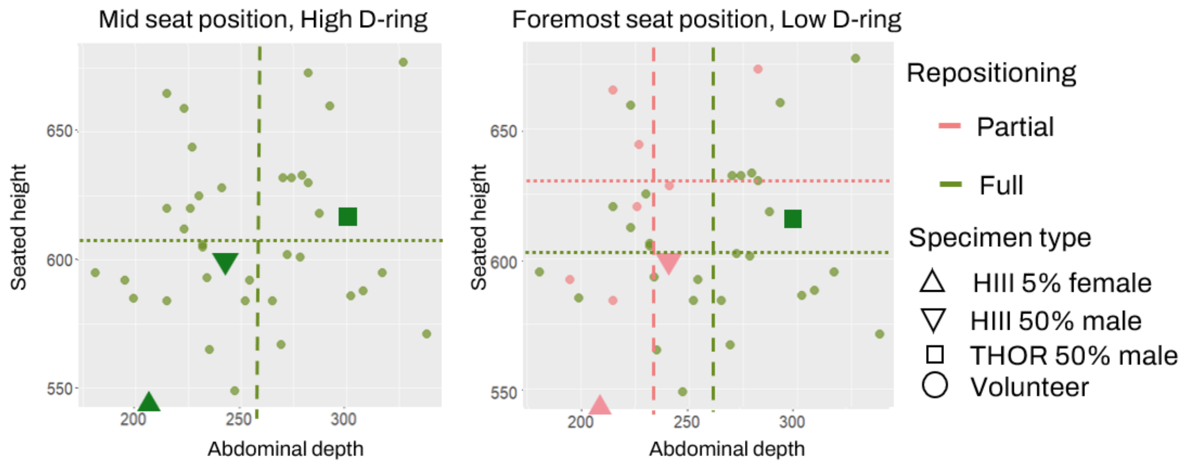


Fig. 5. Two plots showing the repositioning ability for ATDs and volunteers, with an initial seatbelt position 10 cm below acromion, in terms of abdominal depth and seated height for the two configurations. The dashed lines correspond to the average anthropometric measurements for full (green) and partial (pink) repositioning groups.

3. Pretensioner test with ATD in sled environment

The results from the test are presented in Table III. In the sled set-up, like the test rig, the belt did not reposition for the HIII 50% male in the foremost position with the low D-ring. No difference in repositioning was seen when the RPT and the LPT were added. In both the foremost seat position with the high D-ring and the mid seat position with low D-ring the seatbelt was fully repositioned with the PPT, alone and in combination with the RPT and LPT. When the RPT and LPT were used without the PPT, the seatbelt was only partially repositioned. In the mid seat position with the high D-ring, the seatbelt was always fully repositioned. The final seatbelt locations in test configurations where the repositioning was dependant on pretensioner combination, are shown in Fig. 6.

TABLE III

REPOSITIONING OUTCOME (FULL OR PARTIAL) FOR ALL COMBINATIONS OF PRETENSIONERS, WITH ATD IN SLED ENVIRONMENT.

	Foremost			Mid		
D-ring height	PPT	PPT+RPT/LPT	RPT/LPT	PPT	PPT+RPT/LPT	RPT/LPT
High	Full	Full	Partial	Full	Full	Full
Low	Partial	Partial	Partial	Full	Full	Partial

