Car occupant seat belt fit; the effect of belt pre-pretensioning

Master's thesis in Biomedical Engineering

Louise Bohl and Klara Eliasson

Department of Mechanics and Maritime Sciences

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2023
www.chalmers.se

Master's thesis 2023

Car occupant seat belt fit; the effect of belt pre-pretensioning

Louise Bohl and Klara Eliasson

Department of Mechanics and Maritime Sciences
Division of Vehicle Safety
Chalmers University of Technology
Gothenburg, Sweden 2023

Car occupant seat belt fit;
the effect of belt pre-pretensioning
Louise Bohl and Klara Eliasson

Supervisor: Amanda Hederskog, Autoliv
Martin Östling, Autoliv
Examiner: Johan Davidsson, Mechanics and Maritime Sciences

Master's Thesis 2023
Department of Mechanics and Maritime Sciences
Division of Vehicle Safety
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: The test rig used to investigate shoulder belt repositioning

Typeset in LaTeX
Printed by Chalmers Reproservice
Gothenburg, Sweden 2023

Car occupant seat belt fit; the effect of belt pre-pretensioning
Louise Bohl and Klara Eliasson
Department of Mechanics and Maritime Sciences
Chalmers University of Technology

Abstract

In the event of a crash, the seat belt should load the occupant's pelvis, thorax, and clavicle. A shoulder belt segment routed distal of the shoulder, i.e. positioned on the arm, may cause chest and abdominal injuries during a crash. The overriding aim of this study was to investigate if an improperly positioned shoulder belt can be repositioned to a proper position on the clavicle, with the help of a pre-pretensioner for front seat occupants. More specifically, the aims were to investigate if the location of the belt attachment points, occupant body characteristics, belt geometry, belt fit, and friction of clothing affected the ability of the pre-pretensioner to reposition the shoulder belt and from which distances down the arm it was possible.

A volunteer study was conducted to investigate if the shoulder belt could be repositioned for a nominal belt geometry similar to a Volvo S60 and for a belt-in-seat geometry in an adopted test rig. Several anthropometric, belt geometry, and belt fit measurements were collected and analyzed to identify why the belt did not reposition for some individuals compared to others. In addition, the ability of the pre-pretensioner to reposition the shoulder belt for different fore-aft seat positions, D-ring heights, and a belt-in-seat installation were investigated.

17 male and 18 female volunteers were tested. The study found that the location of the belt attachment points affected belt repositioning, since the shoulder belt was not repositioned for the majority of the volunteers in the belt-in-seat installation. The belt repositioned for all volunteers in the most common seat positions while the rate of unsuccessful repositionings increased for more forward seat positions. A high D-ring made belt repositioning possible for all volunteers. Measurements identified as influencing belt repositioning were a taller shoulder height (measured while seated) and a smaller abdominal depth in seat positions forward of the mid position and for the belt-in-seat installation. The belt did not reposition with the lower friction clothing material in the belt-in-seat installation but repositioned for some in a forward fore-aft position. The repositioning commonly failed from positions close to the acromion on the arm.

The results indicate that the upper body shape influences belt repositioning. It could be linked to combinations of upper body measurements, shoulder belt routing, and different belt geometries. Based on the results, future studies should investigate shoulder belt repositioning for additional belt geometries and dynamic scenarios as well as the possibility to implement belt fit warning interventions.

Keywords: belt repositioning, B-pillar installation, belt-in-seat installation, pre-pretensioner, D-ring attachment, and fore-aft position.

Acknowledgments

We are immensely grateful for all the guidance and help we have received from our supervisor Amanda Hederskog at Autoliv. Thank you for your unwavering support, the hours you have spent discussing all aspects of this project with us, and giving constructive feedback on this report. We would also like to thank Martin Östling from Autoliv for the support and setting up the meetings with the project group "Passenger safety to the next level" who set the foundation for the thesis. A special thanks to our examiner Johan Davidsson for all his time, input, and advice. This study would not have been possible without all the practical help from the staff at Autoliv, and we especially want to express our gratitude to Mikael Enänger and Henrik Hermansson. We are extremely thankful for your practical wisdom, the help you have given us, and the way you always brightened up our days.

Louise Bohl and Klara Eliasson, Gothenburg, June 2023

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

ASIS	Anterior Superior Iliac Spine
BMI	Body Mass Index
df	degrees of freedom
SD	Standard Deviation

Contents

List of Figures

List of Tables

1

Introduction

The 3-point seat belt is a restraint system implemented to reduce the injury risk of occupants in a crash. The seat belt is the standard occupant protection system in vehicles and it was implemented to reduce the motion of the occupant in the occurrence of a crash (Kahane, 2015, Schoeneburg et al., 2011). It has been estimated that seat belts saved more than 12,000 lives annually between 2013 and 2017 in the USA, according to NHTSA's National Center for Statistics and Analysis (2019). The shoulder belt should be positioned in the center of the clavicle according to a group of experts that defined proper belt fit for a belt fit intervention study conducted by Buckley et al. (2018). The lap belt should be positioned on the hips where it is in contact with the thighs and it should also be kept as tightly fitted as possible (Buckley et al., 2018). Seat belt routing is essential to safety and to ensure correct loading of the body.

A study by Bohman et al. (2019) indicated that improper seat belt fit is an ongoing issue. The study showed that improper seat belt fit occurs among both the young and elderly participants, although most common among the elderly. Recently, a naturalistic driving study discovered that front seat passengers wear the shoulder belt down on the arm 22% of the time (Reed et al., 2020). Since an improper shoulder belt fit can increase the risk of injury, it is essential to investigate if an improper shoulder belt fit can be corrected into a proper shoulder belt fit to increase occupant safety.

1.1 Background

The electrical pre-pretensioner is a safety system activated in the pre-crash phase with the aim to reduce the injury risk by improving the occupant's seat position (Tobata et al., 2003). The pre-pretensioner retracts the seat belt when an unavoidable crash has been identified or when the driver executes an emergency braking (Fujita et al., 2003). Thereby, the pre-pretensioner can move the occupant to an upright position against the seat back and restrict the occupant's motion (Fujita et al., 2003). Mages et al. (2011) explains that the pre-pretensioner can limit the displacement of the occupant since it activates prior to the accident and thereby increases the effectiveness of the seat belt. The electrical pre-pretensioner is reversible and the retraction mechanism can be used repeatedly (Fujita et al., 2003). The electrical pre-pretensioner is also known as an electrical reversible pretensioner, an electric pretensioner, a motorized shoulder belt tensioner, and a reversible seat belt tensioner, and is henceforth referred to as the pre-pretensioner.

The pre-pretensioner was first launched in 2002 by Mercedes-Benz in a safety system called PRE-SAFE® (Schoeneburg and Breitling, 2005). The aim of the PRE-SAFE® system is to reposition the occupant in the seat during the pre-crash phase and it is activated by the braking behavior of the driver (Schoeneburg and Breitling, 2005). The pre-pretensioner can also be activated by sensors that identify an unavoidable crash situation (Fujita et al., 2003). Schoeneburg et al. (2011) explain that the PRE-SAFE® is activated when the time-to-collision is 1.6 seconds.

The pre-pretensioner has been the focal point of several studies regarding occupant displacement since it was introduced. Fujita et al. (2003) compared the chest displacement in a head-on collision with and without a pre-pretensioner, and the results showed that the displacement was reduced by around 40 mm. Another test with a pre-pretensioner was conducted in a braking scenario with test subjects (Schoeneburg and Breitling, 2005). The results indicated that a vehicle with a pre-pretensioner was able to reduce both head and chest displacement of the occupant when compared to a vehicle without a pre-pretensioner. Mages et al. (2011) also performed studies on occupant displacement, both during an automatic emergency brake as well as during a double lane change event. During the automatic emergency brake scenario, the head and chest displacement were both reduced by around 40% when the pre-pretensioner was activated simultaneously as the automatic emergency breaking compared to a standard belt system without a pre-pretensioner. The double lane change event also showed reduced displacement of the chest and head when the pre-pretensioner was activated.

As described above, the pre-pretensioner has been proven useful in different braking scenarios since it has reduced occupant displacement. Since the study by Reed et al. (2020) indicated that front seat occupants wear the belt down the arm 22% of the time, it is of interest to investigate means to reposition the shoulder belt from an improper shoulder belt fit to a proper. To the best of the authors' knowledge, no study has been conducted on the pre-pretensioner's ability to turn an improper shoulder belt fit into a proper shoulder belt fit. Neither has a corresponding test procedure analyzing belt repositioning been developed. What is yet to be investigated is to what extent the shoulder belt can be repositioned when initially positioned off-shoulder.

1.2 Objectives

The objective of this thesis was to investigate for which positions on the arm a seat belt system, equipped with a pre-pretensioner, could reposition the shoulder belt to an on-clavicle position in a stationary car seat.

The correlating research questions were as follows:

- Does the seat belt installation affect the possibility to reposition the shoulder belt?
- From which levels on the arm can the shoulder belt be repositioned?
- Does upper body characteristics, belt geometry, and belt fit affect the possibility to reposition a shoulder belt?
- Does friction of clothing affect the possibility to reposition the belt?

1.3 Delimitations

The focus of this study was shoulder belt repositioning since the naturalistic driving study by Reed et al. (2020) indicated that front seat occupants more commonly wore the shoulder belt incorrectly down the arm than the lap belt incorrectly on the abdomen. The shoulder belt fit was analyzed in an upright standard seating position with pre-determined seat configurations. The belt repositioning testing was carried out in a stationary test rig, as this was an initial study of shoulder belt repositioning. Sled testing and dynamic testing were therefore excluded since it was considered a possible continuation depending on the thesis' results.

To narrow down and prioritize the parameters, only variations in the fore-aft position and D-ring setting were included in this study. Due to the geometrical boundaries of the test rig several parameters that could affect belt repositioning were kept fixed. These parameters include lap belt attachments and an additional pre-pretensioner. The lap belt attachments consist of the buckle and anchor, which are attached to the seat and therefore kept fixed. A lap belt pre-pretensioner was a possible addition. However, it was expected to mainly affect the lap belt fit, which was outside of the scope of this study, and therefore a lap belt pre-pretensioner was excluded from the study.

1.4 Ethical aspects

The aim of this thesis was to improve vehicle safety, reduce the risk of injuries of occupants who are part of a car crash, and thereby save lives. Society can benefit from the result of this thesis since it is meant to improve the general knowledge of belt repositioning and can increase the understanding of belt repositioning in the research area of vehicle safety. Further research could be conducted on this topic if the thesis discovered that belt repositioning is problematic when the shoulder belt is positioned below the shoulder. The study protocol was reviewed and approved by the Swedish Ethical Review Authority Application 2023-01920-01.

Conducting this study with volunteers was crucial to get authentic, reliable, and trustworthy results that cannot be achieved by performing the same tests on crash test dummies or through simulations. Crash test dummies have a limited variety of shoulder shapes and torso heights, and although simulations can include multiple body shapes the volunteers have more trustworthy responses than the simulations. Volunteers were therefore the most suitable choice for investigating belt repositioning. However, volunteer testing comes with ethical aspects regarding consent and testing.

The main ethical aspect to consider was regarding the volunteers participating in the study since anthropometric measurements, photos, and videos of them were taken. It was important that the volunteers consent to their data being collected and kept for the purpose of this study, and possibly saved for future analysis by employees at Chalmers. Volunteer data was kept on a hard drive which was placed in a safe at Chalmers when the study was completed. Another important ethical aspect was that the volunteers participate by their own volition. All volunteers were informed of what the study would entail before they participated through a document explaining the test procedure and what data would be saved. They were given the option to decline the invitation if they decided they did not want to participate and withdraw at any time throughout the testing.

The testing area where the volunteer study was conducted was made as secluded as possible. Having a secluded testing area was important to ensure the anonymity of the volunteer throughout the study. It also helped keep the volunteers comfortable and ensured that non-authorized personnel did not enter the testing area.

2

Developing test procedure

A literature study was conducted on volunteer studies within the research field of belt repositioning and belt fit. A test method to investigate belt repositioning had to be developed due to the lack of previous studies in the subject. The aim of the literature study was to understand the general setup and the important aspects of a volunteer study. When an understanding of the test procedure and the different aspects had been identified, they were implemented to create the volunteer study developed in this thesis.

Meetings with a project group within the vehicle safety field, part of "Passenger safety to the next level", were conducted with representatives from Autoliv, Volvo, and Chalmers. The input from these meetings provided support in design decisions and helped form the volunteer study. The discussions and input mainly focused on parameter prioritization, how to perform a volunteer study, and standardized anthropometric measurements.

In addition to the literature study and the meetings with the project group, the authors of this thesis participated in a research study in the vehicle and traffic safety field. The research study was conducted by a researcher at Chalmers. The experience was insightful and used as a foundation when developing and carrying out the volunteer study of this thesis.

2.1 Overview of method

In the upcoming sections, the developing process of the volunteer study is presented. During this initial phase the test rig was investigated and necessary changes were made. The parameters influencing belt repositioning were identified and narrowed down by carrying out several different tests in the rig. The parameters were narrowed down to create the test conditions for the volunteer study. The participants in these tests were mainly the authors of this thesis and a few employees at Autoliv. The observations, motivations, and decisions made during the development phase are presented as part of the method since it laid the foundation for the test cases needed for the volunteer study. Based on the findings, the test conditions were assembled and the method of investigating belt repositioning was created. The method consists of incremental steps of shoulder belt repositioning to determine a specific region, called point-of-no-return, from where the belt does not reposition.

In addition to investigating if the belt repositioned or not, several sets of data were collected from both the volunteers and the test rig. The data sets from the volunteers were anthropometric, belt geometry, and belt fit measurements whereas the data from the test rig consisted of belt retraction speed and time. A pilot study was conducted once the parts of the test procedure had been finalized. A summary of the observations made in the pilot study is presented. The next chapter presents a summary of the method developed for the volunteer study, where the final test procedure and test rig instrumentation along with the methods used for the data analysis is presented.

2.2 The test rig

The test rig used to analyze belt repositioning was provided by Autoliv and consisted of a leather car seat (Volvo V60 2012) mounted on a movable aluminum rig, see Figure 2.1. The seat belt seen to the left in the figure was used in this study and it corresponds to a passenger seat in a right-hand traffic vehicle. The figure also depicts the coordinate system used for vehicles, where one H-point was set as origin. In order to relate the fore-aft position between the D-ring and the seat, the H-point was measured out with a SAE H-point mannequin when the seat torso angle was set to 25°. This H-point will be used as a reference throughout the thesis to describe the D-ring attachment relative the seat position. The x-axis is the direction that the car travels, the y-axis is the lateral direction, and the z-axis is the vertical direction. The D-ring attachment is the part which the belt extends from, and it was mounted in the pillar, see Figure 2.2b. The D-ring was attached with a cap screw which it could rotate around. The fore-aft range is the range which the car seat can be moved in the x-direction, see Figure 2.2a.

Figure 2.1: The test rig and the coordinate system, with the origin in one H-point.

Adjustments to the test rig were done for the belt geometry to resemble that of a Volvo S60. The sedan vehicle type represented 41% of the total number vehicles that were included in the naturalistic driving study by Reed et al. (2020). Measurements of the D-ring's position in relation to the tracks of the car seat were taken by manual means from a Volvo S60. The fore-aft position in the test rig was limited by the track length of 205 mm, compared to the 220 mm in the Volvo S60. The same z-axis distance to the D-ring attachment was measured in both the Volvo S60 and the test rig. The distance between the seat track and the D-ring, the y-axis, was similar to the D-ring's position in the Volvo S60. The coordinates relative the H-point at the rearmost position for the B-pillar installation were (-174, -280, 632) mm for the lower end of the D-ring and (-174, -280, 702) mm for the upper end of the D-ring. The most forward position of the seat in the test rig was at (-287, -280, 632) mm for the lower installation and (-287, -280, 702) mm for the upper installation.

(a) B-pillar installation: D-ring range.

(b) Fore-aft range in the test rig.

Figure 2.2: The D-ring range for the B-pillar installation and the fore-aft range in the test rig.

In addition to the B-pillar installation, as seen in Figure 2.1, a mock-up of a belt-in-seat installation could be installed in the test rig. The seat belt installation resembling a belt-in-seat installation was achieved by mounting the D-ring attachment in the beam behind the head rest as shown in Figure 2.3. The coordinates relative to the H-point for the belt-in-seat installations were: (-369, -175, 514) mm and (-345, -175, 514) mm for either end of the webbing, based on an existing belt-in-seat installation. Thereby, the D-ring and fore-aft position is fixed for the belt-in-seat installation. The buckle and anchor of the lap belt were the same for both the B-pillar and belt-in-seat installation.

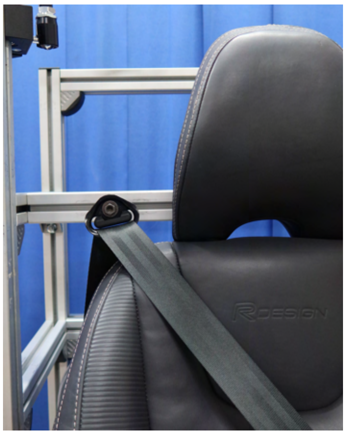


Figure 2.3: The belt-in-seat installation

2.3 Parameters influencing shoulder belt repositioning

To limit the amount tests and pre-pretensioner activations performed on each volunteer in the volunteer study, the parameters influencing belt repositioning were prioritized. These parameters created the basis for the test conditions used in the volunteer study. The seat belt system and the belt retraction components could add up to more degrees of freedom (test setups) than could be tested in a volunteer study. Additional parameters were occupant posture and clothing. A summary of all identified parameters and their respective options and settings that could affect shoulder belt repositioning are found in Table 2.1.

The possibility to determine if shoulder belt repositioning was repeatable was investigated. However, it would mean that the shoulder belt would be retracted in positions where it does not reposition. A shoulder belt that does not reposition causes more discomfort for the volunteer than when it does reposition. Therefore, repeatability testing for volunteers where the belt does not reposition would cause unnecessary strain. Also, to maintain a low amount of belt retractions with the pre-pretensioner the total number of belt retractions was kept as small as possible. To minimize the discomfort and strain for the volunteers and to maintain a low amount belt retractions, repeatability was excluded from the volunteer study.

Table 2.1: The parameters influencing shoulder belt repositioning that were identified along with the available options and settings for each parameter.

Parameter	Options and settings
Belt installation	Two D-ring installations were available, one B-pillar and one belt-in-seat installation.
D-ring height	For the B-pillar installation: There were four available height options of the D-ring. In addition to the height options, the D-ring attachment on the pillar was movable in the y-axis which created more possible D-ring attachment options, see Figure 2.2a. For the belt-in-seat installation: One fixed D-ring height, see Figure 2.3.
Fore-aft position	For the B-pillar installation: The seat was mounted on tracks and could be moved forward and backwards in the test rig, meaning several fore-aft positions were available, see Figure 2.2b. For the belt-in-seat installation: One fore-aft position is set depending on the belt-in-seat configuration.
Seat back angle	The seat back angle could be manually adjusted, creating many options.
Seat height	The height of the seat could be manually adjusted. It simultaneously changes the seat back angle when adjusted.
Occupant clothing	Many different clothing materials could be used: higher friction, lower friction, and bulkier shirts to name a few.
Occupant posture	In addition to a nominal posture, several other volunteer postures could be analyzed. The main identified out-of-position postures in this study were: leaning inboards (towards the center console), leaning outboards (towards the door), and slouching.
Force level of pre-pretensioner	The test rig was equipped with a pre-pretensioner that had the possibility to retract the belt with a force of 250 N and 450 N.
Duration time of pre-pretensioner	The duration time of the pre-pretensioner could be set to any arbitrary time period larger than 600 ms.

2.4 Parameter observations

The parameters in Table 2.1 were investigated and analyzed to determine which parameters to include in the study. The parameters were tested on the authors of this thesis and on a few employees at Autoliv. The observations from this determined what test conditions to include in the volunteer study. A summary of the prioritized and fixed parameters can be found in Section 2.5.

2.4.1 Belt installation

The belt installation was found to be an influential parameter when analyzing belt repositioning. Different B-pillar configurations and belt-in-seat installation were tested. The results showed that the belt installation in combination with the test persons' body characteristics affected belt repositioning. Therefore, both a belt-in-seat and B-pillar installations were included in the volunteer study.

2.4.2 D-ring height

The D-ring position is closely related to the belt installation and is subsequently equally important as a parameter. The D-ring height was tested with all other parameters fixed and the result indicated that the height affects belt repositioning. It was observed that shoulder belt repositioning at the low D-ring height was more difficult compared to the high. Based on these observations, the volunteer study includes belt repositioning for both the low and high D-ring heights. The two extremes were chosen to be analyzed since a larger contrast between the settings would yield a more distinctive difference in belt routing.

For the test procedure, the low D-ring height was decided to be used as a nominal setting since it was identified as most difficult for belt repositioning. One test was used as a reference where both the high and low D-ring position were tested, to validate that the belt repositioned in the high D-ring position as well. The change in D-ring height is only applicable for the B-pillar installation since a singular belt geometry was tested for the belt-in-seat installation.

2.4.3 Fore-aft position

Several fore-aft positions were tested and the findings showed that the further forward from the D-ring attachment the seat was positioned, the more difficult the belt repositioning became. Given these observations, the fore-aft position was found influential to shoulder belt repositioning and was included in the test procedure. For the B-pillar installation, the y-axis distance from the H-point to the D-ring attachment was -280 mm and z-axis distance was 632 mm to the low D-ring and 702 mm to the high D-ring, see Figure 2.1 for coordinate system.

The fore-aft span in the x-axis in the test rig between the D-ring attachment and the H-point range from -174 mm to -387 mm. These values translate to the rearmost position in a Volvo S60 to 93% forward, the shorter track length of the rig limiting the range. The fore-aft positions included in the test were based on the positions that passengers regularly sit. The study by Reed et al. (2020) found that the most common fore-aft position passengers used was between 0% to 50% forward from the aft position. The median seat position in their study was approximately 53 mm forward of the rearmost position, equivalent to 22% of the track length. The corresponding fore-aft position in a Volvo S60 is 48 mm forward of the aft position, adjusted to 49 mm due to the test rig tracks' design. This gives the x-axis coordinate for the 22% forward position of -219 mm.

