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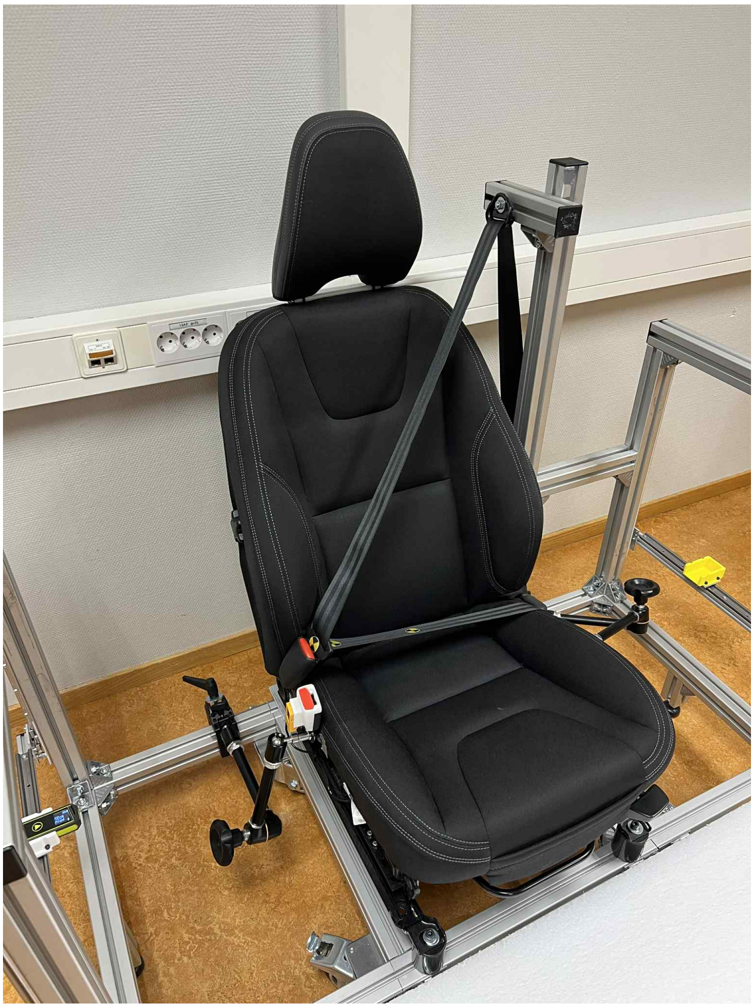

Effects of body characteristics on lap belt fit and comfort

Master's thesis in Biomedical Engineering

William Johansson and Stina Ström

DEPARTMENT OF MECHANICS AND MARITIME SCIENCES
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William Johansson and Stina Ström

Supervisor: Amanda Hederskog, Autoliv; Arun Muthumani, Autoliv
Examiner: Johan Davidsson, Mechanical Engineering

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Mechanics and Maritime Sciences
Division of Vehicle Safety
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

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William Johansson and Stina Ström
Department of Mechanics and Maritime Sciences
Chalmers University of Technology

Abstract

Proper seat belt fit is crucial for occupant safety and comfort, as incorrect positioning may reduce injury protection and increase discomfort, potentially leading to misuse. This study investigates how individual body characteristics influence lap belt fit and perceived comfort, with particular focus on anthropometry and seating posture, determined by the seatback recline angle. A controlled laboratory study was conducted using a test rig representing a vehicle seating environment. Thirty adult participants, balanced by sex and distributed across Body Mass Index (BMI) categories, were evaluated in two seatback configurations (upright and semi-reclined). Three lap belt anchorage conditions were assessed: a manufacturer-defined position (P1), a forward-shifted position (P2), and a user-selected position.

Objective measurements (anthropometry, belt geometry relative to the anterior superior iliac spine, and buckle position) and subjective assessments (perceived comfort, perceived safety, and usability) was used. Statistical analyses were used to identify relationships between body characteristics and belt fit. The results show that seatback recline angle has the strongest influence on lap belt fit, followed by BMI and anthropometric measures. Higher BMI is consistently associated with a more superior lap belt position relative to the pelvis, reflected as an upward displacement of both belt segments. However, the belt position relative to the pelvis in the anterior–posterior direction is strongly affected by seating posture, with reduced anthropometric predictability in the semi-reclined condition.

P2 generally reduced perceived abdominal pressure and improved usability, particularly in terms of buckle accessibility and ease of buckling, but introduced trade-offs such as increased perceived thigh loading and shoulder belt interference. Despite these improvements in local comfort, P2 was perceived as less safe than P1, however, perceived safety does not necessarily reflect actual restraint performance. User-selected positions minimized discomfort in most cases but were typically located outside regulatory acceptance regions, indicating a mismatch between user preference and standards.