PPT | PPT, RPT and LPT | RPT and LPT

Foremost seat position, high D-ring

Mid seat position, low D-ring

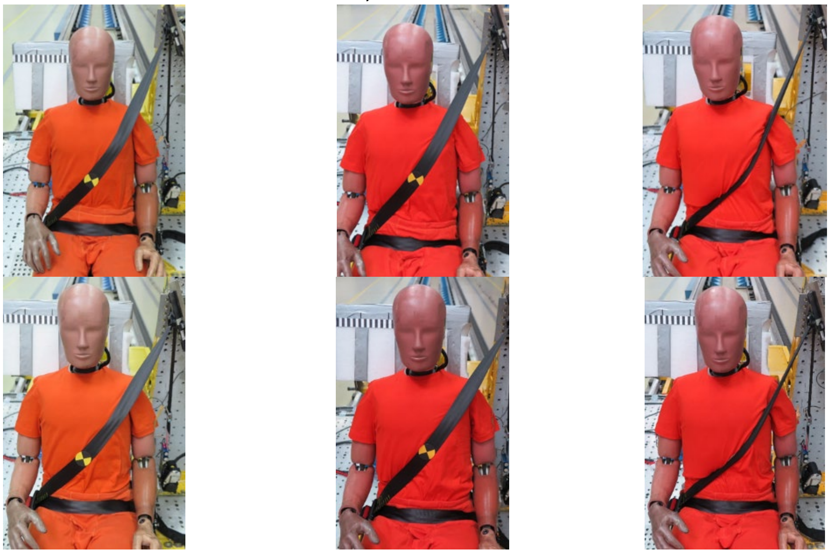


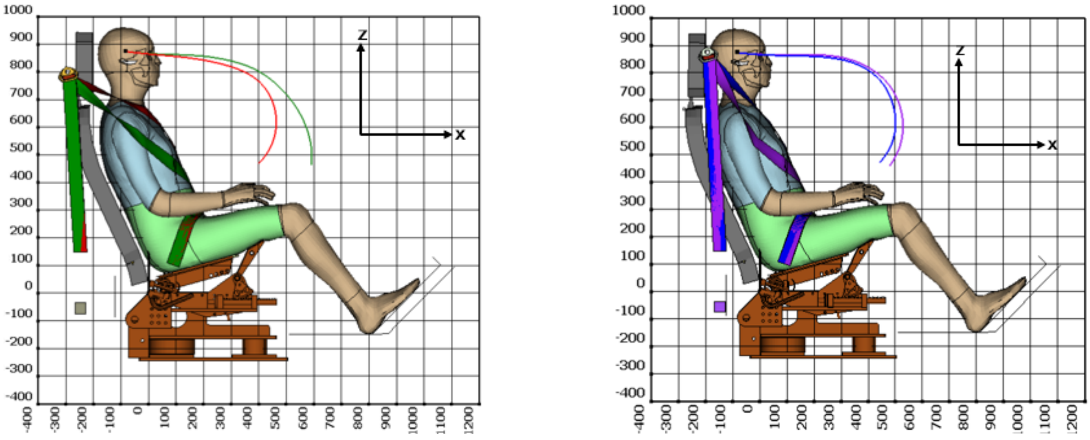
Figure 6. Photos of the post-test seatbelt fit for the test configurations where the repositioning depended on the pretensioner combination.

4. ATD sled testing

In the sled testing with a 40 km/h full-frontal crash pulse, the seatbelt repositioned fully in the mid seat position with a high D-ring and partially in the foremost seat position with a low D-ring with all combinations of pretensioners. In the tests with the PPT, the seatbelt reached its final position before the crash pulse was initiated. In the tests without PPT, the HIII 50% male ATD started to move before the seatbelt had reached its final location, which occurred 25 ms after the start of the crash pulse, in both the full and partial repositioning condition. However, it did not influence the repositioning capability. The seatbelt pay-in/pay-out and the seatbelt force measured at the retractor are shown in Fig. A-4. The seatbelt force, was similar between all tests, reaching a peak force of around 3 kN. Thus, the force was not affected by either an initial off-shoulder seatbelt position or partial seatbelt repositioning. The pay-in differed for the different combinations of pretensioners and seatbelt positions, as well as for the different geometrical configurations of the seat and the seatbelt. The seatbelt pay-out differed less between the tests. In the full repositioning condition, there was a 40 mm difference and in the partial repositioning condition, there was a 5 mm difference between maximum and minimum pay-out.

5. HBM Simulation

In the FE simulations, the seatbelt repositioned fully in the mid seat position with the D-ring in high position and partly in the foremost seat position with the D-ring in low position. The seatbelt reached its final location after 20 ms in the partial repositioning condition and 26 ms in the full repositioning condition. The final seatbelt location in full and partial seatbelt repositioning conditions in FE simulations, compared to sled testing, is illustrated in Fig. A-5. Fig. 7 (a) illustrates the head sagittal plane trajectory for the reference on-shoulder seatbelt compared to the off-shoulder seatbelt in the partial repositioning configuration. In this configuration, the partially repositioned seatbelt—retracted by the RPT and LPT—ended up lateral to the acromion, leading to a forward head excursion 130 mm greater than that of the reference on-shoulder seatbelt. However, in the full repositioning configuration illustrated in Fig. 7(b), the forward head excursion was only 30 mm more in the repositioning test than in the reference test with a nominal seatbelt fit.