Determining belt repositioning in the commonly used fore-aft positions is recognized by the authors as more important than less common positions (50% and further ahead). However, less common positions were included to investigate how the fore-aft position affects belt repositioning. Therefore, two additional fore-aft positions were included in the study: 50% and 75%. 50% forward corresponds to -284 mm and 75% to -346 mm in the x-axis distance between the D-ring attachment and the H-point. A visualization of the fore-aft positions is depicted in Figure 2.4, where the fore-aft position for the belt-in-seat installation at 0% forward of the rearmost position is also depicted.

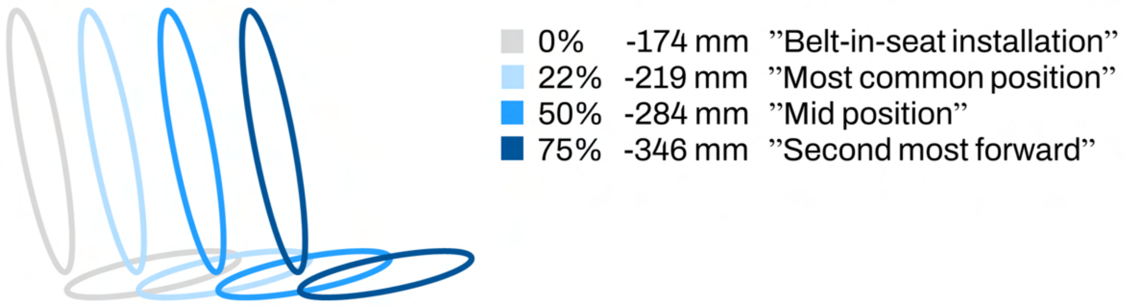


Figure 2.4: A visualization of the car seat at the different fore-aft positions for the preliminary test conditions. The percentages are forward of the rearmost fore-aft position in the test rig, calculated relative the track length of a Volvo S60. The distances in millimeter are given relative the D-ring attachment and the H-point. The final name is a description of its position in the fore-aft range.

2.4.4 Seat back angle

The seat back angle mainly affects the contact point between the passenger and the belt. Increasing the seat back angle increases the distance between the occupant and the belt, thereby making belt repositioning easier. The test rig's seat back angle was therefore kept fixed at 25°, according to the seat torso angle in the Euro European New Car Assessment Programme (NCAP) protocol on mobile progressive deformable barrier collisions from 2023 (2023). The seat back angle was measured together with the H-point with a SAE mannequin.

2.4.5 Seat height

Adjustments of the seat height affects the seat back angle, which as previously mentioned is kept fixed in this study. Changing the seat height created unwanted changes in seat back angle. The seat height was therefore kept fixed at the lowest seat height setting, according to the Euro NCAP protocol from 2023 on mobile progressive deformable barrier collisions (2023).

2.4.6 Occupant clothing

Friction and bulkiness of occupant clothing was identified to potentially influence belt repositioning. Therefore, several clothing options hypothesized to make belt repositioning more difficult were tested: regular long sleeve shirts, a winter coat, knitted sweaters, and a jeans jacket. The findings indicated that clothing affects belt repositioning. The bulkiness of clothing hindered the belt from properly repositioning at times. Reproducing such a hinder and positioning the belt similarly on the arm was problematic. In terms of reproducibility, the difference in cloth sizing and bulkiness was an issue since it is difficult to recreate it similarly for all volunteers. Making belt repositioning more difficult was therefore excluded from this study.

All testing in the volunteer study was going to be conducted with a plain long-sleeved cotton T-shirt. A plain shirt made it easier to position the belt in a similar matter on the arm. In addition to the plain shirt, belt repositioning could be made easier by using a material with a lower friction since making repositioning more difficult was excluded. Using a material with a lower friction was more practical since a thin layer of fabric could easily be placed on the volunteer, see Figure 2.5. It did not interfere with belt positioning on the arm. The material with lower friction was included in the test conditions where belt repositioning failed. The influence that friction has on belt repositioning could therefore be investigated.

Figure 2.5: A photo of how the shoulder was covered with the lower friction material used in the study.

2.4.7 Occupant posture

The postures identified for this study were the nominal posture and out-of-position postures: leaning outboards (towards the door), leaning inboards (towards the center console), and slouching, see Figure 2.6. The nominal posture was identified to have a proper initial belt fit since it allows the belt to reposition to a position across the clavicle, thereby making the posture ideal for this study. The out-of-position postures were not ideal. Leaning inboards did not allow for the belt to be repositioned to an on-clavicle position. Leaning outboards could cause injuries to the volunteers neck when the shoulder belt is retracted and reposition the occupant instead of the belt. Slouching was excluded since it was more relevant when analyzing lap belt fit and since it made the belt repositioning easier. Based on the findings, the nominal posture was the only posture suited for this study. Since the nominal posture was deemed fit for this study the lumbar support was kept in its most retracted position throughout the study.


(a) Nominal posture **(b)** Leaning inboards **(c)** Leaning outboards **(d)** Slouching

Figure 2.6: Belt fit in four postures with B-pillar installation.

2.4.8 Force level of pre-pretensioner

The pre-pretensioner had two activation profiles which retract the belt with 250 N and 450 N respectively. The authors of this thesis decided that a force level of 450 N was too uncomfortable when retracted multiple times during a short period of time whereas the force level of 250 N was more manageable and acceptable to retract several times. In addition to the preferences of the test persons, the functionality of the higher force level was compared to the lower force level. It was investigated if the force level at 450 N could reposition the shoulder belt when the 250 N force level failed. The result showed that this was not the case, meaning the higher force did not reposition the belt better than the lower force. Based on these findings, the 250 N force level was therefore used in the volunteer testing.

2.4.9 Duration time of pre-pretensioner

The shortest possible duration time of the retraction phase of the pre-pretensioner is 600 ms, due to the limits of the pre-pretensioner. Therefore, time periods larger than 600 ms were investigated. The time to reposition the belt was analyzed to determine for how long the pre-pretensioner had to be activated. The duration time had to be long enough to ensure that the belt is able to reposition to an on-clavicle position for all volunteers. In other words, the belt should not stop retracting before the pre-pretensioner has had the chance to reposition the shoulder belt. The duration time was tested, with the force profile of 250 N, in different seat configurations when the belt was placed in different positions on the arm. The findings showed that the belt repositioning time was less than 1 s. Based on these findings, the belt retraction time was set to 2 s to ensure that the possibility that belt retraction time does not affect the belt repositioning outcome.

2.5 Summary of the observations on parameters

A summary of the final option(s) for the parameters that were identified to affect belt repositioning are found in Table 2.2 along with the total number of parameters represented by the octothorp (#) sign. The parameters in the table created the basis for the tests conducted in the volunteer study. As previously mentioned, the D-ring height and fore-aft positions were only adjusted for the B-pillar installation and not for the belt-in-seat installation.

Table 2.2: A summary of the parameters that were prioritized and fixed along with the final option and the total number of parameters (#). Clothing was included for the tests when the belt did not reposition, thereby the (+1) sign.

Parameter	Final option(s)	#
Belt installation	B-pillar and belt-in-seat installation.	2
D-ring height	The high and low D-ring heights according to a Volvo S60 seat configuration for the B-pillar installation whereas the D-ring position was fixed for the belt-in-seat installation.	2
Fore-aft position	The car seat was set at three positions: 22%, 50%, and 75% forward of the rearmost position representative of a Volvo S60 seat configuration for the B-pillar installation. Corresponding to the x-axis position of the D-ring attachment at -219 mm, -284 mm, and -346 mm relative the H-point respectively. Whereas the belt-in-seat installation had a fixed fore-aft position.	2
Seat back angle	Fixed at 25°.	1
Seat height	Fixed at lowest setting.	1

Occupant clothing	Each participant was provided a long-sleeved shirt and additional tests with lower friction was carried out when the belt was not repositioned.	1 (+1)
Occupant posture	The volunteers were asked to sit in a nominal posture.	1
Force level of pre-pretensioner	A force profile of 250 N for the pre-pretensioner.	1
Duration time of pre-pretensioner	A duration time of 2 s for the pre-pretensioner.	1

2.6 Preliminary test conditions

From the summary above, five preliminary test conditions used to investigate the pre-pretensioners ability to reposition the shoulder belt were identified for the volunteer study: a fore-aft position where the D-ring attachment is at -219 mm, -284 mm, and -346 mm relative the H-point in the x-axis respectively (22%, 50%, and 75% forward of the rearmost position), a fourth test with a high D-ring at -284 mm (50% forward of the rearmost position), and a fifth test with a belt-in-seat installation. The test conditions are preliminary since they are to be tested in a pilot study. A summary of the preliminary test conditions is found in Table 2.3, where the belt installation, D-ring height, fore-aft position, and the clothing are specified. For the B-pillar installations the test is complete if the belt is repositioned in the test conditions with the low D-ring. If the low D-ring instead fails to reposition two additional tests are carried out; the first one with lower friction and the second one with a high D-ring. Whereas if the belt repositioning failed for the belt-in-seat installation, the test was repeated with a lower friction material.

Table 2.3: The preliminary test conditions for the volunteer study. The fore-aft position is presented in distance of the D-ring attachment relative the H-point in the x-axis. The test conditions in parenthesis were only conducted if belt repositioning failed in the test with the low D-ring.

Belt installation	D-ring height	Fore-aft position [mm]	Clothing
B-pillar	Low	-219	Cotton shirt
B-pillar	Low	-284	Cotton shirt
B-pillar	High	-284	Cotton shirt
B-pillar	Low	-346	Cotton shirt
(B-pillar)	(Low)	(-346)	(Lower friction)
(B-pillar)	(High)	(-346)	(Cotton shirt)
Belt-in-seat	Fixed	Fixed	Cotton shirt
(Belt-in-seat)	(Fixed)	(Fixed)	(Lower friction)

2.7 Incremental process to find a potential point-of-no-return

To investigate to what extent the pre-pretensioner is able to reposition the belt, the shoulder belt had to be taped with masking tape down on the arm of the volunteer. The aim was to determine if the belt was repositioned or not. If the belt was not repositioned, it was of interest to determine if it got more difficult the further down the arm the belt was positioned and, in that case, determine where the point-of-no-return was. The point-of-no-return being the position furthest down the arm where the belt fails to reposition.

The range down the arm was chosen to be from 5 cm down to 20 cm, in steps of 5 cm as is depicted in Figure 2.8. The distances were measured from the acromion since it could be identified on all volunteers. The acromion was palpated according to the description of its location in (Swedish Standards Institute, 2017), and the acromion's position is depicted in red in Figure 2.7. The maximum distance down the arm was set to 20 cm to ensure that all volunteers could participate in the volunteer study. At around 30 cm down the arm it was also hypothesized that occupants are more likely to place the belt below the elbow or underneath the arm instead, which are cases where the pre-pretensioner cannot improve belt fit. The belt position at 0 cm is henceforth referred to as the reference position.

To investigate belt repositioning, an incremental process was created, see Figure 2.9. The incremental procedure was carried out for each test condition in the volunteer study. A reference belt retraction is performed when the belt is positioned on the shoulder, referred to as 0 cm. The first belt retraction below the shoulder is at 10 cm and if the belt repositioned successfully the next position was 20 cm down the arm. If the belt failed to reposition at 10 or 20 cm, the belt is moved up the arm to 5 cm or 15 cm respectively to identify a potential point-of-no-return.

The shoulder belt was taped with masking tape to the seat when positioned on the arm at all distances from the shoulder. How the belt was fastened using masking tape and how the distance was measured, from the acromion process to the upper edge of the belt, in the B-pillar installation and the belt-in-seat installation is depicted in Figure 2.10 and Figure 2.11, respectively.

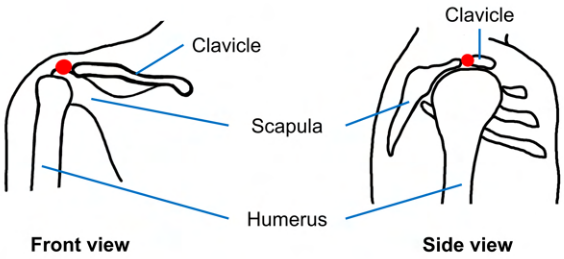


Figure 2.7: The position of the acromion, marked in red, from a frontal and side view of the shoulder.

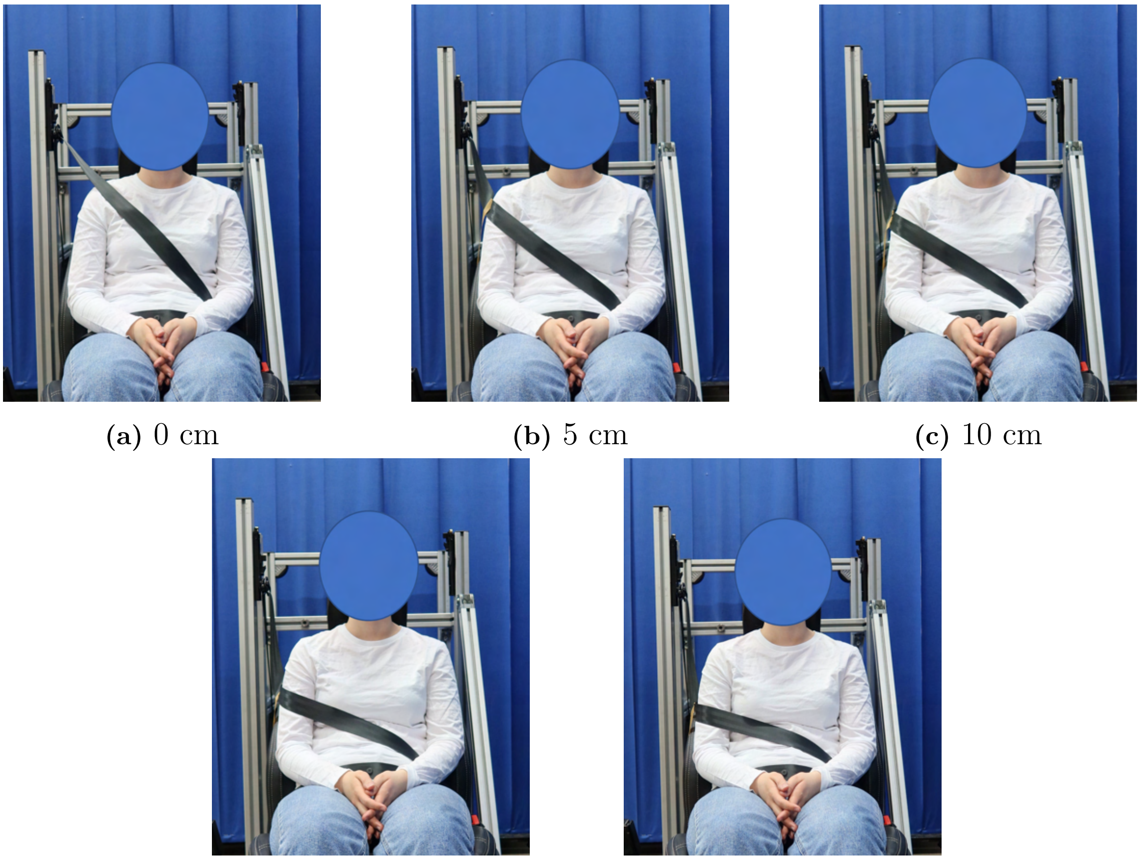

(a) 0 cm **(b)** 5 cm **(c)** 10 cm **(d)** 15 cm **(e)** 20 cm

Figure 2.8: The incremental steps down the arm, measured from the acromion process, with the B-pillar installation.

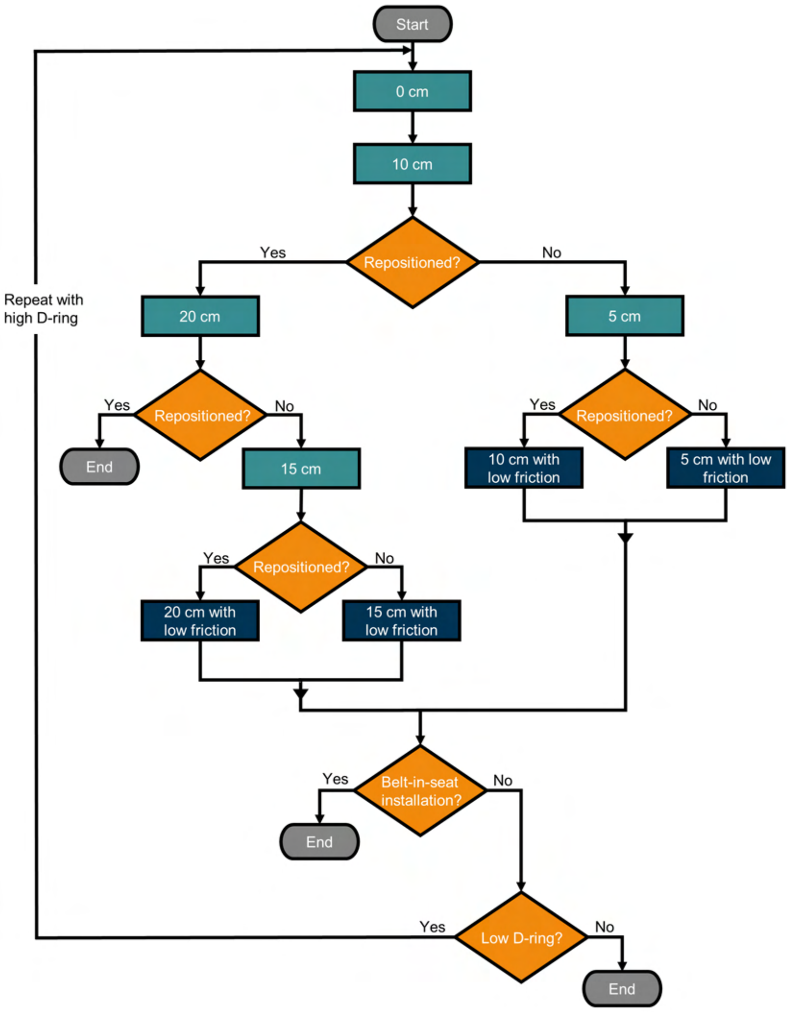
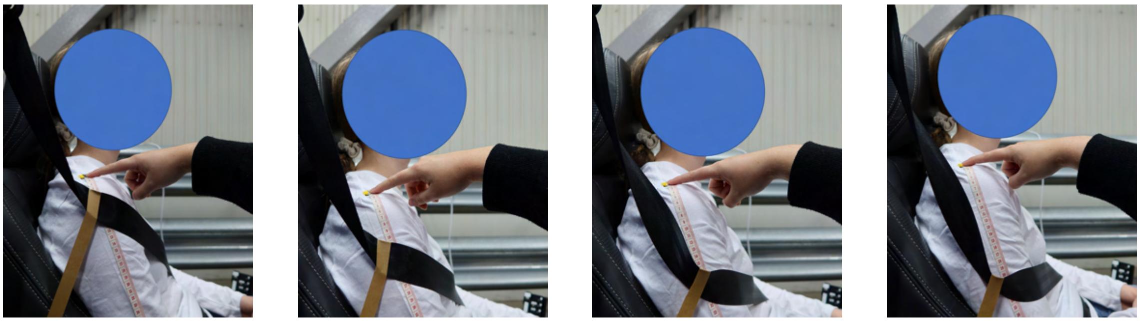


Figure 2.9: A flowchart of the incremental process used to analyze belt repositioning and identify the point-of-no-return if the belt fails to reposition. The blue/green boxes show the distance where the pre-pretensioner was activated. The orange rhombuses show the next step based on the outcome from the green boxes. The dark blue boxes were the last test at the identified point-of-no-return with a material with lower friction.



(a) 5 cm (b) 10 cm (c) 15 cm (d) 20 cm

Figure 2.10: An illustration of how the distances down the arm were measured and fastened using masking tape in the B-pillar installation. The distance was measured from the acromion process to the upper edge of the belt.

(a) 5 cm (b) 10 cm (c) 15 cm (d) 20 cm

Figure 2.11: An illustration of how the distances down the arm were measured and fastened using masking tape in the belt-in-seat installation. The distance was measured from the acromion process to the upper edge of the belt.

2.8 Definition of a repositioned shoulder belt

To determine if the belt was repositioned to an on-clavicle position, a proper and improper shoulder belt fit had to be defined. A proper and improper belt fit has been defined in two studies on belt fit, by Fong et al. (2016) and Bohman et al. (2019). Both studies had to identify and classify belt fit, the former for elderly volunteers and the latter for younger as well as elderly volunteers. Both studies had a similar approach when defining proper and improper belt fit. Fong et al. classified a proper and improper belt fit in regard to the belts' intended loading regions. Both studies classified a proper belt fit as having the shoulder belt in the center area of the shoulder and the lap belt having contact with the thigh. An improper belt fit was in both cases classified as when the shoulder belt was touching the neck, placed on the outer edge of the shoulder, or off the shoulder. In addition to the belt's position on the shoulder, the shoulder belt's position on the abdomen is also mentioned by Bohman et al. (2019).

Based on the two studies on belt fit, the belt was defined as repositioned if the shoulder belt was medial of the acromion process and improper if the shoulder belt was lateral of the acromion process. The shoulder belt position across the torso, especially the belt routing on the abdomen, was considered repositioned if it crossed the sternum similarly as in the reference position. If the shoulder belt crossed the acromion process in the reference position, the seat belt was considered repositioned if it reached the reference position.

2.9 Data collection

Measurements that were of interest for this study were anthropometric, belt geometry, and belt fit measurements. Additional measurements: retracted belt webbing, belt retraction time, and belt repositioning time, were recorded for future research purposes. The criteria to record and collect certain sets of data and the recording method for this study depended on the efficiency of respective data collecting method and to what extent that the belt interfered with the retraction results. The criteria were not met when shoulder belt force measurements were explored. Shoulder belt force measurements were excluded due to the weight of the sensor since the weight could affect the belt angle from the D-ring to the shoulder and thereby influence belt retraction. More detailed information about the included data sets is presented below.