The findings highlight the combined influence of anthropometry, seatback recline angle, and restraint geometry on lap belt fit, showing that no single factor explains occupant variability. This study contributes empirical evidence supporting the need to consider occupant diversity and seatback recline angle in future restraint system design, particularly in the development of more adaptive anchorage positions.

Keywords: Anthropometry, ASIS, BMI, Human factors, Lap-belt fit, Lower belt anchorage position, Occupant posture, Seat belt comfort, and Usability

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Stina Ström & William Johansson, Gothenburg, May 2026

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
Euro NCAP	European New Car Assessment Programme
H-point	Hip-point
PMHS	Post-mortem human subject
P1	Manufacturer lower belt anchorage position
P2	Modified lower belt anchorage position, located 10 cm forward of P1
SAT	Subcutaneous adipose tissue
SgRP	Seating Reference Point

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Introduction

Around 1.2 million people die every year in road traffic crashes and between 20–50 million more suffer non-fatal injuries, some of which result in long-term disability [1]. Measures such as speed limits and seat belt use are essential for reducing crash risk and injury severity [1]. The three-point belt, which was introduced in Sweden in 1959, is one of the most important safety restraints in passive vehicle safety and reduces injuries as well as fatalities in crashes [2]. Globally, the implementation of seat belts is estimated to save approximately 121,000 lives annually [3].

In addition to overall vehicle safety, the fit, and positioning of seat belts are critical for both occupant protection and comfort. Observational studies using video monitoring of front-seat passengers in 75 vehicles showed that, although seat belts were worn in 97% of trips, visibly poor fit, such as placement on the belly, occurred in approximately 12.4% of cases [4]. Lap belt fit is influenced by individual characteristics, including body mass and sex, which can affect both comfort and the effectiveness of restraint during impacts [5], [6]. Understanding how the lap belt and the lower anchorage positions interact with occupant anthropometry is therefore essential for optimizing seat belt design and ensuring safe and comfortable use across diverse populations [7], [8].

1.1 Background

While safety, aesthetics, and packaging remain key considerations in vehicle design, comfort during travel has become increasingly important, particularly in high-income countries where driving is routine and generally perceived as safe [1], [9]. Several studies have shown that poor belt fit can cause discomfort, leading drivers to reposition the belt or use accessories that may compromise safety [10], [11]. In addition, occupant posture influences lap belt fit. More reclined seating positions can change how the belt rests on the body and reduce engagement with the pelvis, potentially increasing the risk of submarining [12]. The shoulder belt should be positioned across the middle of the collarbone, and the lap belt should sit low on the hips, in contact with the thighs and as close to the body as possible [13]. During frontal crashes, the lap belt should load the anterior edge of the ilium so that the anterior superior iliac spine (ASIS) can act as a hook to reduce the risk of the belt sliding into the abdominal region [12]. Suboptimal belt fit can be associated with submarining kinematics, which occurs when the lap belt fails to engage the pelvis and instead loads the soft tissues of the abdomen during a frontal impact [14]. This mechanism has been linked to an increased risk of serious abdominal and thoracic trauma due to concentrated belt forces. In addition, excessive forward motion of the lower body may increase interactions with the vehicle interior, elevating the likelihood of lower extremity injuries.

Previous studies have shown that seat belt fit and comfort vary with individual body characteristics, such as body mass, sex, abdominal shape, and age [5], [6], [15]. Women generally position the lap belt higher on the abdomen than men, although these differences are largely explained by anthropometric variation rather than sex alone [5], [15]. Age has been shown to have a measurable but relatively small effect on belt positioning, with older occupants tending to adopt a slightly more anterior and superior belt position and extracting more webbing from the retractor [16]. These effects are minor compared to those associated with BMI and overall body composition.

Assessment of lap belt position relative to the pelvis is affected by soft tissue thickness, which may lead to underestimation when using skin-based measurements. In a previous study, BMI-based corrections were applied to estimate skeletal landmark locations, indicating that the lap belt is positioned further anterior relative to the bony pelvis than suggested by surface measurements, particularly in individuals with higher BMI [16]. Consistent with this, a retrospective analysis of 230 belted occupants in frontal collisions showed that obese occupants were more likely to position the lap belt superior to the ASIS compared to occupants with normal BMI [17], indicating that increased body mass influences lap belt positioning relative to the pelvis. With BMI levels rising worldwide [18], improper seat belt fit is likely to affect an increasingly larger portion of the population.