(a) (b)

Fig. 7. Head XZ trajectory for (a) the partial repositioning configuration (on-shoulder seatbelt in red and off-shoulder seatbelt in green) and (b) the full repositioning configuration (on-shoulder seatbelt in blue and off-shoulder seatbelt in purple)

IV. Discussion

The volunteer study showed that for most situations and most individuals, the seatbelt could be successfully repositioned to a nominal seatbelt position using the PPT. According to the naturalistic driving study by Reed *et al*. [5], front seat passengers travelled rear of mid-track 81% of the time and the median seat track position was 22% forward of the rearmost position. This corresponds to the mid and rear positions of this study, in which all volunteers experienced full seatbelt repositioning. Taking that into account, the seatbelt would potentially be fully repositioned in many real-world scenarios for the front-seat passengers. Besides the seat fore-aft position, the D-ring position also affected the repositioning ability: all volunteers experienced full seatbelt repositioning when the D-ring was in the high position, regardless of seat fore-aft position, whereas partial repositioning occurred for some volunteers in the forward and foremost seat position when the D-ring was in the low position. The difference in D-ring height between the high and low position was 69 mm. In comparison, the seated shoulder height difference between the tallest and shortest volunteers was 128 mm, and the difference between the tallest volunteer with full repositioning and the shortest volunteer with partial repositioning was 95 mm, as can be seen in Table II. These ranges mean that there were short volunteers in the low D-ring tests who had the same vertical distance from the acromion to the D-ring as tall volunteers in the high D-ring tests—yet the former experienced only partial repositioning while the latter experienced full repositioning. This discrepancy suggests that the vertical distance alone does not explain why all high D-ring tests resulted in full repositioning; the entire belt-to-seat geometry must be taken into account.

As the seatbelt was fully repositioned for all volunteers, regardless of upper body shape, in six of the eight tested configurations, this study suggests that the volunteers' upper body shape had less influence on the repositioning than the vehicle geometry. However, Fig. 5 shows that in the foremost seat position, where the seatbelt did not reposition for seven of the volunteers, there was a trend suggesting that shorter sitting height and greater abdominal depth did tend to increase the likelihood of full seatbelt repositioning. The differences between the full and partial repositioning groups in terms of anthropometric measurements did not, however, show statistical significance, which suggests that there is at least one other factor that influences individual differences in seatbelt repositioning. Factors such as the volunteer’s physiology (bony, muscular, or a thick layer of subcutaneous fat) could have influenced the result. Moreover, this study was conducted with volunteers that, although the average height and weight of the sample was similar to the general population [20][25], did not cover the variety of the population in neither height and weight [20][25], nor seated shoulder height, chest depth, abdominal depth, bideltoid breadth and biacromial breadth [20]. Therefore, the conclusions drawn cannot be directly applied to the entire population, particularly to individuals at the extremes of these measurements.

To achieve broader applicability, additional volunteer testing would be needed. The volunteers were also tested with only one a plain long-sleeve T-shirt, bulkier clothing could potentially also affect the repositioning ability.

ATDs were used to investigate the effect of the RPT on repositioning, as its actuation could be uncomfortable for volunteers. There are of course differences in the upper body shape of an ATD and that of a human: for example, the gap in the shoulder construction of the Hybrid III ATD could affect the seatbelt's ability to reposition.

The intermediate step, putting the ATDs in the same test rig as the volunteers, showed that given the study's specific conditions and purposes, the Hybrid III 50% male ATD could still be used as volunteer surrogate because it gave similar results in terms of repositioning with the PPT.