2.9.1 Anthropometric measurements

Anthropometric measurements, in addition to age and sex, of the volunteer were taken to analyze if specific upper body characteristics were related to shoulder belt repositioning. The majority of the measurements and the corresponding procedure to take the measurements were according to SS-EN ISO 7250-1:2017, Swedish standard institute (2017). Shoulder circumference and shoulder length were not standard measurements, they were defined and taken according to the procedure presented by Hotzman el al. (2011). Elbow-to-elbow breadth is the distance between the elbows when the arms are held out in 90°. A summary of the anthropometric measurements and the equipment to take the measurement is found in Table 2.4, where the two calipers used are depicted in Figure 2.12.

Table 2.4: The anthropometric measurements measured of all volunteers that could be connected with belt repositioning

Posture	Measurements	Equipment
Standing up	Stature	Measuring tape on wall
	Weight	Scale
	Wall-acromion distance	Caliper
	Chest depth	Wooden caliper
	Chest breadth	Caliper
	Chest circumference	Measuring tape
	Waist circumference	Measuring tape
	Shoulder circumference	Measuring tape
	Shoulder length	Measuring tape
Sitting down	Sitting height	Measuring tape on wall
	Shoulder height (sitting)	Wooden caliper
	Shoulder-elbow length	Caliper
	Shoulder (biacromial) breadth	Caliper
	Shoulder (bideltoid) breadth	Caliper
	Elbow-to-elbow breadth	Caliper
	Hip breadth	Caliper
	Abdominal depth	Caliper
	Thorax depth	Caliper

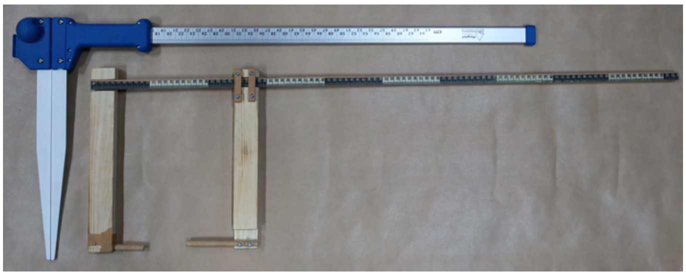


Figure 2.12: The caliper and the wooden caliper with spikes, both used to measure anthropometric measurements.

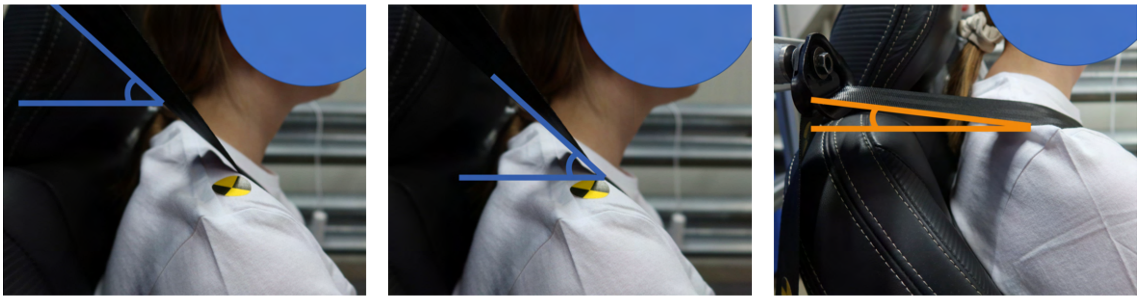
2.9.2 Belt geometry and belt fit measurements

Belt geometry and belt fit data was hypothesized to influence shoulder belt repositioning, especially since belt repositioning was observed to be more difficult with a belt-in-seat installation compared to a B-pillar installation. Based on this finding, more data regarding belt wrapping was determined to be included in the study. Wrapping is defined as how the belt encloses the shoulder. In total, six measurements were taken at the reference position for each of the test conditions in Table 2.3. Three measurements are related to belt geometry and three related to belt fit, one of which is wrapping. In total, six measurements were taken in the reference position for the B-pillar installation and five in the belt-in-seat installation.

2.9.2.1 Belt geometry angles

The first belt geometry angle was taken where the belt extends from the D-ring. The second angle was taken where the belt first was in contact with the volunteer. Both these angles were measured from the XY-plane with a digital protractor. The angles are henceforth referred to as the D-ring angle and the contact angle, respectively. The D-ring and contact angle were measured for the B-pillar installation. For the belt-in-seat installation the D-ring and contact angle are a combined angle since the D-ring and contact point are at the same place. The D-ring and contact angles for respective belt installation are depicted in Figure 2.13.

Figure 2.14 depicts the third belt geometry angle, in the XY-plane, and how it was measured in the two belt installations. It was measured with a L-square ruler and protractor. The L-square ruler was held horizontally against a flat surface on the test rig and the ruler at the end of the protractor was held against the outer edge of the seat belt. The angle was measured on the left side on the protractor.



(a) B-pillar installation: D-ring angle

(b) B-pillar installation: contact angle

(c) Belt-in-seat installation: D-ring angle

(d) How the angle in Figure 2.13a was measured

(e) How the angle in Figure 2.13b was measured

(f) How the angle in Figure 2.13c was measured

Figure 2.13: Illustration of the belt geometry angles and how they were measured using the digital protractor. The angle is presented in the first three figures and the corresponding measurement method in the three below.

(a) B-pillar installation: belt angle in XY-plane.

(b) How the angle in Figure 2.14a was measured.

(c) Belt-in-seat installation: belt angle in XY-plane.

(d) How the angle in Figure 2.14c was measured

Figure 2.14: An illustration of the measured belt angle in the XY-plane and how it was measured in both belt belt installations.

2.9.2.2 Belt fit distances

Reed et al. (2013) and Bohman et al. (2019) both conducted studies using volunteers where they took measurements to investigate belt fit. The belt fit measurements were taken between the suprasternal notch and the shoulder belt, where Reed et al. (2013) measured it horizontally (y-axis) and Bohman et al. (2019) vertically (z-axis). The vertical belt and horizontal belt fit measurements and how they were taken with a measuring taped to the edge of the belt are depicted in Figure 2.15.

(a) The vertical and horizontal belt distance.

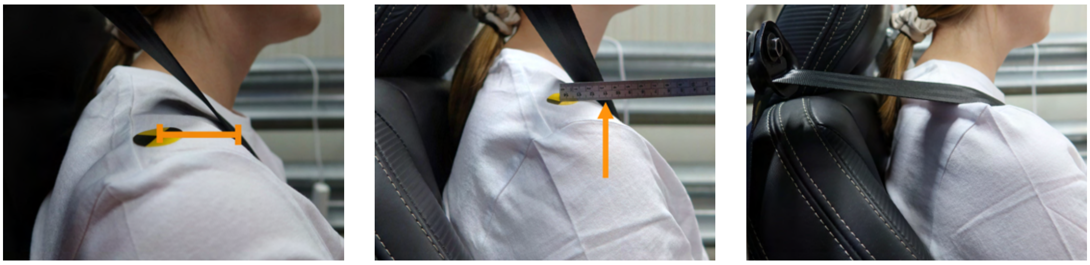
(b) How the vertical belt distance was taken.

(c) How the horizontal belt distance was taken.

Figure 2.15: Illustration of the two belt fit measurements, vertical belt distance and horizontal belt distance, and how they were measured between the suprasternal notch to the edge of the belt.

2.9.2.3 Belt wrapping distances

The belt wrapping distance in the x-axis between the acromion and the outer edge of the belt was measured for the B-pillar and belt-in-seat installation. The belt wrapping distance is depicted in Figure 2.16 for the two installations. The wrapping was 0 cm in Figure 2.16c since there is no distance between the acromion process and the belt, which indicates a high degree of wrapping.



(a) The belt wrapping distance with a B-pillar installation.

(b) How the belt wrapping distance was measured.

(c) The belt wrapping distance with a belt-in-seat installation.

Figure 2.16: The belt wrapping distance in the x-axis, from the acromion process to the outboard edge of the belt and how it was measured for the B-pillar installation. The wrapping distance is not measured if the belt covers the acromion process for the belt-in-seat installation.

2.9.3 Retracted belt webbing and retraction time

The retracted webbing and the belt retraction time provides an indication of the amount of belt slack and how much belt has to be retracted to reach a proper belt fit for occupants with different body characteristics. Several attempts at measuring the retracted webbing were tested, by optic devices, video, and software. The optical approach required a tape to be placed on the belt and this tape would interfere with the D-ring when the belt is retracted. The video approach required photo markers to be positioned on the belt which would have to be done for each volunteer, and thereafter use a software program to analyze the data. This option was excluded due to the large number of volunteers participating which led to large quantities of data. The most efficient method was to measure the retracted webbing using the software CANalyzer, which is used to activate the pre-pretensioner. The belt retraction velocity is recorded, logged, and integrated to obtain the retracted webbing length. The software CANalyzer was found to be the most efficient solution since retracted webbing could easily be recorded during the volunteer study.

2.10 Pilot study

When the different parts of the test procedure described above in this chapter had been decided upon, they were all tested in a pilot study where four individuals participated. Conducting pilot studies is vital since it can help identify and pinpoint the most suitable test procedure, according to Teijlingen and Hundley (2002). They mention that adjustments can be made to the equipment needed for the study and that a research protocol can be established which in turn reveals potential issues with the test procedure. A pilot study was therefore conducted to identify and solve potential problems with the test procedure and protocol at an early stage. The pilot was not only necessary to implement changes to the test procedure, but also to learn and get a routine as to how to conduct the entire test procedure similarly for all volunteers.

2.10.1 Evaluation of the pilot study

The major observation in the pilot study was regarding the belt installations. The result from the pilot study indicated that a belt-in-seat installation could be difficult to reposition since the belt did not reposition for two of the four participants. The findings regarding the B-pillar installation showed that the belt repositioned for all participants at the four test conditions when the D-ring attachment was at -219 mm, -284 mm, and -346 mm relative the H-point. Where -284 mm also was conducted with a high D-ring. Although the result for the B-pillar installation was promising in terms of vehicle safety, a possible connection between anthropometric measurements, belt geometry angles, and belt fit measurements could not be identified if the belt always repositioned. Therefore, an additional test condition was created with the expectation that the belt would not reposition for some participants. The added test case was the most forward position available in the test rig, with a fore-aft position 93% forward of the rearmost position in a Volvo S60. The fore-aft position can also be described as when the D-ring attachment was at -387 mm relative the H-point in the x-axis. It was anticipated that more data regarding failed belt repositioning could be gathered by adding this test case, which was hypothesized to bring light to the relevant data sets affecting belt repositioning. Since one test condition was added, it would affect the total amount of belt retractions. However, the findings regarding the test procedure indicated that the number of extra tests are relatively low and the full test procedure was judged to fit within a reasonable time frame.

3

Methods for volunteer study

The overall structure and implementation of the developed test procedure for the volunteer study for this thesis is presented below. First the volunteer sample is presented and then the final test conditions that were adjusted after the pilot study. Thereafter the test rig instrumentation and the test procedure used during the volunteer study is described. The last section presents the methods used for the data analysis.

3.1 The volunteers

The aim was to recruit around 40 volunteers. The volunteers were recruited through advertisement at Autoliv and several were also approached and asked if they would like to participate. Most volunteers therefore had a background within vehicle safety. In addition to the volunteers from Autoliv, some female students were recruited which was needed to have equally many males and females participants in the study. The students were provided with a gift card of 200 SEK each for their contribution.

All volunteers were informed that the study was voluntary and that they did not have to participate. They were informed that they could decline the meeting invitation if they did not want to participate after reading the document explaining the test procedure. Ensuring that the approach and recruited individuals wanted to participate and did not feel pressured was essential. All volunteers needed to fulfill certain medical requirements, where individuals with previous or current pain in upper body regions could not participate.

Recruitment was mainly performed at Autoliv, which resulted in a convenience sample since the volunteers are chosen since they are easily accessible according to MacFarlane et al. (2014). Few volunteers were approached based on body characteristics, known as purposeful samples (MacFarlane et al., 2014). Specific volunteers are then chosen based on wanting to obtain a certain set of data. Using these samples was necessary to save time and to investigate if failed belt repositioning is more common among certain body characteristics.

3.1.1 Volunteer distribution

If the anthropometric measurements of the sample of volunteers is normally distributed according to the Swedish population, the result can be generalized for the Swedish population. A normal distribution is likely to be achieved if more than 30 volunteers participate, where fifteen or more are males and fifteen or more are females. Within each sex, the volunteer measurements should be equally divided in the three percentile groups: 0^{th} - 33^{th}, 33^{th} - 66^{th}, and 66^{th} - 100^{th}. One anthropometric measurement from each dimension: height, depth, and breadth, were used to determine if the two groups were normally distributed. Sitting height, chest depth, and shoulder bideltoid breadth, were hypothesized to affect belt repositioning the most. Table 3.1 shows the threshold measurements for each percentile and the corresponding value from the Swedish population for both males and females. The measurement from the percentiles from the Swedish population were collected from Antropometri.se, which uses data collected from the Swedish population by Hanson et al. (2009).

Table 3.1: Three percentile ranges with the corresponding measurement for three anthropometric measurements defining the Swedish population. All measurements are given in millimeter.

	Measurement	Percentile groups		
		$<33^{th}$	33^{th} - 66^{th}	$>66^{th}$
Males	Sitting height	928.15	928.15 - 959.17	959.17
	Chest depth	234.95	234.95 - 260.99	260.99
	Shoulder bideltoid breadth	464.63	464.63 - 487.50	487.50
Females	Sitting height	876.76	876.76 - 906.46	906.46
	Chest depth	222.08	222.08 - 253.23	253.23
	Shoulder bideltoid breadth	414.55	414.55 - 434.14	434.14

3.2 Final test conditions for volunteer study

The final test conditions that were implemented in the volunteer study are presented in Table 3.2. The difference compared to the preliminary test conditions presented in Section 2.6 in Table 2.3 is the additional test at the most forward position in the test rig, at -387 mm in the x-axis, which was added after the pilot study. The distances of the D-ring attachment at -219 mm, -284 mm, -346 mm, and -387 mm relative the D-ring is also referred to as 22%, 50%, 75%, and 93% respectively. Also, as the most common seating position, the mid position, the second most forward position, and the most forward position in the test rig. The belt-in-seat installation is in the most rearward position, at 0%. An overview of the fore-aft positions and the corresponding denotations are found in Figure 3.1.

Table 3.2: The final tests for the volunteer study. The fore-aft position is presented in the x-axis distance of the D-ring attachment relative the H-point. The test conditions in parenthesis were only conducted if belt repositioning failed in the test with the low D-ring.

Belt installation	D-ring height	Fore-aft position [mm]	Clothing
B-pillar	Low	-219	Cotton shirt
B-pillar	Low	-284	Cotton shirt
B-pillar	High	-284	Cotton shirt
B-pillar	Low	-346	Cotton shirt
(B-pillar)	(Low)	(-346)	(Lower friction)
(B-pillar)	(High)	(-346)	(Cotton shirt)
B-pillar	Low	-387	Cotton shirt
(B-pillar)	(Low)	(-387)	(Lower friction)
(B-pillar)	(High)	(-387)	Cotton shirt
Belt-in-seat	Fixed	Fixed	Cotton shirt
(Belt-in-seat)	(Fixed)	(Fixed)	(Lower friction)

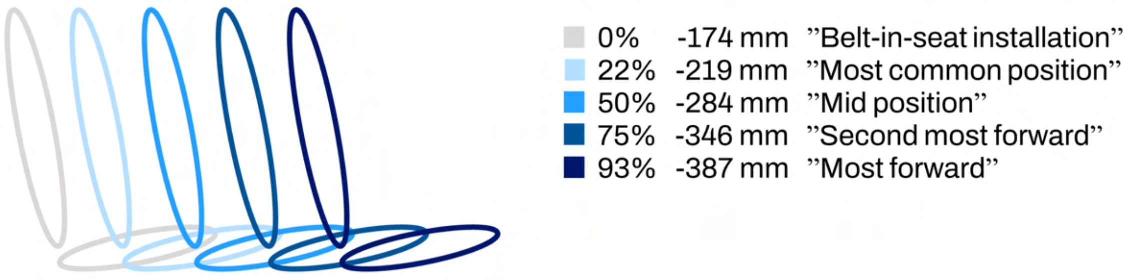


Figure 3.1: A visualization of the car seat at the different fore-aft positions for the test conditions. The percentages are forward of the rearmost fore-aft position in the test rig, calculated relative the track length of a Volvo S60. The distances in millimeter are given relative the D-ring attachment and the H-point. The final name is a description of its position in the fore-aft range.

3.3 Test rig instrumentation

Two GoPro Hero 11 cameras were used to record the belt retraction for all volunteers. One GoPro was positioned on a tripod and recorded the volunteer and the belt retraction from the front, see Figure 3.2a. The frame rate was set to 240 and standard linear field of view setting with no additional zoom was used. The video recorded by the front camera was used to observe the belt fit of the volunteer after the testing had been conducted. The second GoPro was mounted on the test rig and recorded the belt retraction at the spool, where the photo markers were positioned to record the motion of the belt, see Figure 3.2b. The video recorded by the second camera recorded the belt from behind the seat and could be analyzed in the future to investigate the time for the belt to move from an on-arm position to an on-clavicle position. In addition to the GoPro instrumentation, a box was placed in front of the test rig to raise the feet to resemble the foot position in a car.

(a) Front view camera **(b)** Back view camera

Figure 3.2: Placement of the two Gopro cameras.

3.4 The test procedure

The test procedure includes all steps that were conducted when the volunteer was present at the testing area. The test procedure was carried out by two test leaders. One test leader instructed, took the anthropometric measurements, and performed the belt repositioning test conditions. The second test leader documented the anthropometric data, filled in the test protocol, and was main responsible for activating the pre-pretensioner. The entire test procedure lasted around one hour, starting from the moment the volunteer arrived until they left. Preparing, instrumentation, and taking anthropometric measurements of the volunteer took around 25 minutes. The volunteer was seated in the test rig for around 25 to 30 minutes.

3.4.1 Volunteer preparation, instrumentation, and data collection

First, the volunteer was asked to sign a form giving consent to participation, including data collection, video recording, and storing. All information was provided before the testing and was kept available at the testing area. More in-depth information regarding the pre-pretensioner and the functionality was given to the volunteer if desired.

The volunteer was prepared for the study by being asked to change into the assigned shirt. The volunteer was asked to remove their shoes in preparation for the anthropometric measurements. An adjustable necklace was placed on the volunteer which marked the neck region. The acromion processes and the suprasternal notch were palpated and marked with photo markers on the shirt respectively the skin. After the volunteer had been prepared, photos from the front and one from the side were taken while the volunteer was seated and standing, see Figure 3.3, with a Canon PowerShot G7 X Mark III camera. The area and setup where the photos were taken while seated and standing are depicted in Figure 3.3b and Figure 3.3c.

(a) Seated front **(b)** Standing front **(c)** Seated side **(d)** Standing side

Figure 3.3: The photos taken of each volunteer.

The anthropometric measurements were taken and noted in Excel. The area where anthropometric measurements were taken is seen in Figure 3.4. A measuring tape was fixed along the edge of the room divider, see Figure 3.4a, which the volunteer had their back against to measure stature. The white foam could be moved along the edge to be positioned at the top of the head. On top of the white foam was a small spirit level to ensure a horizontal angle. To measure sitting height, the stool with a height of 470 mm and foot support (piece of foam) seen in Figure 3.4c, were positioned in front of the fixed measuring tape.

When all measurements had been taken the volunteer was seated in the test rig. The seat belt was buckled by the volunteer and adjusted if needed, for example if the lap belt was not placed over the pelvic bones. The volunteer was given several instructions on how to sit. They were asked to sit as far back as possible with their back close to the backrest. They were told to keep their hands on their lap. They were informed to sit as similarly as possible throughout the tests to remain consistent throughout the different tests. The volunteer was instructed to fully extend the seat belt after each time the pre-pretensioner was activated. If the belt was not extended during the volunteer study it could also affect the recorded data by the software CANanalyzer, hence the belt speed and retracted webbing. The test leaders thereafter explained the test procedure and the belt repositioning test conditions, see Table 2.3, that were to be performed.

(a) Setup to measure stature and sitting height

(b) Setup to take photos and measurements while standing

(c) Setup to take photos measurements while seated

Figure 3.4: Testing area setup to take anthropometric measurements and photos.

3.4.2 Conducting test procedure

The tests were performed in a randomized order. If the tests began with a B-pillar installation, all tests with that installation was performed before switching to the belt-in-seat installation and vice versa. This was done to remain efficient while conducting the volunteer study. The tests were performed according to the test procedure presented in the flowchart in Figure 2.9. The belt installation, seat position, D-ring height, clothing, and a comment section along with the six additional measurements: three belt geometry and three belt fit, were also noted for each test condition.

Before the belt was retracted in the reference belt position, the three belt geometry and three belt routing measurements were taken, in all test conditions. When the belt was positioned down the arm, at either 5 cm, 10 cm, 15 cm, or 20 cm, it was observed if the belt would sit in the position without being taped or if the belt was retracted to the reference position. It was observed if it would sit by itself since it was hypothesized that a belt that stay by itself is less likely to reposition. The belt was taped for all volunteers regardless of its ability to sit by itself. The tape was torn before each test so that it would break when the belt was retracted. A visual observation was made by the test leaders to determine if the belt was repositioned or not, according to the set definition of repositioned shoulder belt. Belt repositioning was determined with a binary response, repositioned or not repostioned. If there were any uncertainties regarding belt repositioning, a note was made in the test protocol to check belt repositioning in the video recording afterwards. However, a decision on belt repositioning was made on-scene to continue testing according to the increment procedure, see Figure 2.9. The test could also be repeated if it was difficult to determine if the belt repositioned or not.

3.5 Data analysis

To investigate what caused the belt to reposition for some volunteers but not for others, the collected data was analyzed using statistical methods. The collected data include the anthropometric, belt geometry, and belt fit measurements. First, a two sample t-test was conducted to compare the anthropometric, belt geometry, and belt fit measurements in the group of volunteers where belt repositioning was possible to the group where repositioning was not possible. All collected measurements were tested at each seat condition where belt repositioning failed. The aim of the t-test was to determine if there was a statistical difference in mean values between the two groups, repositioned or not repositioned. If a statistical difference between the groups would be identified, then there would be an indication that a certain measurement is linked with the belt repositioning outcome.

3.5.1 Statistical significance by two sample t-test with Bonferroni correction

The two sample t-test was conducted using MATLAB (Inc., 2019a) with the function *ttest2* from the Statistics and Machine Learning Toolbox (2019b). The method to conduct a two sample t-test described is described below and it was derived from Peck et al. (2008) unless otherwise specified. The implemented method assumes unequal variance since if a two sample t-test is conducted when the variance is not equal it could affect the p-values (Peck et al., 2008).

Before a two sample t-test could be conducted the data within each group, repositioned and not repositioned, need to fulfill certain requirements. Within each of the two groups the data should be independent, randomly sampled, and normally distributed. The collected measurements are independently collected but the randomness is limited since the volunteers were from a convenience sample. Normal distribution is usually achieved by having more than 30 samples and the total amount of volunteers in the study was aimed to be around 40. A two sample t-test was deemed fit for this analysis since it would provide indications and show tendencies if the collected measurements affect the pre-pretensioners ability to reposition the belt. It was assumed that the data was normally distributed and quantile-quantile plots were used to check for normality.

Table 3.3 shows the denotations that are used when conducting a two sample t-test. It presents the population mean, sample mean, variance, standard deviation (SD), and sample size. The table refers to the denotations for each group, repositioned (yes) and not repositioned (no).

Table 3.3: The denotations for sample mean, variance, standard deviation, and the sample size.

Group	Population	Sample			
	Mean	Mean	Variance	SD	Sample size
Repositioned	μ_{yes}	$\overline{x}_{yes}$	s^2_{yes}	s_{yes}	n_{yes}
Not repositioned	μ_{no}	$\overline{x}_{no}$	s^2_{no}	s_{no}	n_{no}

The population means, μ_{yes} and μ_{no}, is the average value of each population and it is used to set the null hypothesis. The sample mean is the one calculated from the data collected from the volunteers and it was given by

$$\overline{x} = \frac{\Sigma_{i=1}^{n} x}{n} \tag{3.1}$$

where the collected measurement x is x_{yes} or x_{no}, and the corresponding sample size was n_{yes} or n_{no}.

The sample variance, s^2, for each group was found by

$$s^2 = \frac{\Sigma(x - \overline{x})^2}{n - 1} \tag{3.2}$$

where the collected measurement x is x_{yes} or x_{no}, and the sample mean is $\overline{x}$ is $\overline{x}_{yes}$ or $\overline{x}_{no}$.

To investigate statistical significance, the null hypothesis, H_0, was set to

$$H_0 : \mu_{yes} = \mu_{no} \tag{3.3}$$

and alternative hypothesis, H_1, was set to

$$H_1 : \mu_{yes} \neq \mu_{no} \tag{3.4}$$

for all collected measurements. The null hypothesis states there is no difference between the means of the two groups. If the null hypothesis is rejected, the alternative hypothesis is accepted, meaning there is not a statistical difference between the two mean values. If rejected, the result would therefore indicate a possible connection between the specific collected measurement(s) and belt repositioning.

A significance level, α, was used to determine if the null hypothesis should be rejected or not. The significance level was set to 0.05. This significance level mean there is a 5% chance that a correct null hypothesis will be rejected. Collecting and performing two sample t tests on large quantities of data sets is called ”fishing”, which according to Rice (2007) means that it increases the chance that you incorrectly reject a null hypothesis. Rice mentions that a fishing study can be viewed as a step that is performed to provide recommendations for future research. A Bonferroni correction was also implemented to the significance level to compensate for the large amount of collected measurements that were analyzed. If not implemented it is more likely that a null hypothesis is incorrectly rejected when more measurements are analyzed (Rice, 2007). The correction was implemented by adjusting the size of α in regard to the total amount of collected measurements, denoted by k. The Bonferroni corrected significance value, α_B, is therefore given by

$$\alpha_B = \frac{\alpha}{k} \tag{3.5}$$

where k is the amount of collected measurements (Rice, 2007). The corresponding amount of collected measurements, k, in the study include the anthropometric, belt geometry, and belt fit measurements.

Once the sample mean, sample variance, and sample, the null hypothesis, and significance level are known, the test statistic t and the degrees of freedom (df) could be calculated. The t-value and df are needed to find the corresponding p-value. The test statistic t was calculated by

$$t = \frac{\overline{x}_1 - \overline{x}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} \tag{3.6}$$

with the corresponding df given by

$$df = \frac{(V_{yes} + V_{no})^2}{\frac{V_{yes}^2}{n_{yes}-1} + \frac{V_{no}^2}{n_{no}-1}} \tag{3.7}$$

where V_{yes} was replaced by $\frac{s_{yes}^2}{n_{yes}}$ and V_{no} by $\frac{s_{no}^2}{n_{no}}$. The p-value is obtained through the software program, but it can also be obtained through a table by using the calculated t-value and df. If the p-value from the software program/table was less than the significance level, p-value $< H_0$, the null hypothesis was rejected and the alternative hypothesis was accepted.

3.5.2 Binary logistic regression

The software program IBM SPSS Statistics (IBM Corp., 2021) was used to perform binary logistic regression using the *Binary Logistic Regression* function. The following description was implemented from Fritz and Berger (2015). Binary logistic regression is a method that creates and fit a model according to a collected measurement. Binary logistic regression was a suitable method for the data collected in this study since the belt repositioning outcome was binary, the belt had either repositioned or it had not repositioned, and since anthropometric, belt geometry or belt fit data had been collected from all volunteers. Thereby, it could be used to predict the probability if the belt will reposition for an individual if their measurement is known. Binary logistic regression was implemented for the measurements that showed potential from the t-test results in predicting if the belt would reposition or not reposition.

The logistic regression for one independent variable (one of the collected measurements) was given by

$$Y = \beta_0 + \beta_1 \cdot X_1 \tag{3.8}$$

where Y is given by either 1 or 0, which represents the binary repositioning outcome, repositioned or not repositioned. The β_0 is the intercept with the y-axis and β_1 is the slope. The collected measurement is given by X_1. If the number of independent variables is two (two of the collected measurements) the logistic regression was given by

$$Y = \beta_0 + \beta_1 \cdot X_1 + \beta_2 \cdot X_2 \tag{3.9}$$

where X_2 is the data from the second measurement and β_1 is the corresponding slope. The β_0, β_1, and β_2 in the expressions (3.8) and (3.9) are found by using the software program IBM SPSS Statistics. The binary repositioning outcome, repositioned or not repositioned, and the collected measurement(s) was used as input. Once the variables β_0, β_1, and β_2 (if two independent variables were used) were set, the final probability curve could be set up. The variables were used as input in the expression given by

$$Y = \frac{e^{(\beta_0 + \beta_1 \cdot X_1)}}{1 + e^{(\beta_0 + \beta_1 \cdot X_1)}} \tag{3.10}$$

and by

$$Y = \frac{e^{(\beta_0 + \beta_1 \cdot X_1 + \beta_2 \cdot X_2)}}{1 + e^{(\beta_0 + \beta_1 \cdot X_1 + \beta_2 \cdot X_2)}} \tag{3.11}$$

if two measurements were implemented. These were the final probability curves used to investigate how well the model fits to the data. How well the model fit the data was tested in SPSS by using the Hosmer and Lemeshow goodness-of-fit test.

4

Results

The result is presented in five sections. First the volunteers that participated in the study and their anthropometric measurements are presented. Then overviews of the results from the B-pillar installation and the belt-in-seat installation are given. A more in-depth analysis follows, focusing on what causes the belt to reposition or not reposition in the different seat configurations. The analysis investigates if anthropometric measurements, belt geometry, and belt fit can be linked to belt repositioning. In the result section, not all data that were recorded during the volunteer study is presented. Additional data, such as the retracted belt webbing and belt retraction time, were recorded and could be used for future research purposes in the subject of belt repositioning.

All test conditions, see Table 3.2, mentioned below are referred to by their fore-aft position where they are given as the distance between the D-ring attachment and H-point in x-direction, the H-point being the one presented in Section 2.2. The fore-aft positions for the B-pillar installation are therefore at -219 mm, -284 mm, -346 mm, and -387 mm, and the belt-in-seat installation at -369 mm. The test conditions are also referred to by their fore-aft position in the test rig as the most common seat position, the middle, the second foremost, and the foremost position respectively. Whereas the belt-in-seat installation is referred to by its name. Throughout the result section, males and females are represented in blue and orange respectively. A more opaque nuance of blue and orange in the figures indicate two or more data points overlapping from several volunteers having similar data values.

4.1 Volunteers

In total, 37 volunteers participated in the volunteer study, 19 males and 18 females. Two males were excluded from the study. Their data is not presented as part of the result. In the end, the data collected from 35 volunteers, 17 males and 18 females, were included in the data analysis.

Table 4.1 shows the distribution of volunteers, males and females separately, divided into three percentile groups based on the anthropometric measurements of the Swedish population. Three chosen measurements are compared, corresponding to height, width, and depth of the upper body: sitting height, shoulder (bideltoid) breadth, and chest depth. The volunteers are divided into the percentile groups based on their individual measurements. An overview of the volunteer group's measurements is presented in Table 3.1. Since the distribution of the volunteers is not equal between the groups, the volunteers are not normally distributed for any of the three dimensions. Therefore, the result from this study cannot be generalized to the Swedish population. The result is only representative of the sample collected in this volunteer study. The anthropometric measurements of the volunteers is found in Appendix A. A summary of the mean, standard deviation, minimum, and maximum value of the volunteers' anthropometric measurements is found in Appendix B.

Table 4.1: The number of volunteers that fit into the three percentile ranges for three anthropometric measurements presented in Section 3.1.1 of the Swedish population.

	Measurement	Percentile groups		
		<33th	33th - 66th	>66th
Males	Sitting height	7	3	7
	Chest depth	5	8	4
	Shoulder bideltoid breadth	1	7	9
Females	Sitting height	5	9	4
	Chest depth	17	1	0
	Shoulder bideltoid breadth	2	5	11

4.2 Shoulder belt repositioning in the B-pillar installation

Shoulder belt repositioning at the different fore-aft positions is depicted in Figure 4.1. The shoulder belt repositioned for all volunteers in the most common seating position and in the mid position, when the x-axis position of the D-ring attachment was -219 mm and -284 mm relative the H-point. At the seat position -346 mm and forward, belt repositioning started failing. The belt did not reposition for 5.7% of the volunteers, corresponding to two volunteers. That corresponds to 5.9% of the males and 5.6% of the females. Whereas at -387 mm, the belt failed to reposition for 20% of the volunteers, a total of 7 volunteers. It failed to reposition for 23.5% of the males and 16.7% of females, corresponding to four males and three females. Images of the volunteers that the belt did not reposition for at -346 mm is found in Appendix C and the corresponding images at -387 mm is found in Appendix D.

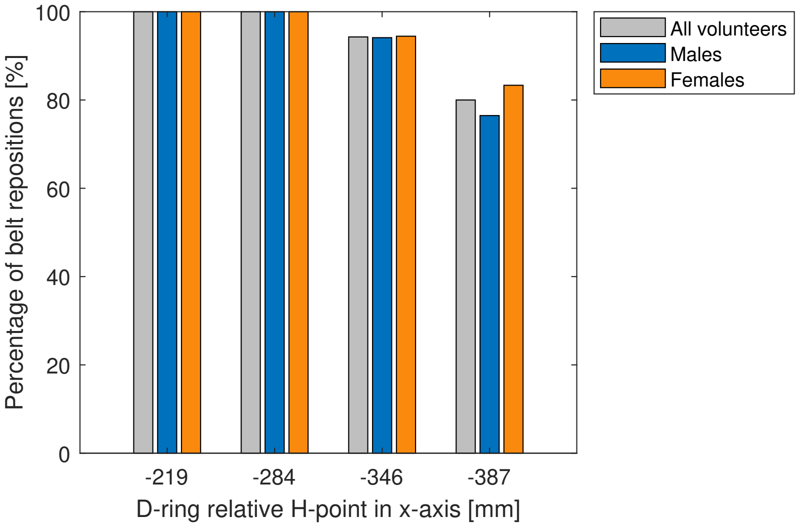


Figure 4.1: Illustration showing to what extent the belt repositioned for the volunteers in the different fore-aft positions. All volunteers are depicted in gray whereas the males and females are depicted in blue and orange respectively.

Moving the seat further forward, further away from the D-ring attachment, from -219 mm to -387 mm, decreases the wrapping distance and the D-ring angle as seen in Figure 4.2 and Figure 4.3. The biggest difference in wrapping distance is between -284 mm and -346 mm, while the difference is relatively small between -219 mm and -284 mm, as well as between -346 mm and -387 mm. The difference between the female and male mean in wrapping distance is ≤0.6 cm, as seen in Figure 4.2. The difference between the means for males and females in D-ring angle is between 3° and 6°, the angle decreasing when the seat is moved forward away from the D-ring. Both the decrease in wrapping distance and D-ring angle relates to the shoulder belt's routing across the chest and how it encloses the shoulder, i.e. wrapping the shoulder more when the seat is positioned further from the D-ring.

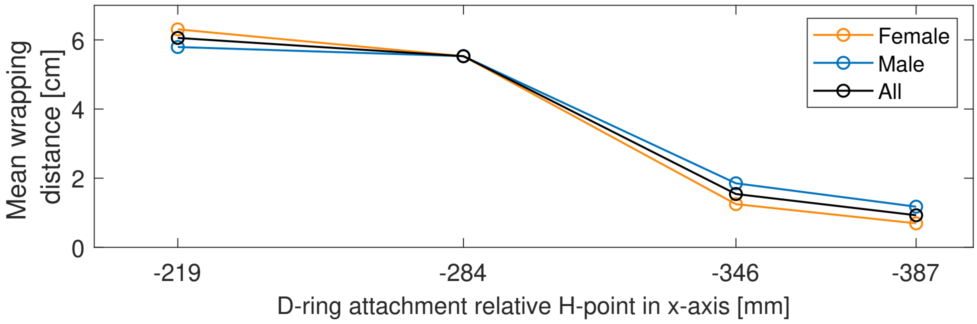


Figure 4.2: The mean wrapping distance for all volunteers and the males and females separately in the different fore-aft positions.

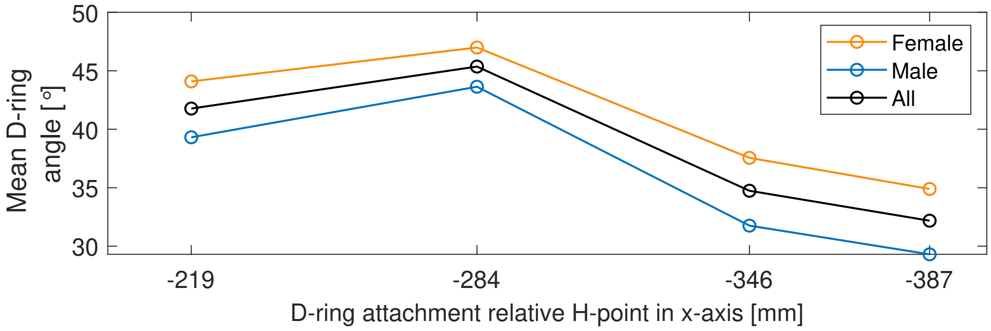


Figure 4.3: The mean D-ring angle for males and females in the different fore-aft positions.

All tests presented above were conducted with a low D-ring. In the cases when the belt did not reposition, the tests were repeated with a high D-ring. The belt repositioned for all volunteers in the seat positions when the high D-ring was implemented. The high D-ring was tested at -346 mm and at -387 mm for two and seven volunteers respectively.

The impact of material with lower friction was assessed at -346 mm and -387 mm, the two most forward fore-aft positions for the B-pillar installation where the belt failed to reposition. The lower friction material did not affect belt repositioning for the two volunteers at -346 mm; the belt did not reposition. Whereas at -387 mm, the lower friction material made belt repositioning possible for 57% of the volunteers, corresponding to four out of seven volunteers. The belt repositioned when the lower friction material was added for the volunteers whose point-of-no-return was 10 cm. For the cases with point-of-no-return at 5 cm, the lower friction material did not change the outcome.

The percentage of volunteers for which the belt can sit by itself below the shoulder is shown in Figure 4.4. There is a gradual increase of the belt sitting on the arm by itself, increasing from 0% in -219 mm to 14%, 57%, up until 86% in -387 mm. Corresponding to zero, five, twenty, and thirty volunteers in respective fore-aft position. It follows the same trend as the number of failed repositioned shoulder belts. The belt could sit by itself for the two volunteers and the seven volunteers that the belt did not reposition for at -346 mm and -387 mm respectively.

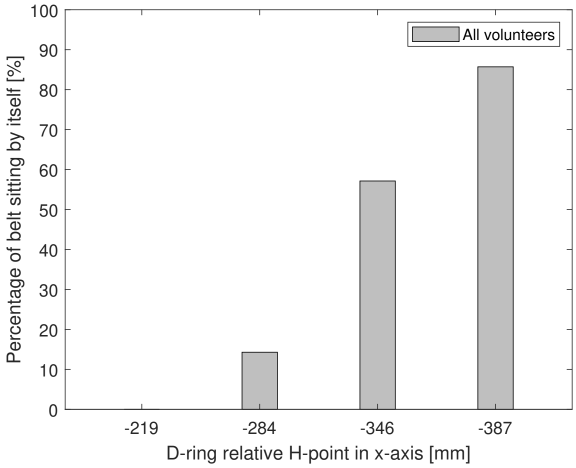


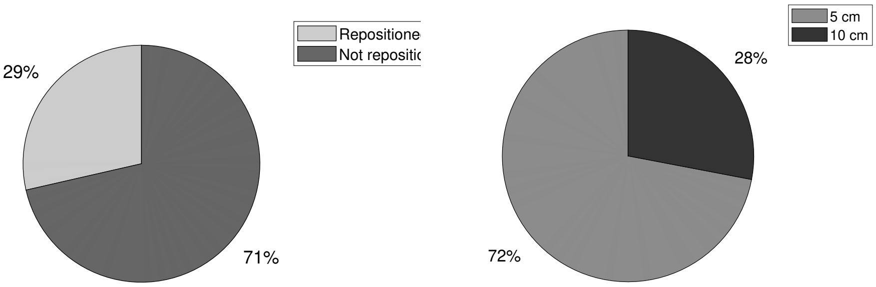
Figure 4.4: An overview of the belt sitting by itself without tape at the different positions in the fore-aft range.

4.3 Shoulder belt repositioning in the belt-in-seat installation

For the belt-in-seat installation, the shoulder belt repositioned for 29% of the volunteers, corresponding to 10 volunteers, see Figure 4.5a. The belt failed to reposition for 71% of the volunteers, corresponding to 25 volunteers. The point-of-no-returns were identified to be either 5 cm or 10 cm. A point-of-no-return of 5 cm means that the belt failed to reposition for both the 10 cm and the 5 cm incrementation, while a point-of-no-return of 10 cm means a failed belt reposition at 10 cm with a successful reposition at 5 cm. Images of the volunteers that the belt did not reposition for at the belt-in-seat installation is found in Appendix E.

The most common point-of-no-return was at 5 cm, representing 72% of the failed belt repositioning cases, see Figure 4.5b. The corresponding number of volunteers with a point-of-no-return at 5 cm was 18 volunteers whereas seven volunteers had a point-of-no-return at 10 cm. A majority of the point-of-no-returns at 5 cm were male, while the majority for 10 cm were female. As seen in Figure 4.6a, eleven males and seven females had their point-of-no-return at 5 cm, 61% and 39% respectively. Similarly, Figure 4.6b shows the three males and four females who had their point-of-no-return at 10 cm, 43% and 57% respectively.

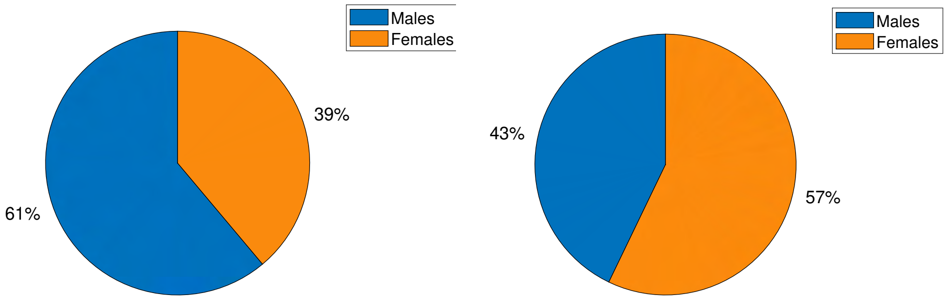
The shoulder belt sat by itself without tape at different levels for all volunteers when positioned on the arm in the belt-in-seat installation. For 30 of the volunteers the belt could sit at 10 cm or below on the arm. For five volunteers the belt only stayed by itself at 5 cm or less on the arm below the acromion. The belt repositioned for the five volunteers. The belt sat by itself at 10 cm for the 30 volunteers that the belt repositioning failed for.



(a) The repositioned and not repositioned shoulder belts in the belt-in-seat installation.

(b) The two point-of-no-returns for the volunteers that the belt did not reposition for.

Figure 4.5: Illustration showing the relation between repositioned and not repositioned shoulder belts in the belt-in-seat installation, and the corresponding points-of-no-return at 5 cm or 10 cm that belt repositioning failed for.



(a) The division among males and females with the point-of-no-return at 5 cm in the belt-in-seat installation.

(b) The division among males and females with the point-of-no-return at 10 cm in the belt-in-seat installation.

Figure 4.6: The percentage of belt repositioning between the males and females at the identified point-of-no-return for the males and females.

4.4 Two sample t-test to test statistical significance

The analysis in this section is based on the outcome of belt repositioning from the incrementation 10 cm down the arm. This was the increment where belt repositioning was tested for all volunteers since the belt was not positioned at 5 cm or 20 cm down the arm for all volunteers. The analysis is made by two sample t-tests for each test condition where the belt repositioning failed. The test conditions were at -346 mm, -387 mm, and the belt-in-seat installation. The two sample groups were split based on the belt repositioning outcome, a repositioned or not repositioned shoulder belt. The anthropometric, belt geometry, and belt fit measurements were thereby sorted into the respective sample groups. The collected measurements are all measurements listed in Table 2.4, body mass index (BMI), D-ring angle, contact angle, belt angle in XY-plane, vertical and horizontal belt distance, and wrapping distance. A significance level of 0.05 was implemented. After a Bonferroni correction using equation (3.5), which take the 25 collected measurements into account, the significance level was calculated to $\alpha_B = \frac{0.05}{25} = 0.002$.