The RPT was not more effective at repositioning the seatbelt than the PPT; it neither helped reposition the belt when the PPT could not, nor could it reposition the belt in as many situations as the PPT alone could. Although this study did not investigate the reason for this difference, it is hypothesised that a difference in retraction speed is responsible. The PPT retracted more slowly and allowed the belt to slide over the shoulders of the ATD whereas the faster retracting of the RPT did not provide enough time for this to occur, instead pulling the seatbelt into the ATD. There is, of course, a possibility that the difference between the volunteer test rig and the semi-rigid seat in ATD testing affected the outcome, but the results with the PPT only were similar, so this is unlikely.

The sled test demonstrated that the addition of a crash pulse did not affect the pretensioners' ability to fully reposition the seatbelt. As the seatbelt force and pay-out were similar in all tests, seatbelt repositioning appears to have no effect on the overall performance of the seatbelt system during a full-frontal crash.

Repositioning in the simulations was similar to the repositioning in the sled tests, in terms of final seatbelt location (Fig. A-5) and timing of the seatbelt repositioning. Although the interaction between the SAFER HBM and the seatbelt has not been validated for this type of seatbelt repositioning, the similar timing and the similar final seatbelt position after repositioning suggest that the HBM simulations can be used for evaluating the kinematic response in this scenario.

The simulation results, seen in Fig. 7, showed that the head excursion was substantially larger with a partially repositioned seatbelt compared to the reference test with a nominal seatbelt position. This suggests that a poor seatbelt fit could increase the risk of head contact with interior parts and, thus, the risk of injuries in a crash. These findings support the hypothesis by Östling *et al*. [8] that a poor shoulder belt fit could result in unfavourable in-crash head kinematics and may increase the risk of injury. However, considering that the seatbelt potentially would be fully repositioned in many real-world scenarios, as many cars are equipped with RPTs, and that the forward head excursion was similar when comparing a fully repositioned seatbelt to a nominal seatbelt, one could assume that wearing the seatbelt lateral to the clavicle may not be a major cause of injuries among front seat passengers in real-world crashes. For drivers, wearing the seatbelt lateral to the clavicle is less likely, as the seatbelt would not remain off-shoulder if the driver keeps the hands on the steering wheel. However, if the outboard hand is not on the steering wheel, the seatbelt could be placed down on the arm, making the findings of this study relevant for drivers as well.

It is, however, important to note that the volunteer study was only performed in a static environment, meaning the effects of different pre-crash manoeuvres were not investigated. Firm braking or turning of the vehicle in the pre-crash phase could affect the posture of the passenger, and possibly add load to the seatbelt before the crash happens, in a way that would potentially hinder full seatbelt repositioning. The effect of different initial sitting postures was not investigated, either. It should also be noted that the tests have only been carried out with one set-up corresponding to one vehicle geometry, meaning the results may differ in other vehicles. To apply these findings to different vehicle environments, the relative distance between the D-ring and the seat in the x-, y- and z-directions, should be considered, rather than the percentage of seat track length and the specific D-ring heights. To draw conclusions on the effect of shoulder belt fit on injury outcome in the field, future studies should investigate how pre-crash maneuvers, sitting posture variations and other vehicle environments affect the repositioning ability of the pretensioner. This research is necessary before drawing definitive conclusions about the extent that poor shoulder seatbelt fit affects injury outcome in real-world crashes.

V. CONCLUSION

This study was the first to investigate how various combinations of seatbelt pretensioners can return an off-shoulder seatbelt to an on-shoulder position. The results showed that the seatbelt could be repositioned in most seating positions tested, even when a crash pulse was applied. The seatbelt-to-seat geometry was the most important factor for seatbelt repositioning. The PPT enabled repositioning in more situations compared to using only pyrotechnical pretensioners. Moreover, the results showed that an off-shoulder seatbelt negatively affected the head kinematics in a crash. However, if the seatbelt was repositioned early in the crash phase from an off-shoulder position to on-shoulder position, it provided effective restraining of the front seat passenger, minimizing forward head excursion. These findings have important implications for vehicle safety, suggesting that incorporating PPTs in restraint systems could enhance seatbelt fit and occupant protection and be a complement to seatbelt misuse reminders. Future studies should explore how these findings apply across a broader range of vehicle geometries and real-world crash scenarios to further refine seatbelt repositioning strategies and improve safety standards.