4.4.1 Two sample t-test and analysis of collected measurements at the second most forward test condition in the test rig

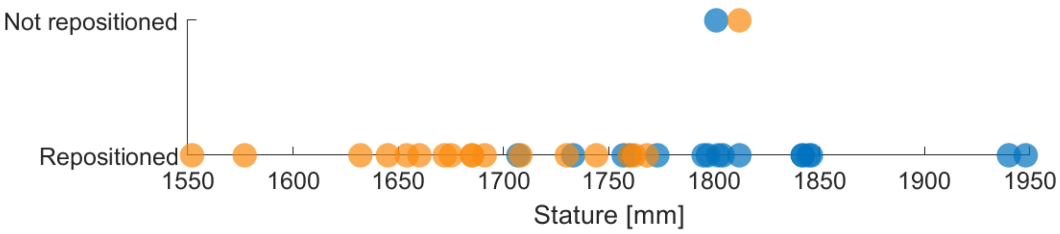
At the second most forward position in the test rig, the belt repositioned for 33 volunteers and did not reposition for two volunteers, one male and one female. Thereby, $n_{yes} = 33$ and $n_{no} = 2$. The null hypothesis of equal means was for a total of four collected measurements when conducting the two sample t-test and therefore the alternative hypothesis was rejected, the data being the D-ring angle, vertical belt distance, stature, and chest breadth. Therefore, there is a statistical difference in mean values. The corresponding t-values, df, and p-values are found in Table 4.2. The collected measurements that were statistically significant after Bonferroni correction are depicted in Figure 4.7, the group for which the belt did not reposition for are in the top of each figure.

It is visible in Figure 4.7 that the two volunteers that belt repositioning failed for have similar stature, chest breadth, D-ring angle, and vertical belt distance. The two volunteers had the same measurements in both chest breadth and vertical belt distance, hence their data points overlapping in Figure 4.7b and Figure 4.7d. The stature in Figure 4.7a shows that the female is the tallest of all female volunteers while the male is around the mean stature. Regarding chest breadth, the male is at the lower end of the span for the males whereas the female is around the mean for the females. The female has the lowest D-ring angle of the group whereas the male is around the mean. Regarding the vertical belt distance, the volunteers' measurements overlap at the same value above the mean.

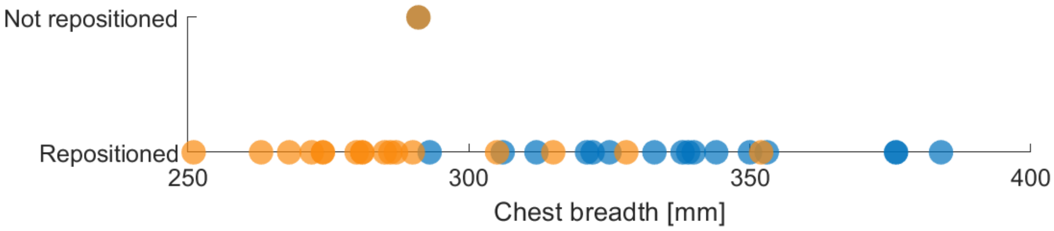
Table 4.2: A summary of the collected measurements at the second most forward position in the test rig, at -346 mm, that were statistically significant after Bonferroni correction between the two groups the volunteers that the belt repositioning repositioned for and not. All measurements are given in millimeter.

Measurement	Repositioned		Not repositioned		T-test data		
	Mean	SD	Mean	SD	t	df	T-test data
Stature	1746	91	1807	7.8	-3.64	27	0.0011
Chest breadth	312	36	291	0.0	3.42	32	0.0017
D-ring angle	35	5	31	0.4	4.83	30	<0.001
Vertical belt distance	9	2	11	0.0	-5.15	31	<0.001

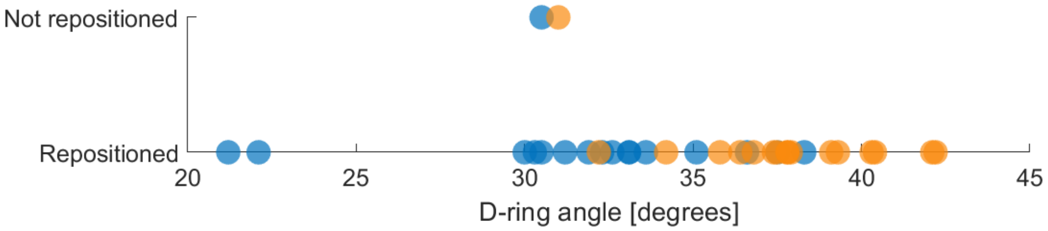
In addition to the measurements that were statistically significant after Bonferroni correction, other measurements were identified where the two volunteers were distinguishable from the others. These measurements were the shoulder height (sitting), waist circumference, abdominal depth, and thorax depth, see Figure 4.8. The corresponding p-values for these measurements were 0.085, 0.067, 0.01, and 0.493. The figures depict that both volunteers have a tall shoulder height (sitting) and a smaller waist circumference compared to their respective sex's measurements. The female's abdominal depth is below the mean value for the females whereas the male has one of the smallest abdominal depths of all males. The female's thorax depth is the lowest, while the male's is slightly below the males' mean.



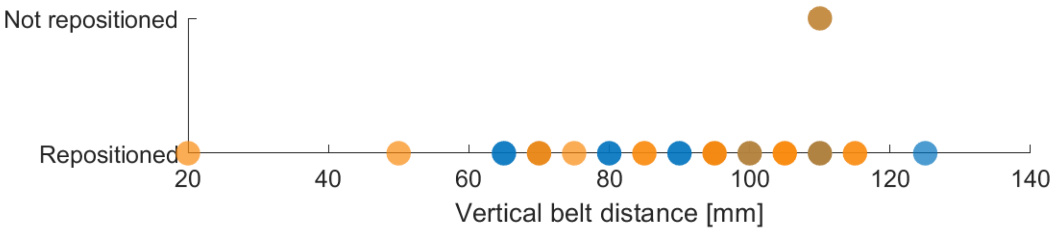
(a) The stature of the two volunteers that the belt did not reposition for illustrated against the 33 volunteers at the second most forward test condition in the test rig.



(b) The chest breadth of the two volunteers that the belt did not reposition for illustrated against the 33 volunteers at the second most forward test condition in the test rig.

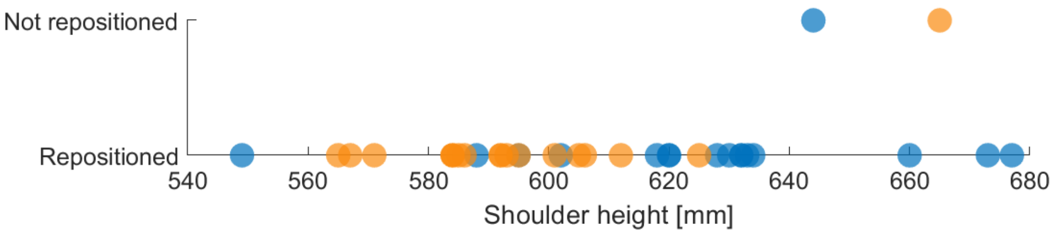


(c) The measured D-ring angle of the belt for the two volunteers that the belt did not reposition for illustrated against the 33 volunteers at the second most forward test condition in the test rig.

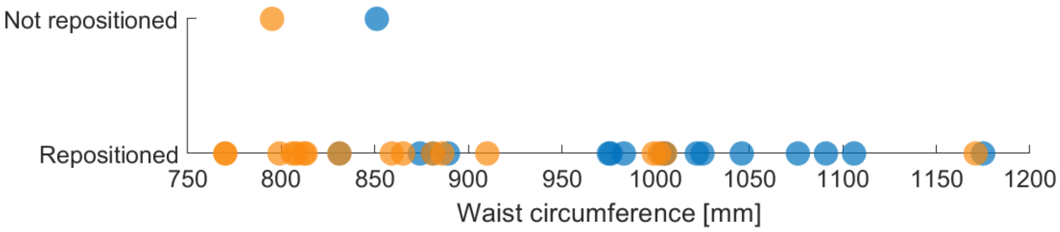


(d) The measured vertical belt distance, between the suprasternal notch and upper edge of the belt, for the two volunteers that the belt did not reposition for illustrated against the 33 volunteers at the second most forward test condition in the test rig.

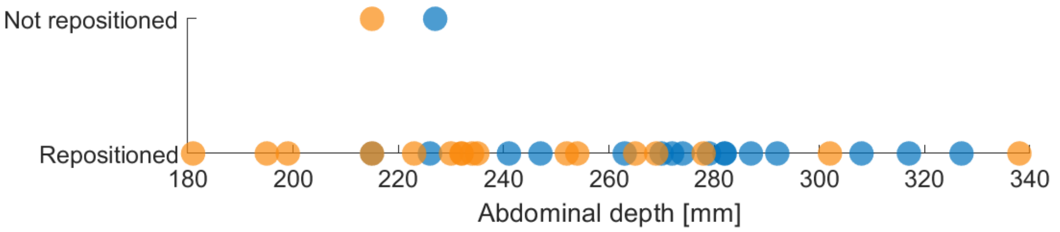
Figure 4.7: An overview of the collected measurements that were statistically significant after Bonferroni correction in a two sample t-test for belt repositioning from 10 cm in the B-pillar installation at the second most forward test condition in the test rig, at -346 mm.



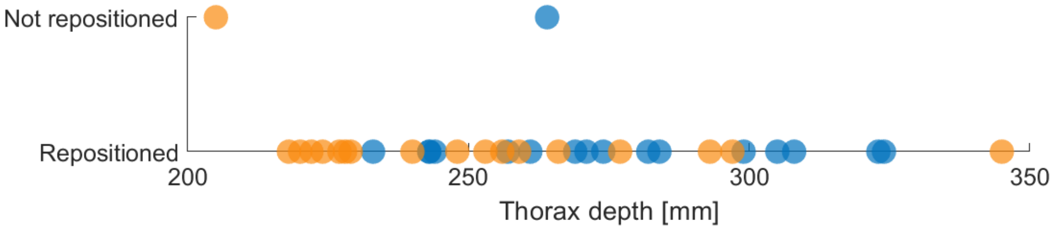
(a) The shoulder height (sitting) of the two volunteers that the belt did not reposition for illustrated against the 33 volunteers at the second most forward test condition in the test rig.



(b) The waist circumference of the two volunteers that the belt did not reposition for illustrated against the 33 volunteers at the second most forward test condition in the test rig.



(c) The abdominal depth of the two volunteers that the belt did not reposition for illustrated against the 33 volunteers at the second most forward test condition in the test rig.



(d) The thorax depth of the two volunteers that the belt did not reposition for illustrated against the 33 volunteers at the second most forward test condition in the test rig.

Figure 4.8: The extra anthropometric measurements where the two volunteers that the belt did not reposition for were distinguishable compared to the other volunteers in the second most forward test condition in the test rig.

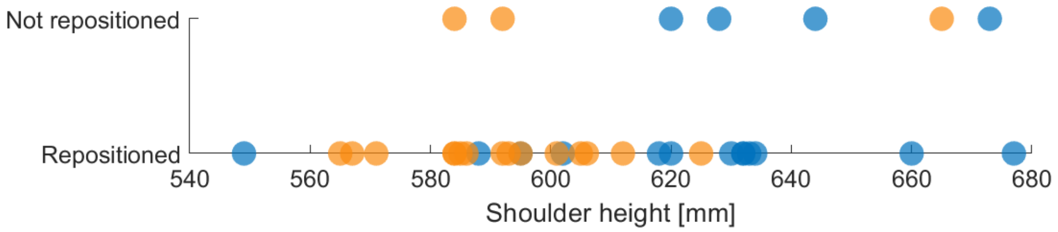
4.4.2 Two sample t-test and analysis of collected measurements at the most forward test condition in the test rig

For the most forward test condition, the size of the group where belt repositioning succeeded was $n_{yes} = 28$ volunteers and the other group where belt repositioning failed was $n_{no} = 7$ volunteers. The two volunteers whom the belt did not reposition for at -346 mm are also part of the volunteers whom the belt did not reposition for at -387 mm. The null hypothesis of equal means was not rejected for any collected measurements when conducting a two sample t-test with the Bonferroni correction, meaning that the alternative hypothesis was never accepted. The measurements with the lowest p-values from this analysis are presented in Table 4.3 with the corresponding t-values, df, and p-values. The measurements are depicted in Figure 4.9 for the two groups. The group that the belt did not reposition for is at the top of each figure.

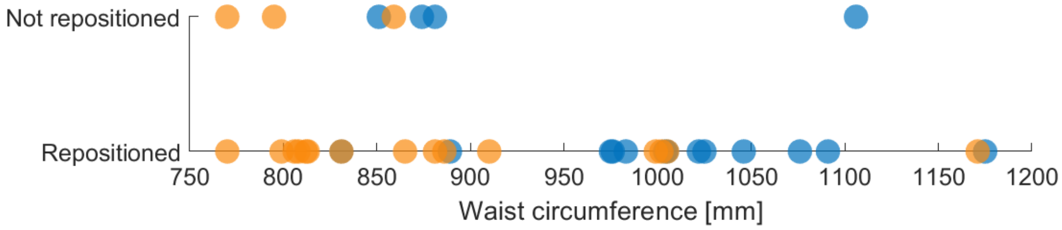
Table 4.3: A summary of the data for the smallest p-values found after the two sample t-test analysis of the two groups: repositioned and not repositioned, of the result obtained at -387 mm. All measurements are given in millimeter.

Measurement	Repositioned		Not repositioned		T-test data		
	Mean	SD	Mean	SD	t-value	df	p-value
Shoulder height (sitting)	695	38	629	34	1.75	8	0.117
Waist circumference	945	115	877	109	-1.46	9	0.117
Abdominal depth	263	38	229	27	-2.70	12	0.019
Vertical belt distance	80	21	95	18	1.80	10	0.100

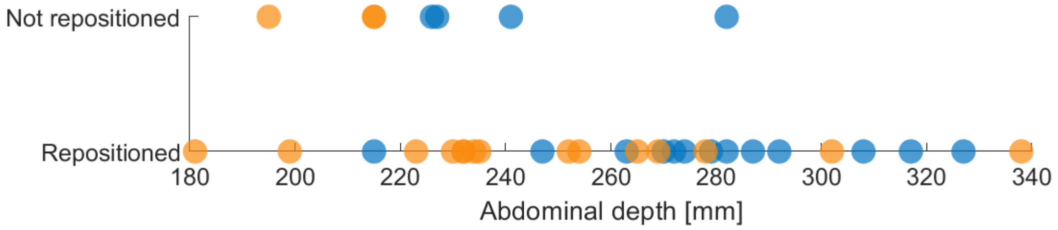
The shoulder height (sitting) and vertical belt distance measurements is seen in Figure 4.9a and 4.9d. The waist circumference and abdominal depth measurements, see Figure 4.9b and Figure 4.9c, convey information about the same body part. The distribution of volunteer measurements show that the majority of failed belt repositions were for volunteers with small waist circumference and abdominal depth.



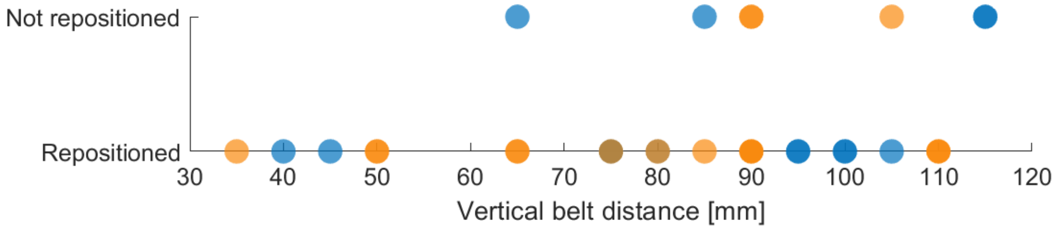
(a) The shoulder height (sitting) of the seven volunteers that the belt did not reposition for illustrated against the 28 volunteers at most forward test condition in the test rig.



(b) The waist circumference of the seven volunteers that the belt did not reposition for illustrated against the 28 volunteers at most forward test condition in the test rig.



(c) The abdominal depth of the seven volunteers that the belt did not reposition for illustrated against the 28 volunteers at most forward test condition in the test rig.



(d) The measured vertical belt distance between the suprasternal notch and upper edge of the belt for the two volunteers that the belt did not reposition for illustrated against the 28 volunteers at most forward test condition in the test rig.

Figure 4.9: An overview of the collected measurements which were not statistically significant after Bonferroni correction according to the two sample t-test for belt repositioning from 10 cm in the B-pillar installation at the most forward position in the test rig, at -387 mm.

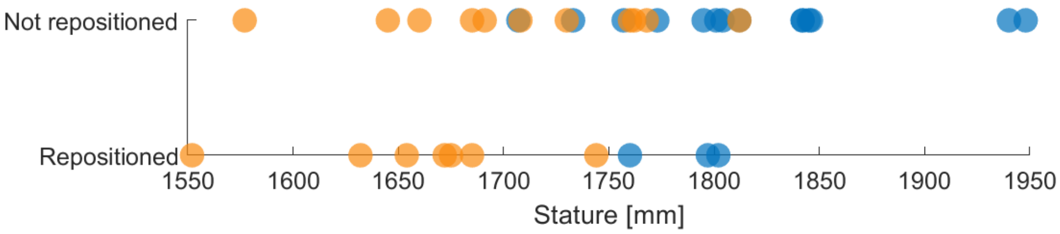
4.4.3 Two sample t-test for belt-in-seat installation

In the belt-in-seat installation, the belt repositioned for ten volunteers and did not reposition for 25 volunteers, thereby $n_{yes} = 10$ and $n_{no} = 25$. The null hypothesis of equal means was not rejected for any collected measurement when conducting a two sample t-test with the Bonferroni correction, meaning that the alternative hypothesis was never accepted. The collected measurements with the lowest p-values from this analysis are presented in Table 4.4 and the data is illustrated in Figure 4.10 for the two groups. The group that the belt did not reposition for is at the top of each figure.

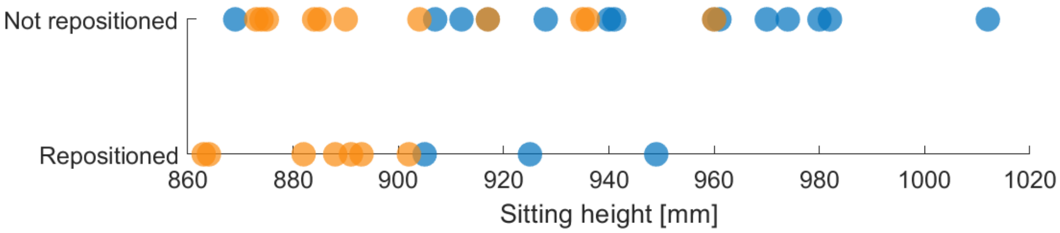
Table 4.4: A summary of the data for the smallest p-values found after the two sample t-test analysis of the two groups: repositioned and not repositioned, of the result obtained in the belt-in-seat. All measurements are given in millimeter expect the D-ring angle that is given in degrees.

Measurement	Repositioned		Not repositioned		T-test data		
	Mean	SD	Mean	SD	t-value	df	p-value
Stature	1697.3	78.6	1769.7	86.2	2.4	18.2	0.028
Sitting height	896.2	26.2	927.4	40.4	2.70	25.6	0.012
Shoulder height (sitting)	590.2	26.9	617.8	29.5	2.67	18.2	0.016
Abdominal depth	274.8	43.9	248.8	33.7	-1.71	13.4	0.110
D-ring angle	12.9	6.8	6.3	9.0	-2.36	22.2	0.028

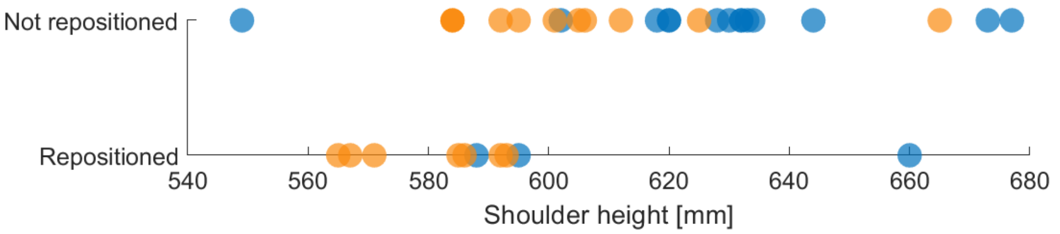
Observing the stature and sitting height in Figure 4.10a and Figure 4.10b, the stature and sitting height have a threshold for the belt not repositioning above 1820 mm and 960 mm respectively. These thresholds are based on the male's data distribution and separate thresholds can be set for females: stature above 1750 mm and sitting height above 910 mm. There is a cluster of volunteers that the belt repositioned for with a low shoulder height (sitting), where the belt reposition for shoulder heights less than 595 mm. A similar cluster of volunteers shows that the belt did not reposition for volunteers with a taller shoulder height (sitting). The threshold for the belt not repositioning for shoulder heights (sitting) above approximately 600 mm, see Figure 4.10c. For abdominal depth, see Figure 4.10d, a cluster of volunteers that the belt did not reposition for is observed below 290 mm. A similar gathering of volunteers is observed regarding the D-ring, where the belt did not reposition for a majority of volunteers with a negative D-ring angle.



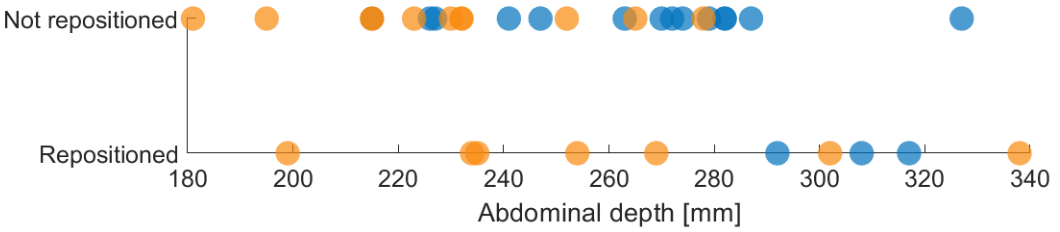
(a) The stature of the 25 volunteers that the belt did not reposition for illustrated against the ten volunteers in the belt-in-seat installation.



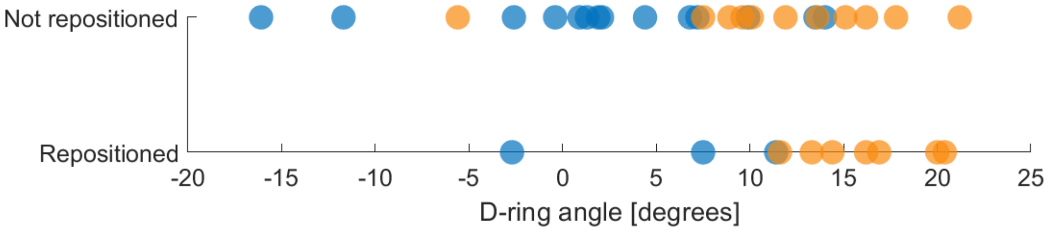
(b) The sitting height of the 25 volunteers that the belt did not reposition for illustrated against the ten volunteers in the belt-in-seat installation.



(c) The shoulder height (sitting) of the 25 volunteers that the belt did not reposition for illustrated against the ten volunteers in the belt-in-seat installation.



(d) The abdominal depth of the 25 volunteers that the belt did not reposition for illustrated against the ten volunteers in the belt-in-seat installation.



(e) The D-ring angle of the 25 volunteers that the belt did not reposition for illustrated against the ten volunteers in the belt-in-seat installation.

Figure 4.10: An overview of the collected measurements which were statistically significant after Bonferroni correction according to the two sample t-test for belt repositioning from 10 cm in the belt-in-seat installation.

4.5 Logistic regression curves for belt-in-seat installation result

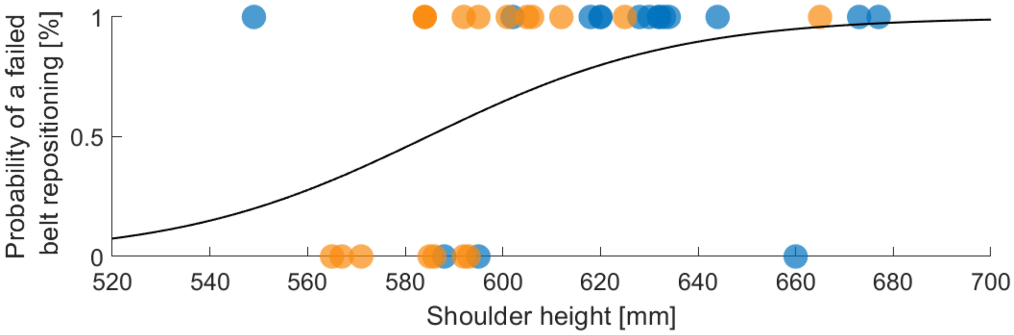
A similar pattern between the belt's ability to reposition and the volunteer's stature, sitting height, and shoulder height (sitting) is observed in Figure 4.10a, Figure 4.10b, and Figure 4.10c. Since the three measurements are related, shoulder height (sitting) will be further analyzed for its effect on belt repositioning. The patterns of the belts' ability to reposition was observed in the shoulder height (sitting) Figure 4.10c compared to stature and sitting height in Figure 4.10a and Figure 4.10b. The three measurements are also related, thereby only shoulder height was further analyzed in the aspect of investigating the measurements related to the probability of a failed belt repositioning.

Probability curves for three of the collected measurements: shoulder height (sitting), abdominal depth, and D-ring angle were created by using logistic regression. The variables for the logistic regression curves were found by (3.8) and thereafter the functions for the probability curve were determined by (3.10). The combined p-value in the table was found through a Hosmer and Lemeshow goodness-of-fit test performed in SPSS. The variables for the probability functions for shoulder height (sitting), abdominal depth, and D-ring angle are found in Table 4.5 and the corresponding probability curves are depicted in Figure 4.11. Table 4.5 also presents the variables for for two probability curves where two independent variables were combined, abdominal depth with shoulder height and D-ring angle respectively. Similarly, these variables were found by (3.9) and (3.11). The abdominal depth was chosen as input the fixed value in the probability functions using the 25^{th}, 50^{th}, and the 75^{th} percentile value of the volunteer data, which was 227.8 mm, 254 mm, and 281.3 mm respectively. All figures also display the belt repositioning results, from Section 4.4.3, as well for the volunteers.

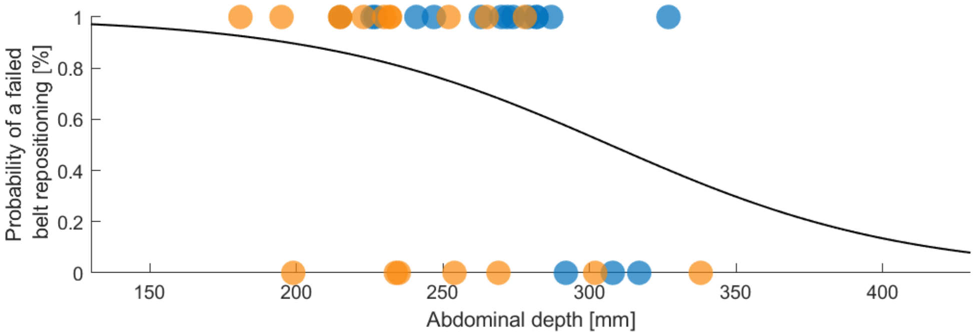
Table 4.5: The variables used as input to create the binary logistic regression curves. The input for the one independent variable and two independent variables are separated by the mid line.

Measurement(s)	β_0	β_1	β_2	Comb. p-value
Shoulder height (sitting)	-22.798	0.039	-	0.37
Abdominal depth	6.142	-0.020	-	0.45
D-ring angle	2.109	-0.119	-	0.44
Shoulder height & abdominal depth	-17.58	0.043	-0.028	0.82
D-ring angle & abdominal depth	24.094	-0.420	-0.076	0.18

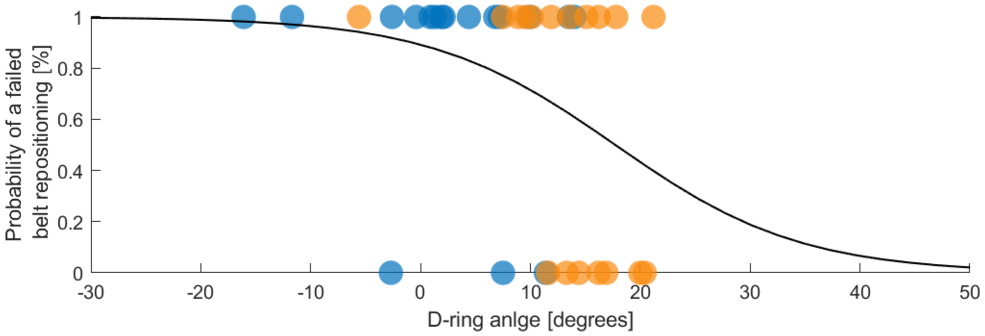
The probability curve in Figure 4.11a indicates that the probability of a failed belt repositioning increase with an increasing shoulder height (sitting). Figure 4.11b displays that the shoulder belt is more likely to reposition with a larger abdominal depth. Figure 4.11c display that the shoulder belt does not reposition as often when the digital angle at the D-ring is negative or around 5°.



(a) A probability curve of a failed belt repositioning depending on shoulder height (sitting).



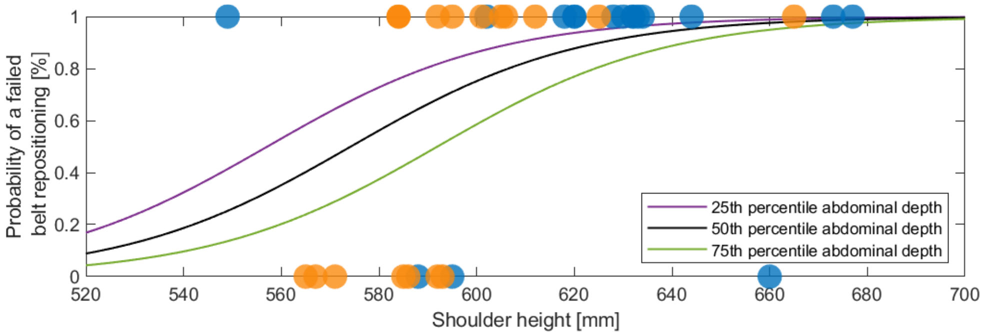
(b) A probability curve of a failed belt repositioning depending on abdominal depth.



(c) A probability curve of a failed belt repositioning depending on D-ring angle.

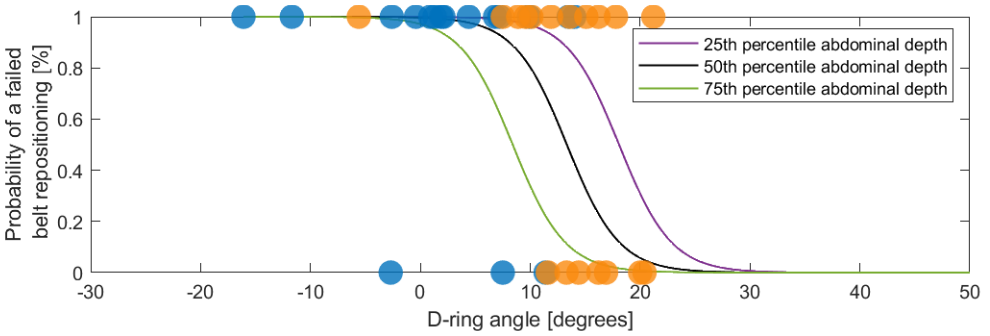
Figure 4.11: The probability curve of the belt not repositioning depending on shoulder height (sitting), abdominal depth, and D-ring angle for the belt-in-seat installation.

The interpretation of the curves in Figure 4.12a is that the probability of the belt not repositioning is higher for individuals with a smaller abdominal depth than with a large abdominal depth. This pattern is visible when comparing the steeper increase of the purple curve with the green curve. The corresponding p-value for shoulder height (sitting) and abdominal depth is 0.016 and 0.052 respectively. The interpretation of the curves in Figure 4.12b is that that the belt is more likely to reposition for a larger abdominal depth than a smaller one. The corresponding p-values for abdominal depth and D-ring angle are 0.011 and 0.013, which had the smallest p-values. They were statistically significant after Bonferroni correction for the significance level of 0.0018, meaning the null hypothesis is rejected and the alternative hypothesis is accepted for all probability functions.



(a) The probability curve of the belt not repositioning depending on shoulder height (sitting) and abdominal depth for the belt-in-seat installation.

ov



(b) The probability curve of the belt not repositioning depending on D-ring angle and abdominal depth for the belt-in-seat installation.

Figure 4.12: The probability curves of the belt not repositioning depending on three of the collected measurements: shoulder height (sitting), abdominal depth, and D-ring angle, in regard to three percentile values of the volunteer data for the belt-in-seat installation.

5

Discussion

The discussion is split into ten sections, where the overall results of belt repositioning in the B-pillar installation and belt-in-seat installation are discussed first. Then the influence of upper body characteristics, belt geometry, belt fit, and friction. Thereafter the effect of the identified outliers is discussed. Then the limitations of the study, the research methodology, future suggestions, and observations from the volunteer study are discussed. All coordinates mentioned below are given for the x-axis position of the D-ring attachment relative the one H-point.

5.1 Shoulder belt repositioning in the B-pillar and belt-in-seat installation

This study found that the pre-pretensioner was able to retract the belt from an on-arm position to an on-clavicle position for 100% of the volunteers in the most common fore-aft positions with a B-pillar installed D-ring. The common fore-aft positions being the D-ring attachments -219 mm and -284 mm relative the H-point in the x-axis of a Volvo S60. The pre-pretensioner was able to reposition the shoulder belt when positioned both 10 cm and 20 cm down the arm, when measured from the acromion. The results therefore indicate that the pre-pretensioner could have the possibility to reposition the belt if it is put below the shoulder for all volunteers in the most common fore-aft ranges, which is where 80% of occupants have their seat according to Reed et al. (2020). However, that is based on a stationary setting and a dynamic scenario may give a different result. Additionally, the volunteers included in the study were not normally distributed according to the three measurements from the Swedish population, but did represent parts of it.

When positioning the seat in the second most forward and the most forward position for the B-pillar installation, the findings indicated that belt repositioning became problematic. Since an improper belt fit could increase the risk of injury, it means that occupant safety is not ensured for all front seat passengers who wear the belt on the arm in the more forward seat configurations. The two seat configurations where repositioning failed are however less common according to Reed et al. (2020). However, the remaining 20% who sit more forward than the middle of the range are important to consider. It was not the range alone that was important for belt fit and repositioning, but also the relationship between the D-ring attachment and

H-point. Solely the fore-aft range does not inform one of how the belt routing on the occupant will be, but will be a result from the relation between D-ring attachment and H-point as well as the body characteristics.

In addition to the findings from the B-pillar installations, the results indicated that belt repositioning was even more problematic in the belt-in-seat installation. The belt repositioned for 29% of all volunteers, but not for 71% of the volunteers from the 10 cm increment. This finding is cause for concern for vehicle safety since the pre-pretensioner was not sufficient in repositioning the belt. It was however able to move the shoulder belt closer to the acromion for most volunteers, even when failing to reposition. Belt repositioning with a belt-in-seat installation should be further investigated to ensure that the belt is in a proper position across the clavicle and sternum for all front seat occupants in the event of a crash.

The belt repositioned for fewer volunteers in the belt-in-seat installation compared to the most forward position in the test rig. This is likely due to the difference in the D-ring attachment and thereby the amount of wrapping in the two belt installations. Wrapping was prominent among all volunteers in the belt-in-seat installation since the wrapping distance was 0 cm. Whereas in the B-pillar installation it decreased the more forward the seat was but it was not full wrapping in the most forward position for all volunteers. Compared to the B-pillar installation, the D-ring attachment in the belt-in-seat installation was positioned much closer to the shoulder in the y-axis and thereby increased the amount of wrapping. This indicates that the D-ring attachment influences belt repositioning. With this, the amount of wrapping is likely to affect the pre-pretensioners ability to reposition the shoulder belt.

The test condition at -284 mm with the high D-ring was not presented in the results since the purpose of this test condition was to compare the outcome with the low D-ring. The belt repositioned for all volunteers at -284 mm with both the low and high D-ring, therefore no comparison could be made. The belt repositioned for all volunteers where a test was performed with a high D-ring, decided by the increment method. The data with the high D-ring could be used in future analysis if one is interested in comparing, for example, the belt retraction speed and belt retraction time with the corresponding data from the low D-ring.

5.2 Effect of upper body characteristics, belt geometry, and belt fit on belt repositioning

Some upper body characteristics showed indications of being linked with shoulder belt repositioning when tested using a two sample t-test. Stature, shoulder height (sitting), and abdominal depth often appeared as an indicator for belt repositioning, as well as the D-ring angle and vertical belt distance. The two latter being the angle where the belt extends from the D-ring and the vertical belt distance which was measured from the suprasternal notch down to the upper edge of the belt. Most of these collected measurements were not statistically significant after Bonferroni correction. However, the results still show tendencies and indications of possible relationships between the measurements and shoulder belt repositioning. The measurements may not be related to belt fit by themselves, but could be when combined.

In the second most forward position, the belt did not reposition for 5.7% of the volunteers which corresponded to two volunteers. They had a lot of similar measurements, such as stature, chest breadth, D-ring angle, and the vertical belt distance. A general trend among the two was a tall shoulder height (sitting) and a small waist circumference, abdominal depth, and thorax depth. Their body characteristics indicated that a taller shoulder height (sitting) and an overall thin build could be the reason why the belt did not reposition for them.

The body characteristics of the 20% of the volunteers that the belt did not reposition for at the most forward position in the B-pillar installation suggest that shoulder height (sitting) and abdominal depth affect belt repositioning. A taller shoulder height (sitting) and smaller abdominal region seem to make belt repositioning more difficult. Abdominal depth had the lowest p-value of these measurements, but it would not be statistically significant even if disregarding the Bonferroni correction and using a significance level of 0.05.

Belt repositioning in the belt-in-seat installation failed for most volunteers and was therefore further analyzed with logistic regression curves showing the probability of a failed belt repositioning. Logistic regression was done for shoulder height (sitting), abdominal depth, and D-ring angle respectively. The overall result of the logistic regression indicates that the belt does not reposition as often for volunteers with a smaller abdominal depth, a taller shoulder height (sitting), or a negative D-ring angle. There is not a clear transition for when belt repositioning becomes more or less frequent in the data points, especially not in Figure 4.11a for shoulder height (sitting) where there is an overlap of successful and failed belt repositioning from approximately 570 mm until 590 mm. A similar overlap is observed in Figure 4.11c for the D-ring angle from 10° until 20°. A slightly clearer transition is observed in Figure 4.11b, if overlooking the outliers, where the belt did not reposition for most volunteers with an abdominal depth in the range of 200 mm to 270 mm, and the transition between not repositioned and repositioned would be at approximately 290 mm. There are outliers that do not follow the identified pattern in all three above mentioned figures. The outliers could affect the resulting variables α and β_0 and thereby the final probability curve.

When two independent variables were combined in the probability curves, the logistic regression function changed as well. When the belt repositioning outcome for abdominal depth was combined with the corresponding outcome for the D-ring angle, it increased the slope of the curve and made the transition clearer, compare Figure 4.11c with Figure 4.12b. A similar change was observed between Figure 4.11a and Figure 4.12a, but on a much smaller scale. This indicates that combining measurements to predict a certain belt repositioning outcome has potential. The overall concern for logistic regression is that the measurements should not be correlated, which was the case with the D-ring angle and shoulder height (sitting) data.

Many of the measurements are correlated and thereby it may be difficult to include more anthropometric measurements that are not correlated while still linked to belt repositioning in probability curves.

The individuals with a larger abdominal depth, see the three males and two females that the belt repositioned for with an abdominal depth >300 mm in Figure 4.10d, had varying shoulder heights (sitting) and weight. The male volunteer with an abdominal depth of 327 mm also had a shoulder height 82 mm taller than the second tallest of the five volunteers. The other four volunteers' shoulder heights (sitting) only differed 24 mm. Based on these observations, we can see that a larger abdominal depth generally makes it easier for the belt to reposition. However, the belt's ability to reposition may also be linked to belt routing across the abdomen. It may influence how the belt lays across the upper body, something observed in Figure 5.1 where its routing differed depending on abdominal depth. Figure 5.1a shows that the belt lies diagonal across the stomach, whereas Figure 5.1b shows how it lies above the stomach, both figures taken in the belt-in-seat installation. Repositioning does vary depending on the rest of the body measurements. It may be the case that the abdominal depth is able to describe, or be related to, the overall body characteristics of the occupant.

Belt fit has previously been linked with BMI. A study by Reed et al. (2012) found a correlation between BMI and improper belt fit. The study showed that an increase in BMI was associated with the lap belt being positioned higher above the anterior superior iliac spine (ASIS) and that the distance between the lap belt and ASIS also increased. A more recent study by Jones et al. (2021) also showed that the lap belt was placed both further away from the pelvis and higher above the ASIS for increased BMI. Both studies reflected on the fact that high BMI leads to added slack, which puts the occupant at higher risk of injury. Although these studies focused on the lap belt, they observed a similar phenomenon of a changed seat belt routing and fit depending on the upper body characteristics of the passenger as in this study. During this volunteer study, it was observed that a larger abdominal area would affect how the belt was routed across the upper body. The belt would start crossing the torso higher up on individuals with a larger abdominal area compared to individuals with a smaller abdominal area, whom the belt would lay along the diagonal between buckle and D-ring.

(a) A volunteer with an abdominal depth almost two standard deviations below the males' mean.

(b) A volunteer with an abdominal depth almost one standard deviations above the males' mean.

Figure 5.1: Belt routing across the abdomen for two volunteers with different abdominal depths in the belt-in-seat installation, positioned 10 cm down the arm.

Another body characteristic that may have influenced belt repositioning is the individual shape of the volunteer's arm. In this study there were a variety of builds of the arms; smooth curves from shoulder to elbow, prominent muscular features with depressions, and lean arms following the bone and tendon structure. The variety of arm builds, in combination with the angle between the shoulder's slope and the arm, could have influenced the repositioning outcomes as much as the shoulder height (sitting) or abdominal depth, and should be further investigated. The angle between the shoulder and the arm may be connected to a larger abdominal depth since that measurement is closely related to the general shape of the abdominal area. The difference in the shape of the arm can be observed when comparing the arm of the volunteer in Figure 5.1a with the volunteer in Figure 5.1b. The belt did not reposition for the volunteer in Figure 5.1a whereas it did reposition for the volunteer in Figure 5.1b.

Another aspect that could have affected belt repositioning was the shape of the car seat. The seat was a sports model with wings on the side of the seat, as can be seen in Figure 2.1. The width of the abdomen and hip area affected if the arms of a person would lay between the wings or if they would lay on top. The difference in arm placement resulted in different positions for where the elbows were placed in x-direction, affecting the angles of the arms. A wider individual would have their arms on the wings and with that their arms would lay forward of the seat and created a slope which could have eased the belt's repositioning. A way to measure this possible effect could be by measuring how much the abdominal and chest area protrudes from the chair in comparison to the arms. These measurements could capture the effect of different sized chest areas, as a few observations were made of the belt not repositioning due to tissue or muscle in the chest area, rather than the arm or shoulder shape which was the general cause. The differences in where the shoulder belt gets stuck during the belt repositioning can be observed between the most forward position at -387 mm and the belt-in-seat, see Appendix D and Appendix E.