VI. ACKNOWLEDGEMENTS

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VII. CONFLICT OF INTEREST

Several authors work at Autoliv Research, located in Vårgårda, Sweden. Autoliv Research is part of Autoliv (https://www.autoliv.com), a company that develops, manufactures, and sells for example protective safety systems to car manufacturers. Results from this study may impact how Autoliv choose to develop their products.

VIII. REFERENCES

[1] Buckley, L., Jones, M. L. H., Ebert, S. M., Reed, M. P., Hallman, J. J. (2017) Evaluating an intervention to improve belt fit for adult occupants: Promoting positive beliefs, *Journal of Safety Research*, 64, pp. 105–111. https://doi.org/10.1016/j.jsr.2017.12.012.

[2] Bohman, K. Osvalder, A. L., Ankartoft, R., Alfredsson, S. (2019) A comparison of seat belt fit and comfort experience between older adults and younger front seat passengers in cars, *Traffic Injury Prevention*, 20(sup2), pp.7–12. https://doi.org/10.1080/15389588.2019.1639159.

[3] Reed, M.P., Ebert, S.M., and Rupp, J.D. (2012) 'Effects of obesity on seat belt fit,' *Traffic Injury Prevention*, 13(4), pp. 364–372. https://doi.org/10.1080/15389588.2012.659363.

[4] Reed, M.P., Ebert, S.M. and Hallman, J.J. (2013) 'Effects of driver characteristics on seat belt fit,' *SAE Technical Papers on CD-ROM/SAE Technical Paper Series* [Preprint]. https://doi.org/10.4271/2013-22-0002.

[5] Reed, M.P., Ebert, S., Jones, M.L.H., and Hallman, J.J. (2020) 'Prevalence of non-nominal seat positions and postures among front-seat passengers,' *Traffic Injury Prevention*, 21(sup1), pp.7–12. https://doi.org/10.1080/15389588.2020.1793971.

[6] Forman, J. L., Booth, G. *et al.* (2024) 'Variability in body shape, superficial soft tissue geometry, and seatbelt fit relative to the pelvis in automotive Postures—Methods for volunteer data collection with open magnetic resonance imaging,' *Journal of Biomechanical Engineering*, 146(3). https://doi.org/10.1115/1.4064477.

[7] Fong, C. K., Keay, L., Coxon, K., Clarke, E., and Brown, J. (2015) 'Seat belt use and fit among drivers aged 75 years and older in their own vehicles,' *Traffic Injury Prevention*, 17(2), pp.142–150. https://doi.org/10.1080/15389588.2015.1052420.

[8] Östling, M., Jeppson, H., Forman, J. (2024) Injury Observations in High-exposure, Low-severity Frontal Car Crashes – a GIDAS Investigation. Proceedings of IRCOBI Conference, 2024. Stockholm, Sweden.

[9] Forman, J. L., Östling, M., Mroz, K., Lubbe, N. (2023) Potential Injury Criteria for Collisions with Heavy Goods Vehicles. The 27th International Technical Conference on the Enhanced Safety of Vehicles Conference, Yokohama, Japan, 2023.

[10] Forman J. L., McMurry T. L. 2018. Nonlinear models of injury risk and implications in intervention targeting for thoracic injury mitigation. Traffic Injury Prevention, 19(s2): pp.103-108.

[11] Ekambaram, K., Frampton, R., Lenard, J. (2019) Factors associated with chest injuries to front seat occupants in frontal impacts. Traffic Injury Prevention, 20(S2): pp.37-42.

[12] Jones, M.L.H., Buckley, L., Ebert, S.M., Reed, M.P., and Hallman, J.J. (2018) Evaluating an intervention to improve belt fit for adult occupants, *Journal of Safety Research*, 64, pp.93–104. https://doi.org/10.1016/j.jsr.2017.12.013.

[13] Chun, S., Ghalehjegh, N.H., *et al.* (2019) NADS-Net: A Nimble Architecture for Driver and Seat Belt Detection via Convolutional Neural Networks. Proceedings of IEEE/CVF International Conference on Computer Vision Workshop, 2019. Seoul, South Korea.

[14] Hartleitner, F., Koppisetty, A. and Bohman, K. (2022) 'Automated quantification of occupant posture and shoulder belt fit using safety specific key points,' *IEEE Open Journal of Intelligent Transportation Systems*, 3, pp.89–103. https://doi.org/10.1109/ojits.2022.3140612.

[15] Euro NCAP Protocol - Safe Driving - Occupant Monitoring, https://www.euro-ncap-protocol-safe-driving-occupant-monitoring-v10.pdf, Accessed 31th March 2025.

[16] Reagan, I. J., Cicchino, J. B., Kerfoot, L. B., Weast, R. A. (2017) Crash avoidance and driver assistance technologies – Are they used?'*Transportation Research Part F Traffic Psychology and Behaviour*, 52, pp.176–190. https://doi.org/10.1016/j.trf.2017.11.015.

[17] Flannagan, C. LeBlanc, D., *et al.* (2016) *Large-Scale Field Test of Forward Collision Alert and Lane Departure Warning Systems*. https://trid.trb.org/view/1415844.

[18] Swedish Standards Institute. (2017). Basic human body measurements for technological design – part 1: Body measurement definitions and landmarks (iso 7250-1:2017)

[19] Bohl, L., Eliasson, K. (2023) Car occupant seatbelt fit: the effect of belt pre-pretensioning. Master thesis in Biomedical Engineering, Department of Mechanics and Maritime Sciences, Division of Vehicle Safety, Chalmers University of Technology, Gothenburg, Sweden. Available at: https://odr.chalmers.se/server/api/core/bitstreams/8331c811-b549-4317-a125-178e27a75d3c/content

[20] Hanson, L., Sperling, L., Gard, G., Ipsen, S., Vergara, C. O. (2008) 'Swedish anthropometrics for product and workplace design,' *Applied Ergonomics*, 40(4), pp.797–806. https://doi.org/10.1016/j.apergo.2008.08.007.

[21] Uriot, J., Potier, P., *et al.* (2015) Reference PMHS Sled Test to Assess Submarining. Stapp Car Crash Journal, 59: pp.203-223.

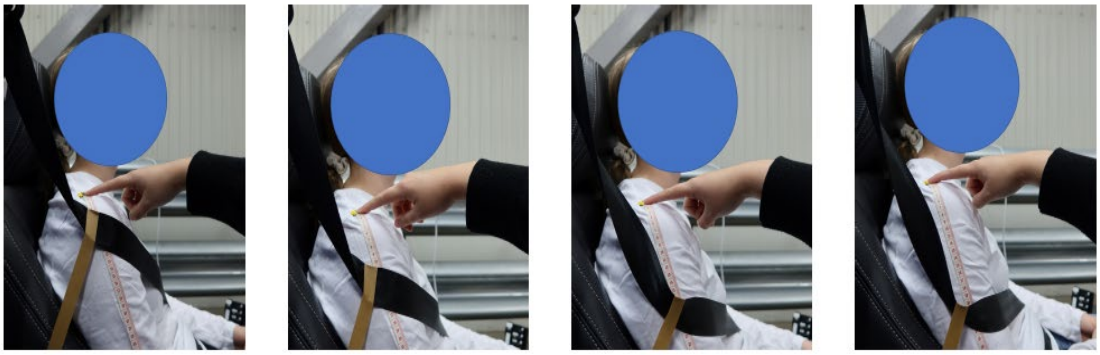
[22] Höschele, P., Smi,t S., Tomasch, E., Östling, M., Mroz, K., Klug, C. 2021. Generic Crash Pulses Representing Future Accident Scenarios of Highly Automated Vehicles. SAE Int. J. Trans. Safety 10(2):2022, doi:10.4271/09-10-02-0010.