5.3 Effect of friction on belt repositioning

This study found that friction had different effects in the B-pillar and belt-in-seat installation. In the B-pillar installation, the lower friction material did not ease belt repositioning for the two volunteers at -346 mm, indicating that the belt is stuck and cannot pass the shoulder without additional intervention. This outcome was the same in the belt-in-seat installation. The reason why the belt did not reposition at the two test conditions is likely caused by the large amount of wrapping. The belt could stay by itself on the two volunteers at -346 mm and in the belt-in-seat installation, which also is an indicator of wrapping.

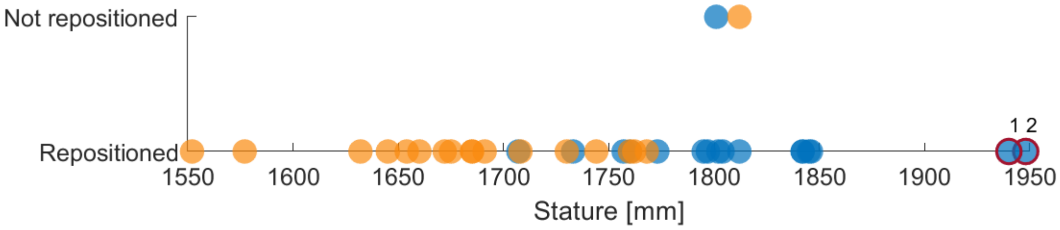
One interesting finding was at -387 mm, where the lower friction material made belt repositioning possible for the volunteers with a point-of-no-return at 10 cm but not at 5 cm. This outcome could be due to the belt velocity, since when it is placed at 10 cm it has a higher velocity, compared to 5 cm, when reaching the shoulder. Given that a point-of-no-return at 10 cm entails that the belt was repositioned for the 5 cm increment, it can mean that the belt's repositioning for these four volunteers with a point-of-no-return at 10 cm are more susceptible to small changes in initial belt placement. One thing to consider is that when the volunteers put on the lower friction material they could have changed their posture. The difference in result for lower friction may be due to the change in posture rather than the lower friction material. Another possible cause for a posture change is that the volunteer subconsciously changed their posture since they expect the belt to not reposition. Since this observation was made for 10 cm and 5 cm on only three volunteers at each point-of-no-return, the sample is too small to determine the actual effects of the lower friction material.

5.4 Outliers at the test conditions where belt repositioning failed

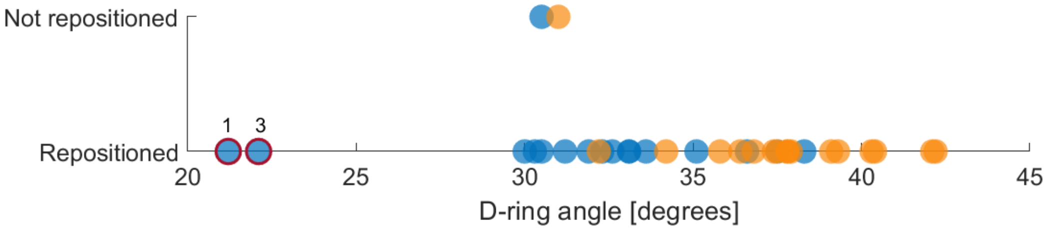
Outliers were distinguishable in the Results chapter's figures since they did not follow the pattern of belt repositioning for the collected measurements. In other words, for some volunteers the belt repositioning outcome contradicted the identified pattern. It is interesting to investigate the reasons why the belt did or did not reposition according to the identified pattern. Also, to learn to what extent these outliers affect the two sample t-test and if they were the reason why the mean values were not statistically significant.

Outliers were identified for the seat configurations where belt repositioning failed; at -346 mm, -387 mm, and the belt-in-seat installation. For the seat position at -346 mm there are two clear outliers in the stature data, see Figure 5.2a, from here on referred to as Outlier 1 and Outlier 2. Two outliers are also observed in D-ring angle, Figure 5.2b, where Outlier 1 is the same outlier as for D-ring angle. The new outlier in Figure 5.2a is referred to as Outlier 3. If all three outliers were overlooked it would have been a clear trend that a taller stature makes it more difficult to reposition the belt, as well as a lower D-ring angle.

When analyzing Outlier 1, included in both stature and D-ring angle, the volunteer was generally larger than the mean. The measurements were above one standard deviation from the male mean for stature, chest depth, chest breadth, chest circumference, waist circumference, shoulder circumference, abdominal depth, and thorax depth. The same trend is seen for Outlier 3 as the volunteer was above one standard deviation from the mean for the same measurements. Together, these two outliers suggest that the higher up in the z-axis and the further out in the x-axis the shoulder is, the smaller the D-ring angle is. The shoulders position in relation to the seat would explain why their D-ring values are lower than for all other volunteers. However, when doing the same analysis for Outlier 2, stature was the only measurement of the previously listed that was outside of one standard deviation of the mean. This observation indicates that although the trend shows that higher stature should increase the difficulty for belt repositioning, the combination of body measurements influences the success of belt repositioning.



(a) The two outliers who the belt reposition for with a tall stature of around 1950 mm at the second most forward test condition in the test rig.

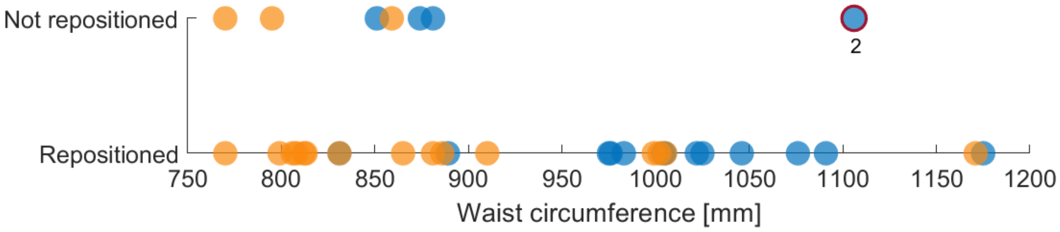


(b) The two outliers who the belt reposition for with a small D-ring angle of around 21 ° to 22 °, measured where the belt extend from the D-ring, at the second most forward test condition in the test rig.

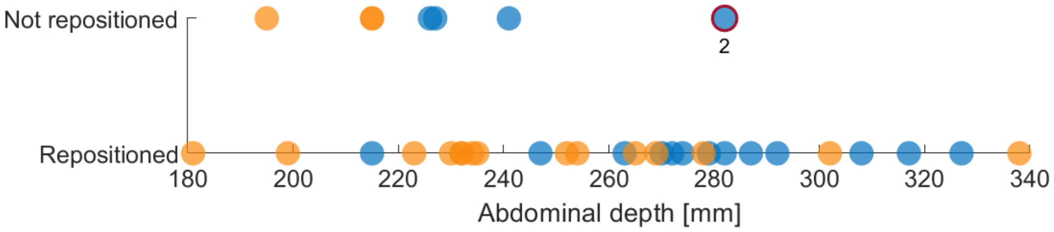
Figure 5.2: The outliers identified at the second most forward test condition in the test rig, at -346 mm.

The outlier observed at the most forward test position in the test rig is depicted in Figure 5.3. Outlier 2 is deviating from the trend that the belt does not repositions for volunteers with a smaller waist circumference and abdominal depth. Belt repositioning fails for Outlier 2, despite a larger waist circumference and abdominal depth seem to ease belt repositioning. A possible explanation that the belt did not reposition for that waist circumference and abdominal depth is the volunteer's other measurements. The belt could have failed to reposition due to a combination of a tall shoulder height (sitting), broad shoulders, and a deep chest depth. This combination is hypothesized since Outlier 2, as previously mentioned, was above 1 standard deviation in shoulder height (sitting), shoulder bideltoid breadth, chest depth, and shoulder circumference. This combination indicates a larger physical build compared to the rest of the volunteers. The wrapping distance between the belt and acromion process was 0 cm for Outlier 2 in this test condition, which indicates that the belt encloses the upper part of the shoulder.

Outlier 2, depicted in Figure 5.3a and Figure 5.3b, may be the reason why neither measurements were statistically significant. When removing these volunteers the waist circumference and abdominal depth become statistically significant. The p-value for the waist circumference decreased from 0.1137 to 0.001 and the p-value for the abdominal depth decreased from 0.0187 to <0.001. These lowered p-values suggest that Outlier 2 was highly influential to the outcome of the statistical significance in the two sample t-test.



(a) The outlier who the belt did not reposition for with a waist circumference of approximately 1100 mm at the most forward test condition in the test rig.



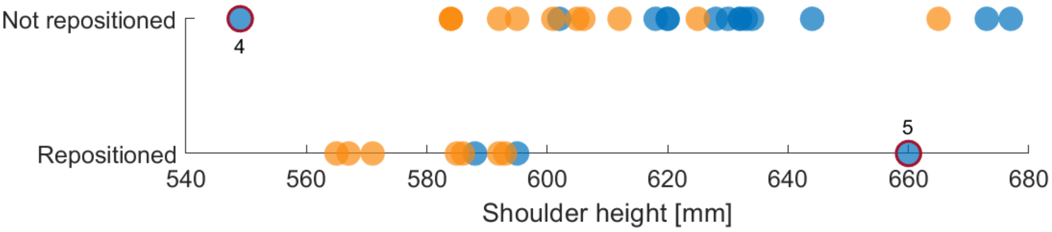
(b) The outlier who the belt did not reposition for with an abdominal depth of approximately 280 mm at the most forward test condition in the test rig.

Figure 5.3: The two outliers identified at the most forward test condition in the test rig, at -387 mm.

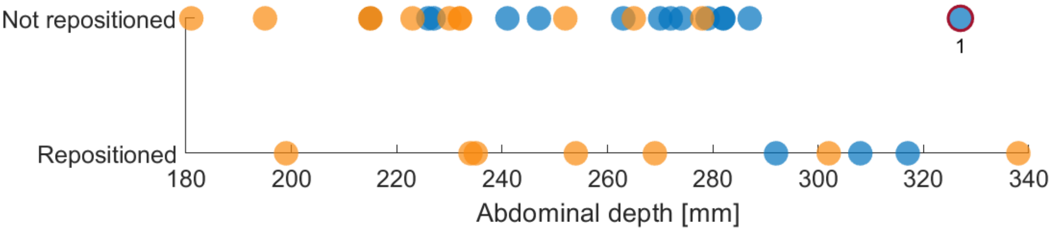
New outliers were identified in the belt-in-seat data, see Figure 5.4. Two male outliers are observed in Figure 5.4a. One male with a shoulder height (sitting) of around 550 mm and the second with a shoulder height of around 660 mm, henceforth referred to as Outlier 4 and Outlier 5 respectively. The belt does not reposition for Outlier 4, who had the shortest of all volunteers, despite the trend of the belt repositioning for short shoulder heights (sitting). The opposite is true for Outlier 5, where the belt repositioned even though a tall shoulder height (sitting) seemingly makes belt reposition more difficult. Regarding the D-ring angle of the belt, Outlier 5 breaks the trend of the belt not repositioning for a negative D-ring angle. This volunteer is the only one with a negative D-ring angle who had the belt reposition. For the abdominal depth in Figure 5.4b, Outlier 1 is again an outlier. A small abdominal depth made belt repositioning more difficult for many volunteers, and a larger abdominal depth made belt repositioning easier. However, this is not the case for Outlier 1. As previously mentioned for Outlier 1, their measurements are generally larger than the mean of the volunteers which probably affected the outcome. Since the outliers do not follow the identified trends for belt repositioning, other measurements may have influenced the belt's ability to reposition.

When observing Figure 5.4a, it is clear that Outlier 4 has the shortest shoulder height (sitting) of all volunteers. This outlier is one standard deviation below the men's mean for shoulder bideltiod breadth, chest depth, and shoulder circumference. These measurements indicate that Outlier 4 has a smaller upper body compared to the other male volunteers. However, Outlier 5 was around the mean value in shoulder height (sitting) but one standard deviation above the mean for the other three upper body measurements. One possible explanation that the belt did not reposition for Outlier 4 while repositioning for Outlier 5 is the relation between the shoulder and the arm. Depending on the torso shape and general upper body structure, the angle created by the shoulder and arm varies between people. For some, there is close to a 90° angle, while it is more of an obtuse angle for others. A more obtuse arm angle in combination with a soft arm seemed to ease belt repositioning while a lean arm with close to a right angle made it more difficult. Meaning, the belt for Outlier 4 may not have repositioned since the arms were closer to the body. Whereas the belt may have repositioned for Outlier 5 since the arms were further away from the body. Another contribution factor, explaining why the belt may have repositioned for Outlier 5 despite the tall shoulder height (sitting) and a negative D-ring angle, is the larger waist circumference and abdominal depth. A large abdominal region changes the belt route, since instead of being positioned across the stomach it is positioned above the stomach.

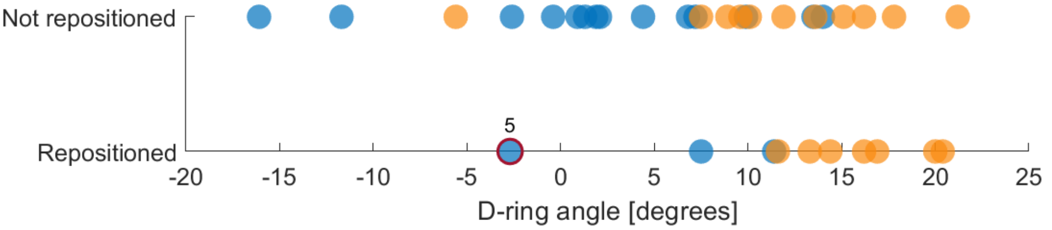
The outliers may have affected the statistical significance of the measurements. Outlier 4 and Outlier 5 may have impacted if shoulder height (sitting) were statistically significant or not. Similarly, Outlier 1 could have impacted the abdominal depth while Outlier 5 could have impacted the D-ring angle. If, hypothetically, first removing Outlier 4 and Outlier 5 from the shoulder height (sitting) data set, then the p-value decreased from 0.016 to <0.001. If removing Outlier 1 from the abdominal depth data set, the p-value is lowered from 0.110 to 0.073. If Outlier 5 is removed from the D-ring angle data set the p-value is lowered from 0.028 to 0.001. This hypothetical calculation mean if outliers were removed from the corresponding data set, then shoulder height (sitting) and D-ring angle would be statistically significant but not abdominal depth. Indicating that the outliers influenced the outcome of the two sample t-test.



(a) The two outliers, one who the belt did not reposition for with a shoulder height (sitting) of approximately 550 mm and one who the belt repositioned for with a shoulder height (sitting) of around 660 mm in the belt-in-seat installation



(b) The outlier that the belt did not reposition for with an abdominal depth of approximately 330 mm in the belt-in-seat installation



(c) The outlier that the belt did not reposition for with an D-ring angle, measured where the belt extend from the D-ring, of approximately -3° in the belt-in-seat installation

Figure 5.4: The three outliers identified at the belt-in-seat installation.

5.5 Limitations

This thesis is subject to several limitations, one being the lack of previous studies within the topic of shoulder belt repositioning. Another limitation is the test rig setup and the small sample size. Since no studies on shoulder belt repositioning was identified, the test procedure in this study was based on procedures from studies in related fields. The test rig setup was a second limitation since the D-ring attachment was based on one vehicle model, the Volvo S60, and therefore it is not representative of the entire vehicle fleet. The test rig itself also has structural differences from a vehicle, meaning the test rig was as close of a replica of a Volvo S60 as possible. Thereby, the outcome of this study is only applicable for the Volvo S60 and vehicles with a similar belt geometry.

The volunteers in this study resulted in a sample that was not representative of the normal distribution of the Swedish population. The outcome is therefore only applicable to this specific sample. Anthropometrically speaking, it means that certain body characteristics may not have been represented in this sample and therefore it is unknown if the belt will reposition for individuals with those measurements. In future belt repositioning studies, it would be beneficial to include a larger sample with a normal distribution of anthropometric measurements to investigate belt repositioning.

5.6 Evaluation of test procedure

An issue with the incremental process was that the belt failed to reposition at 10 cm, but repositioned at 20 cm for some volunteers. This was found since extra tests were conducted out of curiosity for some individuals at 20 cm, even though belt repositioning failed at 10 cm. If one follows the described incremental process in Figure 2.9, the increment at 20 cm should not have been tested. However, this finding indicates that there could be a potential gap in the incremental process. The point-of-no-return defined previously in this study might not exist, but rather critical region(s) or section(s) on the arm where the belt cannot reposition properly. Future studies can implement a different process which includes more increments on the arm and avoids the assumptions made in this study.

The incremental process may not have been an ideal approach to investigate belt repositioning. Belt repositioning was investigated at 10 cm for all volunteers, and thereafter either 5 cm or 20 cm depending on the outcome at 10 cm. The problems arise during the data analysis since it is assumed that the belt will be repositioned at 5 cm if the belt reposition at 10 cm. However, that assumption may be incorrect. There could, for example, be a difference in the belts' velocity at 5 cm compared to 10 cm. When the belt is retracted from 10 cm it may have a higher velocity when reaching the shoulder compared to the velocity at 5 cm. It would have been optimal to have tested belt repositioning at 5 cm for all volunteers to know for sure that the belt reposition at 5 cm and thereby avoid the assumption that it will reposition.

5.7 Excluded volunteers

One male volunteer was excluded due to an improper belt fit. The belt is in contact with the neck in all seat configurations. To avoid unnecessary strain and injuries on the volunteer due an improper belt fit in the reference positions the testing on this volunteer was not finalized. The excluded volunteer brings light to the potential issues that could arise when the belt is repositioned, since it may interfere with the occupant or end up in a worse belt fit than before. This observation indicates that there are several aspects to consider when investigating the possibility to reposition the belt with a pre-pretensioner.

A second male volunteer was excluded from this study due to several big posture changes throughout the testing. The test leaders noticed changes in arm posture during the test, but the largest indication that the occupant adjusted their posture was observed in the test results. Belt repositioning was tested at -346 mm, where it failed. It was therefore hypothesized that belt repositioning would fail at -387 mm. However, this was not the case since belt repositioning succeeded at -387 mm. The test at -346 mm was therefore repeated and this time belt repositioning succeeded. This result indicates that belt repositioning in the seat configuration was not repeatable. When analyzing the video recordings it was found that the volunteer changed their arm, torso, and leg positions throughout the volunteer study. No other volunteer had as distinguishable posture changes during the tests. For the initial test conducted at -346 mm, when belt repositioning failed, the volunteer seemed to have a more upright posture compared to when the test at -387 mm and at the repetition of -346 mm conducted later on. The results from this volunteer therefore provided the insight that posture is an important factor and that it should be investigated further in future belt repositioning studies.

5.8 The data analysis methods

A statistical significance was not achieved between belt repositioning and any of the anthropometric, belt geometry, or belt fit measurements for the most forward position in the test rig and in the belt-in-seat installation. A statistical significance could have been identified if fewer measurements were collected, since the large amount of collected data required a Bonferroni correction. The correction drastically lowered the significance level and no statistical significance in mean values could be identified. However, it is noticeable that very small p-values were obtained for some measurements. The small p-values indicate that certain measurements show tendencies to be linked with belt repositioning, but the difference between the groups could not be statistically significant due to the Bonferroni correction. These measurements were therefore highlighted in the analysis to further investigate possible connections with belt repositioning.

Several measurements that potentially could be linked with the belt repositioning outcome may have been eliminated through the Bonfeeroni correction. Elimination is the purpose of the correction since the chance to make a false rejection of a null hypothesis increases when more measurements are analyzed. To benefit from the two sample t-test it could have been better to therefore have taken fewer measurements in the volunteer study. Fishing can be applicable to this study since it sets the basis for future belt repositioning studies. Therefore, the relevant measurements for belt repositioning identified in this study could be the focal points in future studies. Additionally, the less relevant measurements can be excluded from future studies.

The main data analysis conducted in this thesis is on a fundamental basis with the two sample t-test which compares the mean value of all measurements separately. This analysis is limited and does not include the potential links between several measurements and belt repositioning. For the belt-in-seat data the logistic regression was used to show one example of a possible combination between the measurements. Another way to further analyze the data would be to combine and compare more of the measurements using other methods than the ones implemented in this study. Other methods could provide a more in-depth connection and links between the shoulder belts' ability to reposition and several anthropometric, belt geometry, and belt fit measurements. Meaning, there is a lot of potential analyzes that can be performed on the data collected in this study.

5.9 Suggestions for future research on shoulder belt repositioning

Several suggestions for future studies have been mentioned throughout this discussion. There are however general improvements that can be made that have not been addressed yet. A good starting point for continuing this research would be to learn more about how the belt is worn when positioned on the arm. In the study by Reed et al. (2020), the 22% who wore the shoulder belt incorrectly were identified without details on how they positioned it or what seat positions they used. Identifying and being aware of the occupants' body characteristics, what cars they traveled in, and the critical seat setups (fore-aft position, D-ring position, seat height, and seat back angle) can alter the initial conditions for testing and should therefore be investigated.

The measurements taken were standard anthropometric measurements and, although they are good measurements to relate the volunteers to the general population, they do not reflect the volunteer's measurements while sitting in a car seat. A person's posture differs between sitting upright on a flat surface and comfortably in a car seat. Measuring abdominal depth, shoulder position, and width between elbows with the volunteer seated in the car seat would give a more accurate description of their body posture and hopefully what the main influencing factor on belt repositioning is. With the volunteer seated, it would be interesting to measure where the D-ring is positioned in relation to body parts of the volunteer, the acromion process as one example. One suggestion is to map out the volunteer with a FARO arm, a device used to take coordinates in a three-dimensional coordinate system. That could give understanding for how the position of the shoulder as well as slopes and angles of the arm and shoulder region affect belt repositioning.

An interesting continuation of belt repositioning studies would be to test how to improve belt repositioning in instances where it does not reposition by itself. Investigating if there are adjustments or changes to the current belt installation or change how the pre-pretensioner retracts the belt to help repositioning would be interesting. A change of the algorithm may be relevant since in some instances the belt got stuck on the shoulder and slipped into a more correct position once the pre-pretensioner deactivated. A possible research topic could be on how belt repositioning can be combined with additional safety systems in the car that recognize an improper belt fit, based on some set parameters. Chun et al. (2019) developed a belt detection system that uses image analysis to identify the seat belt on the driver and front seat passenger. Such a belt detection system has the potential to identify if the belt is positioned in a spot from where it cannot be properly repositioned, and in that case issue an auditory warning similar to the fasten seat belt warning in cars.