[23] Östling, M., Eriksson, L., Dahlgren, M., Forman, J. L. (2023) Frontal Head-On Car-to-Heavy Goods Vehicle Crashes and their Effect on the Restraint System. The 27th International Technical Conference on the Enhanced Safety of Vehicles Conference, Yokohama, Japan

[24] Iraeus, J., Brynskog, E., John, J., Östh, J., Pipkorn, B., & Davidsson, J. (2024). Development of SAFER HBM v11. In Development of SAFER HBM v11. Zenodo. https://doi.org/10.5281/zenodo.10886711

[25] Fryar, C. D., Carroll, M. D., Gu, Q., Afful, J., Ogden, C. L. (2021). Anthropometric reference data for children and adults: United states, 2015-2018. Vital and health statistics. Series 3, Analytical and epidemiological studies; no. 46. https://stacks.cdc.gov/view/cdc/100478

IX. APPENDIX



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

Figure A-1. Illustration showing how the seatbelt was positioned in (a) 5 cm, (b) 10 cm, (c) 15 cm, (d) 20 cm from acromion.

TABLE A-I
RESULTING ABSOLUTE RELATIVE MEASUREMENTS BETWEEN THE D-RING LOCATION AND THE H-POINT IN THE SLED SET-UP.

	Mid seat position [mm]	Foremost seat position [mm]
High D-ring	x: 278 y: 305 z: 708	x: 380 y: 305 z: 708
Low D-ring	x: 278 y: 305 z: 633	x: 380 y: 305 z: 633

TABLE A-II
ANTHROPOMETRIC MEASUREMENTS OF VOLUNTEERS AND ATDS, MEASURED IN [MM]

	All volunteers (n=35)				Females (n=18)		Males (n=17)		ATDs		
Anthropometric measurements	Mean	SD	Min	Max	Mean	SD	Mean	SD	HIII-50M	HIII-5F	THOR-50M
Seated shoulder height	611	31	549	677	595	23	625	31	600	535	615
Shoulder biacromial breadth	355	25	308	417	338	18	372	20	310*	260*	340*
Shoulder bideltoid breadth	470	37	397	548	443	25	497	26	470	380	490
Chest depth	219	33	166	287	195	19	243	24	270	200	240
Abdominal depth	257	39	181	338	241	39	271	32	235	215	300

* Due to limitations in the ATD design where the dummies do not have any acromion, the biacromial breadth is only an estimation based on the available design and cannot be interpreted as for the volunteers.

Fig. A-2. Photos before (top row) and after activation (second row) of each of the volunteers experiencing partial seatbelt repositioning in the foremost seat position with the low D-ring. The initial off-shoulder seatbelt location was 10 cm below acromion.

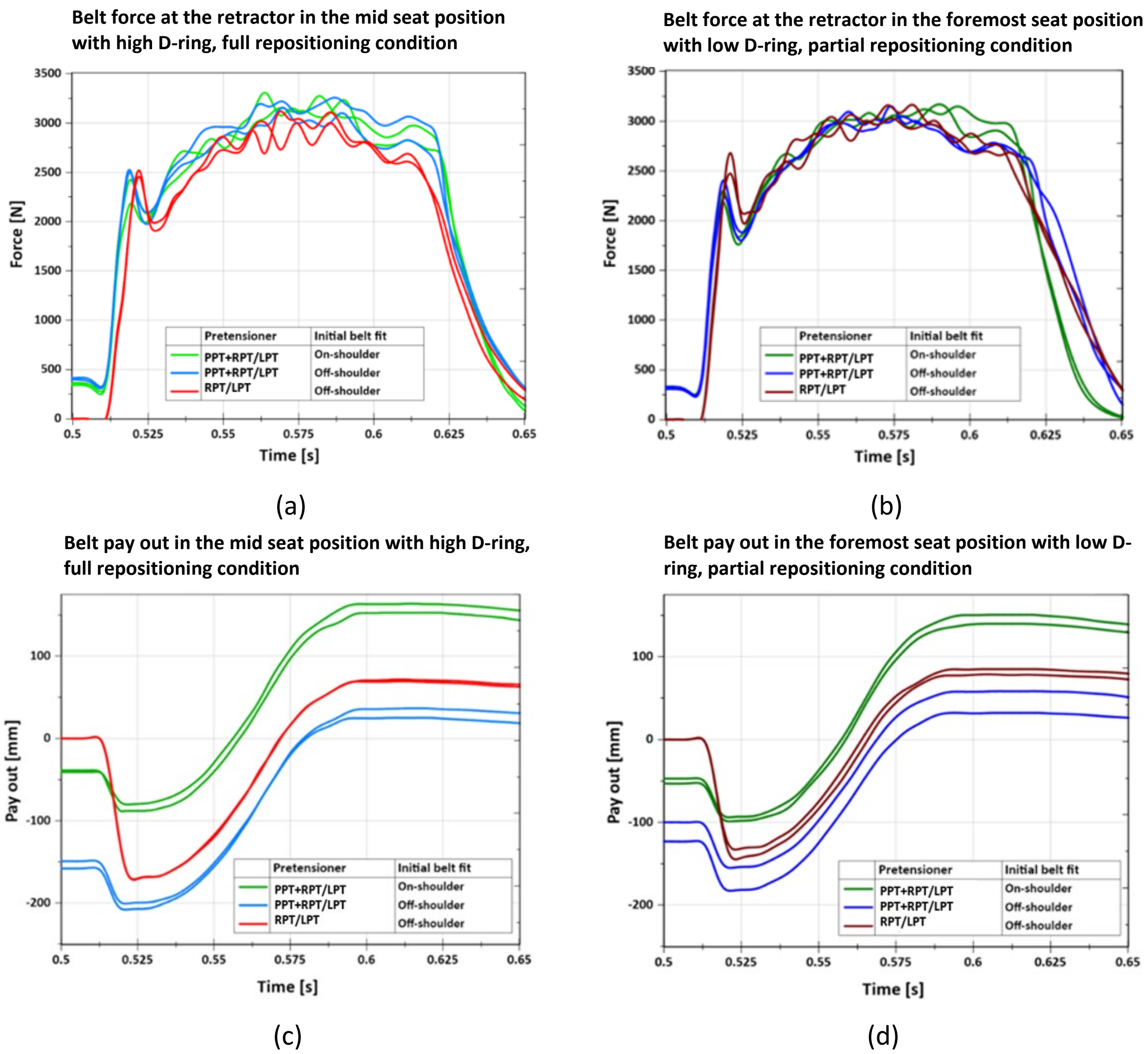
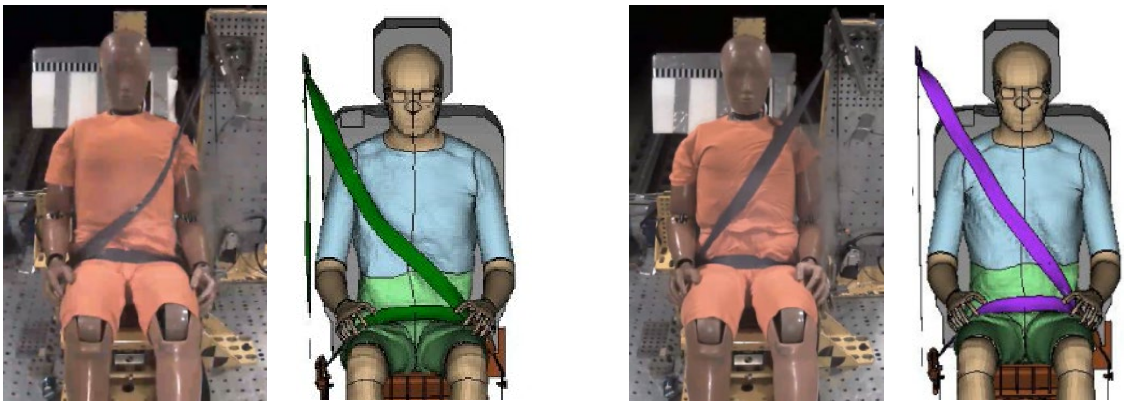


Figure A-4. Seatbelt force and pay-out for full seatbelt repositioning (a) and (c) and seatbelt force and pay-out for partial seatbelt repositioning (b) and (d).



(a) (b)

Fig. A-5. Pictures comparing the final seatbelt location after repositioning of the seatbelt in the sled tests to the simulations for (a) partial repositioning, with foremost seat position and low D-ring, and (b) full repositioning, with mid seat position and high D-ring.