Finally, since this study only tested belt repositioning in a static environment in a test rig, future studies in dynamic settings are advisable. In a pre-crash scenario there will likely be steering maneuvers, braking, and kinematic forces on the car occupants which can interfere and counteract the pre-pretensioner's belt retraction. The additional forces that load the belt during deceleration or steering could make repositioning difficult with the pre-pretensioner. Therefore, testing the repositioning abilities in dynamic sled tests, and possibly dynamic volunteer tests, is important to understand if the force level used in this study would be enough to retract the belt and how the kinematics influence the results. If repositioning is proven more difficult, warning interventions would be an option to improve belt fit before a critical scenario occurs. Posture and seating positions are also important aspects to test.

5.10 Observations from performing the volunteer study

Throughout the volunteer tests there were several observations made that were not quantifiable with the general results, but worth noting for future research. Some of these are previously touched upon in the discussion, but will be summarized in the following list:

- Slight posture changes seem to make a difference for belt repositioning outcome for some individuals. How much it affects belt repositioning does however seem to vary between people and be related to the body characteristics.

- The belt repositioned for all volunteers in the most common fore-aft position and the mid position but not further forward for the B-pillar installation, indicating that a lower distance between D-ring and H-point in x-direction makes belt repositioning possible. Since a higher D-ring made repositioning possible for all volunteers and the belt-in-seat failed for many volunteers, a larger distance in z-directions seem to make repositioning easier. However, what needs to be considered for the most common seating positions is the general belt fit since the shoulder belt was not in contact with the clavicle or sternum for many volunteers in these positions.

- The arm's angle and position have been discussed briefly. One hypothesis the authors of this thesis have on the subject is that how far out the arm lays in comparison to how far out the chest and abdomen lays plays a part in belt repositioning, in the x-direction and y-direction. It would be interesting to perform these tests on individuals with a bigger difference in chest protrusion compared to abdominal protrusion in combination with how the arms rest on the sides of the car seat.

- When positioning the shoulder belt on the arm there are different ways to route the belt across the abdomen and chest for some individuals. The shape of the abdominal and chest area would for some volunteers create different paths across the upper body. One routing option hypothesized to affect belt repositioning is the placement across the protruding chest area. As previously mentioned in the discussion, the belt seemed to not reposition due to the chest area rather than the shoulder and arm shape for some volunteers, and the initial placement of the shoulder belt could affect the outcome of the repositioning.

- For some volunteers that the belt did not reposition for, the retraction of the shoulder belt with the pre-pretensioner would push the volunteer to the side or press their shoulder upwards, especially in the belt-in-seat installation. This could increase the risk of injury for these individuals since they are moved out of position, something that needs to be addressed given that a similar outcome could be caused by a pyrotechnical pretensioner.

- Although the belt did not reposition for several volunteers, the pre-pretensioner did move the belt closer to the acromion and improved belt fit to some extent. See Appendix C, D, and E for comparisons of the belt position before and after pre-pretensioner activation for several failed belt repositionings. Investigating the effect of a partially repositioned shoulder belt is a possible continuation of this study.

6

Conclusion

This thesis set out to investigate to what extent a shoulder belt positioned on the arm can be repositioned to an on-clavicle position with the help of a belt pre-pretensioner. The aim was to investigate the effect of belt installation, anthromopetric, belt geometry, and belt fit measurements on belt repositioning. Also, from which on arm positions the belt could be repositioned from.

The results from 17 male and 18 female volunteers show that, in a test rig resembling a Volvo S60, the shoulder belt was successfully repositioned for all volunteers in the most common fore-aft positions. Belt repositioning failed for two volunteers in the second most forward position and seven failed in the most forward position. Belt repositioning failed for 25 volunteers in the belt-in-seat installation. For the majority of the 25 volunteers, the belt did not reposition for any tested positions on the arm. Even when repositioning failed, the belt was repositioned to some extent. A common body characteristics of the volunteers that the belt repositionig failed for were a tall shoulder height (sitting) and small abdominal depth. Clothing with lower friction did not affect belt repositioning when the D-ring was at the second most forward position in the rig or in the belt-in-seat installation. The lower friction material made belt repositioning possible in the most forward position in the rig for four out of seven volunteers.

The belt repositioned for all volunteers in the most common seating positions. However, the number of failed repositionings increased with a further forward seat position for a B-pillar mounted D-ring, and failed most frequently in the belt-in-seat installation. The volunteers were not evenly distributed according to the Swedish population, but do represent parts of it. Therefore, additional research should be done to ensure safety for all passengers, especially for belt-in-seat installations. The recommended next step would be to investigate belt repositioning for a variety of car models and different seat configurations to determine to what extent the belt is repositioned in other seat configurations. Future studies should investigate shoulder belt repositioning for additional belt geometries and dynamic scenarios as well as the possibility to implement belt fit warning interventions.

Bibliography

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 [PMID: 31411924]. *Traffic Injury Prevention*, *20*(sup2), S7–S12. https://doi.org/10.1080/15389588.2019.1639159

Buckley, L., Jones, M. L., Ebert, S. M., Reed, M. P., & Hallman, J. J. (2018). Evaluating an intervention to improve belt fit for adult occupants: Promoting positive beliefs. *Journal of Safety Research*, *64*, 105–111. https://doi.org/https://doi.org/10.1016/j.jsr.2017.12.012

Chun, S., Ghalehjegh, N. H., Choi, J. B., Schwarz, C., Gaspar, J. G., McGehee, D. V., & Baek, S. S.-Y. (2019). Nads-net: A nimble architecture for driver and seat belt detection via convolutional neural networks. *2019 IEEE/CVF International Conference on Computer Vision Workshop (ICCVW)*, 2413–2421.

Fong, C. K., Keay, L., Coxon, K., Clarke, E., & Brown, J. (2016). Seat belt use and fit among drivers aged 75 years and older in their own vehicles [PMID: 26158309]. *Traffic Injury Prevention*, *17*(2), 142–150. https://doi.org/10.1080/15389588.2015.1052420

Fritz, M., & Berger, P. D. (2015). Chapter 11 - will anybody buy? logistic regression. In M. Fritz & P. D. Berger (Eds.), *Improving the user experience through practical data analytics* (pp. 271–304). Morgan Kaufmann. https://doi.org/https://doi.org/10.1016/B978-0-12-800635-1.00011-2

Fujita, K., Fujinami, H., Moriizumi, K., Enomoto, T., Kachu, R., & Kato, H. (2003). Development of pre-crash safety system. https://www-esv.nhtsa.dot.gov/Proceedings/18/18ESV-000544.pdf

Hallman, J., Reed, M., & Ebert, S. (2013). Effects of driver characteristics on seat belt fit. *57th Stapp Car Crash Conference*. https://doi.org/https://doi.org/10.4271/2013-22-0002

Hanson, L., Sperling, L., Gard, G., Ipsen, S., & Olivares Vergara, C. (2009). Swedish anthropometrics for product and workplace design. *Applied Ergonomics*, *40*(4), 797–806. https://doi.org/https://doi.org/10.1016/j.apergo.2008.08.007

Hotzman, J., Gordon, C. C., Bradtmiller, B., Corner, B. D., Mucher, M., Kristensen, S., Paquette, S., & Blackwell, C. L. (2011). Measurer's handbook: Us army and marine corps anthropometric surveys, 2010-2011.

IBM Corp. (2021). *Ibm spss statistics for windows* (Version 28.0). Armonk, NY: IBM Corp.

Inc., T. M. (2019a). *Matlab version: 9.11.0.1769968 (r2021b)*. Natick, Massachusetts, United States. https://www.mathworks.com

Inc., T. M. (2019b). *Statistics and machine learning toolbox: 12.2 (r2019b)*. Natick, Massachusetts, United States. https://www.mathworks.com

Jones, M. L. H., Ebert, S. M., Varban, O., Hu, J., Reed, M. P., Weerappuli, P., Sundarajan, S., & Barbat, S. (2021). Effect of class i–iii obesity on driver seat belt fit [PMID: 34402347]. *Traffic Injury Prevention*, *22*(7), 547–552. https://doi.org/10.1080/15389588.2021.1945590

Kahane, C. J. (2015). Lives saved by vehicle safety technologies and associated federal motor vehicle safety standards, 1960 to 2012 – passenger cars and ltvs – with reviews of 26 fmvss and the effectiveness of their associated safety technologies in reducing fatalities, injuries, and crashes. *NHTSA Technical Report*. https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/812069

MacFarlane, I., McCarthy Veach, P., & LeRoy, B. (2014). *Genetic counseling research: A practical guide* [ProQuest Ebook Central]. Oxford University Press, Incorporated. https://ebookcentral.proquest.com/lib/chalmers/detail.action?docID=1681097

Mages, M., Seyffert, M., & Class, U. (2011). Analysis of the pre-crash benefit of reversible belt pre-pretensioning in different accident scenarios.

Peck, R., Olsen, C., & Devore, J. (2008). *Introduction to statistics & data analysis*. Thomson Brooks/Cole.

Reed, M. P., Ebert, S. M., & Jones, M. L. (2020). *Naturalistic passenger behavior: Postures and activities* (tech. rep. UMTRI-2020-2). University of Michigan, Transportation Research Institute. Michigan.

Reed, M. P., Ebert-Hamilton, S. M., & Rupp, J. D. (2012). Effects of obesity on seat belt fit [PMID: 22817551]. *Traffic Injury Prevention*, *13*(4), 364–372. https://doi.org/10.1080/15389588.2012.659363

Rice, J. (2007). *Mathematical statistics and data analysis*. Thomson Brooks/Cole.

Schoeneburg, R., Baumann, K., & Fehring, M. (2011). The efficiency of pre-safe®systems in pre-braked frontal collision situations.

Schoeneburg, R., & Breitling, T. Enhancement of active passive safety by future pre-safe systems. In: Publisher National Highway Traffic Safety Administration, 2005, June.

Euro NCAP. (2023). European new car assessment programme (euro ncap). https://cdn.euroncap.com/media/70318/euro-ncap-mpdb-testing-protocol-v113.pdf

National Center for Statistics and Analysis. (2019). Lives saved in 2017 by restraint use and minimum drinking-age-laws [(Traffic Safety Facts Crash • Stats. Report No. DOT HS 812 683)]. *National Highway Traffic Safety Administration*. crashstats.nhtsa.dot.gov/Api/Public/%20ViewPublication/812683

Swedish Standards Institute. (2017). Basic human body measurements for technological design – part 1: Body measurement definitions and landmarks (iso 7250-1:2017) [Edition 2].

Tobata, H., Takagi, H., Pal, C., & Fukuda, S. (2003). Development of pre-crash active seatbelt system for real-world safety.

van Teijlingen, E. R., & Hundley, V. (2002). The importance of pilot studies. *Nursing standard*, *16(40)*, 33–6. https://doi.org/10.7748/ns2002.06.16.40.33.c3214

A

Volunteer measurements

The table below present all anthropometric data collected from the volunteers, where volunteer 36∗ and 37∗ were excluded from the study.

Volunteer number	Age (years)	Sex (F/M)	Weight (kg)	Stature (mm)	Wall-acromion distance (mm)	Sitting height (mm)	Shoulder height (sitting) (mm)	Chest depth (mm)	Chest breadth (mm)	Chest circumference (mm)	Waist circumference (mm)
1	34	M	94,6	1948	145	961	634	256	353	1109	1004
2	19	F	67,2	1744	100	902	593	179	285	896	770
3	27	M	71,2	1773	120	907	620	237	312	1021	874
4	34	M	78,6	1801	109	982	644	241	291	1020	851
5	56	M	81,6	1760	98	905	588	229	321	1023	1046
6	52	M	82,7	1846	117	980	628	237	339	1068	881
7	46	F	76,4	1691	106	884	584	208	274	984	1005
8	56	M	95,5	1802	149	925	595	279	376	1232	1091
9	53	M	85,7	1845	92	960	630	220	340	1040	1005
10	37	M	112,6	1940	128	1012	677	273	376	1219	1175
11	51	M	101,2	1804	150	928	618	242	350	1149	1022
12	31	M	79,8	1812	122	974	632	214	325	1005	983
13	46	F	63,8	1645	123	885	584	193	263	976	859
14	47	F	65,4	1762	108	875	584	192	274	915	812
15	51	F	73,6	1768	80	935	625	193	286	955	886
16	50	M	108,7	1842	159	970	673	268	384	1216	1106
17	46	F	54,5	1577	86	873	592	175	251	860	770
18	52	M	95,5	1797	137	949	660	239	338	1059	1076
19	57	F	75,6	1672	111	882	567	211	305	981	910
20	49	F	80,8	1660	117	874	601	212	315	1055	999
21	64	F	84,4	1654	129	864	571	245	352	1150	1171
22	44	M	74,2	1757	127	940	620	208	306	986	889
23	38	M	74,1	1707	123	869	549	208	293	939	831
24	43	F	65,2	1730	100	890	595	185	281	898	808
25	24	F	88	1685	87	893	586	213	328	1115	1002
26	61	M	80,9	1795	144	917	633	246	322	1011	975
27	27	F	65,3	1708	103	917	606	195	281	905	806
28	42	M	83,6	1842	145	941	632	254	333	1098	976
29	29	F	63,8	1812	107	960	665	169	291	872	795
30	49	F	62	1675	114	888	585	177	287	905	799
31	45	M	94,9	1733	138	912	602	287	344	1159	1025
32	22	F	76,4	1685	117	904	605	209	290	982	881
33	20	F	68	1632	85	891	592	192	268	898	831
34	19	F	78,4	1760	105	936	612	166	280	973	813
35	35	F	60,3	1552	97	863	565	189	272	879	865
36*	19	M	78,6	1911	117	1454	659	369	310	1006	853
37*	69	M	76,4	1640	123	1311	558	397	342	1109	1057

Volunteer number	Shoulder circumference (mm)	Shoulder length (mm)	Shoulder-elbow length (mm)	Shoulder (biacromial) breadth (mm)	Shoulder (bideltoid) breadth (mm)	Elbow-to-elbow breadth (mm)	Hip breadth (mm)	Abdominal depth (mm)	Thorax depth (mm)
1	1296	172	420	417	538	552	442	263	282
2	1064	135	373	356	454	403	433	234	227
3	1186	134	393	356	475	498	375	226	257
4	1205	124	389	351	473	496	408	227	264
5	1180	133	377	366	473	463	408	308	261
6	1243	142	386	378	499	533	401	241	269
7	1139	115	344	326	461	465	433	265	277
8	1370	140	396	369	503	511	402	317	324
9	1264	154	394	408	506	512	377	282	243
10	1383	144	418	388	548	575	498	327	308
11	1295	130	386	361	505	506	406	287	299
12	1209	133	372	358	486	471	372	270	233
13	1075	115	329	333	424	425	399	215	259
14	1002	123	387	324	402	435	385	252	248
15	1085	136	365	348	447	421	433	230	256
16	1331	140	404	403	539	569	456	282	305
17	985	114	318	322	397	359	409	195	218
18	1233	140	387	375	498	502	414	292	274
19	1125	146	356	374	457	454	465	269	266
20	1189	134	349	344	474	495	441	278	297
21	1208	134	361	367	469	499	427	338	345
22	1165	143	362	365	468	441	392	215	243
23	1167	132	383	350	462	451	369	247	244
24	1060	126	367	332	428	409	385	181	224
25	1226	145	359	355	498	487	416	302	293
26	1131	141	399	365	472	435	370	279	271
27	1054	124	353	346	425	411	400	232	229
28	1209	140	406	359	486	475	406	274	284
29	1046	131	378	347	436	372	399	215	205
30	1084	121	346	314	432	405	407	199	220
31	1291	130	389	356	516	562	435	272	323
32	1135	116	355	308	433	397	451	232	253
33	1098	115	360	326	448	429	448	254	228
34	1139	136	364	339	458	445	420	223	240
35	1092	121	334	340	438	418	401	235	222
EXC	1199	145	400	682	504	491	416	223	233
EXC	1176	124	354	358	466	556	394	294	285

B

Summary of volunteer measurements

Table B.1: A summary of all anthropometric measurements that were taken presented for all volunteers. All measurements above the midrule were taken while standing and the ones below while seated. All data is given in millimeter except age and weight that is given in years and kilograms respectively.

Measurement	Males				Females			
	Mean	SD	Min	Max	Mean	SD	Min	Max
Age	44.9	10.0	27	61	38.5	14.2	19	64
Weight	88.0	12.2	71.2	112.6	70.5	9.1	54.5	88
Stature	1812.0	63.4	1707	1948	1689.6	66.8	1552	1812
Wall-acromion distance	129.6	18.8	92	159	104.2	13.6	80	129
Chest depth	243.4	23.9	208	287	194.6	19.4	166	245
Chest breadth	335.5	27.4	291	384	287.9	24.2	251	352
Chest circumference	1079.6	88.3	939	1232	955.5	82.2	860	1150
Waist circumference	988.8	97.4	831	1175	876.8	106.0	770	1171
Shoulder circumference	1244.6	73.8	1131	1383	1100.3	65.2	985	1226
Shoulder length	139.5	10.9	124	172	127.1	10.4	114	146
Sitting height	943.1	35.7	869	1012	895.3	26.5	863	960
Shoulder height (sitting)	625.6	31.2	549	677	595.1	23.2	565	665
Shoulder-elbow length	391.8	15.0	362	420	355.4	17.2	318	387
Shoulder biacromial breadth	372.1	20.4	350	417	338.9	17.7	308	374
Shoulder bideltoid breadth	496.9	26.4	462	548	443.4	24.9	397	498
Elbow-to-elbow breadth	503.1	44.1	435	575	429.4	39.2	359	499
Hip breadth	407.7	34.4	369	498	419.6	23.2	385	465
Abdominal depth	271.1	31.9	215	327	241.6	38.9	181	338
Thorax depth	275.5	28.4	233	324	250.4	35.3	205	345

C

Failed belt repositioning images of volunteers at -346 mm

(a) Volunteer 4: Before **(b)** Volunteer 29: Before

(c) Volunteer 4: After **(d)** Volunteer 29: After

Figure C.1: The shoulder belt position when positioned 10 cm down the arm, before, and the position after the pre-pretensioner was activated (after). The after image is taken when the belt pre-pretensioner held the belt with a constant force in an improper position for the volunteers.

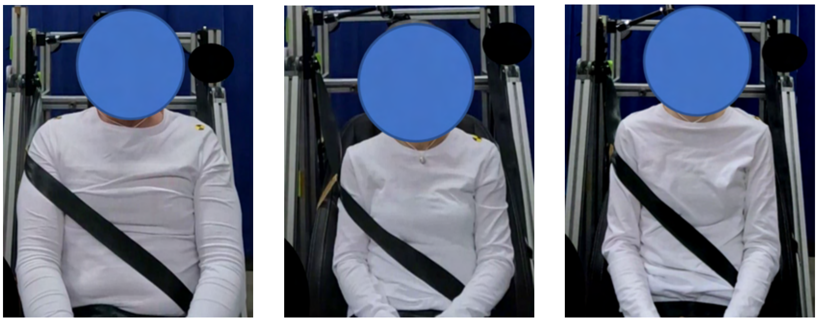
D

Failed belt repositioning images of volunteers at -387 mm

(a) Volunteer 3: Before **(b)** Volunteer 4: Before **(c)** Volunteer 6: Before **(d)** Volunteer 13: Before

(e) Volunteer 3: After **(f)** Volunteer 4: After **(g)** Volunteer 6: After **(h)** Volunteer 13: After

Figure D.1: Images displaying the before and after for 4 out of the 7 volunteers the belt did not reposition for. The shoulder belt position when positioned 10 cm down the arm, before, and the position after the pre-pretensioner was activated for the most forward position in the test rig. The before images are depicted in the top row while the corresponding after images are depicted in the bottom row. The after image is taken when the belt pre-pretensioner held the belt with a constant force in an improper position for the volunteers.



(a) Volunteer 16: Before **(b)** Volunteer 17: Before **(c)** Volunteer 29: Before

(d) Volunteer 16: After **(e)** Volunteer 17: After **(f)** Volunteer 29: After

Figure D.2: Images displaying the before and after for the remaining 3 out of the 7 volunteers the belt did not reposition for. The shoulder belt position when positioned 10 cm down the arm, before, and the position after the pre-pretensioner was activated for the most forward position in the test rig. The before images are depicted in the top row while the corresponding after images are depicted in the bottom row. The after image depicts when the belt pre-pretensioner held the belt with a constant force in an improper position for the volunteers.

E

Failed belt repositioning images of volunteers at the belt-in-seat installation

Only a selection, 8 of 25, of the volunteers that the belt did not reposition for are depicted in Figure E.1 and Figure E.2.

(a) Volunteer 1: Before **(b)** Volunteer 3: Before **(c)** Volunteer 4: Before **(d)** Volunteer 6: Before

(e) Volunteer 1: After **(f)** Volunteer 3: After **(g)** Volunteer 4: After **(h)** Volunteer 6: After

Figure E.1: Images displaying the before and after for 4 out of the 25 volunteers the belt did not reposition for. The shoulder belt position when positioned 10 cm down the arm, before, and the position after the pre-pretensioner was activated in the belt-in-seat installation. The before images are depicted in the top row while the corresponding after images are depicted in the bottom row. The after image depicts when the belt pre-pretensioner held the belt with a constant force in an improper position for the volunteers.

(a) Volunteer 7: Before

(b) Volunteer 9: Before

(c) Volunteer 14: Before

(d) Volunteer 20: Before

(e) Volunteer 7: After

(f) Volunteer 9: After

(g) Volunteer 14: After

(h) Volunteer 20: After

Figure E.2: Images displaying the before and after for 4 out of the 25 volunteers the belt did not reposition for. The shoulder belt position when positioned 10 cm down the arm, before, and the position after the pre-pretensioner was activated in the belt-in-seat installation. The before images are depicted in the top row while the corresponding after images are depicted in the bottom row. The after image depicts when the belt pre-pretensioner held the belt with a constant force in an improper position for the volunteers.

DEPARTMENT OF SOME SUBJECT OR TECHNOLOGY
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden
www.chalmers.se