Consequently, the variations in lap belt positioning caused by different body characteristics lead to perceived comfort being closely related to belt fit. However it still remains difficult to quantify and this is mainly due to its subjective nature. While comfort is broadly defined as a general feeling of well-being, discomfort is typically a direct response to physical disturbances, such as localized pressure or irritation from improper belt routing [19], [20], [21]. Because objective physical interactions must ultimately be correlated with subjective human perception, there is a clear need to better understand how changes in belt fit affect both the belt–pelvis interaction and perceived discomfort across diverse body types.

Furthermore, the geometry of the lap belt is not solely determined by occupant characteristics, but is also constrained by the location of the belt anchorage points, which define the belt routing relative to the pelvis. As a result, the achievable belt position and angle are limited by the fixed geometry of the restraint system. Current regulatory frameworks, such as UNECE Regulation No. 14 [22] and FMVSS Standard No. 210 [23], define allowable positions for lower belt anchorages primarily based on safety performance. While these regulations are essential for ensuring occupant protection, they also constrain design flexibility. A study of older occupants has shown that up to 40% exhibit poor lap belt fit, most commonly with the belt positioned too high over the abdomen [5]. Such belt positioning may reduce effective interaction between the lap belt and the pelvis, potentially increasing the risk of submarining during a frontal impact. Research has shown that lap belt angle is the most influential design parameter affecting lap belt-to-pelvis interaction, while occupant characteristics such as pelvis angle and adipose tissue thickness can further increase the risk of the belt sliding over the pelvis [7]. Recent experimental research using post-mortem human subjects (PMHS) demonstrates that forward-positioned lower belt anchors, which reduce the belt-to-pelvis angle, allow higher lap belt loads while lowering the risk of pelvic wing fractures [8]. These findings suggest that adjusting the lap belt anchorage positions may enhance safety by reducing the risk of submarining and promoting more optimal load distribution across the pelvis.

Developing seat belt solutions that enhance comfort while maintaining high safety standards for a diverse population is therefore crucial for increasing correct seat belt usage and improving occupant protection in real-world scenarios.

1.2 Objectives

The objective of this master's thesis was to investigate how individual body characteristics and sitting posture affect lap belt fit and perceived comfort. This was explored by conducting a volunteer study to identify user-preferred lap belt anchorage positions in relation to perceived comfort, as well as lap belt fit.

The research questions for this project are formulated as follows:

1. How does lap belt fit vary with occupant body characteristics and sitting posture?
2. How does lap belt geometry influence perceived comfort during use?
3. How do user-preferred adjustments to lap belt anchorage positions influence lap belt fit and perceived comfort?

1.3 Delimitations

This project focused on lap belt fit and perceived comfort in a controlled static seating environment. To maintain a feasible scope, the following delimitations are defined:

- The study does not include dynamic loading or crash testing. Consequently, the results are limited to static belt fit, subjective comfort assessment, and safety assessment in a laboratory environment.
- The shoulder belt geometry and belt tension are not evaluated in terms of their influence on posture or lap belt fit. The D-ring is adjustable and set to three predefined positions, but its effect on posture and lap belt fit is not analyzed in this study. The shoulder belt is included to reflect a realistic seating environment and is otherwise kept constant.
- Only a simplified vehicle seating environment is considered. Factors such as vehicle motion and long-duration driving are not included and may influence

comfort in real-world conditions.
- The study focuses on adult occupants only.
- The participant sample size is limited to what is feasible within the time frame of a master's thesis.
- The study evaluates perceived comfort and user preference rather than objective measures, such as physiological responses.
- This study evaluated positions of the lower belt anchorages that are outside the accepted range stated in the regulations [22], [23]. It investigated perceived comfort and lap belt fit rather than the regulatory issues.

These delimitations are necessary to ensure that the project remains achievable while still providing meaningful insights into lap belt fit and comfort.

1.4 Societal, Ethical, and Ecological Aspects

The study was conducted in accordance with ethical guidelines for research involving human participants. All participants provided informed consent and were informed about the purpose and procedure of the study. It was clearly communicated that no dynamic loading or crash testing was involved, and participant well-being was prioritized throughout the experiment. Participants were also informed that they could withdraw at any time without providing a reason and without any consequences. To reduce occupational bias and ensure a diverse sample, recruitment was conducted by an external third party, thereby avoiding over-representation of individuals with a professional background in automotive safety.

The study addresses societal aspects related to vehicle occupant safety and comfort, which are directly linked to public health outcomes. Improved understanding of lap belt fit and comfort may contribute to increased seat-belt acceptance and reduced injury risk at a population level. Inclusivity was considered by including participants of varying biological sex, age, and body mass index, supporting the development of restraint systems that better accommodate a diverse user population.

Data privacy was ensured by handling all sensitive information, including anthropometric measurements, in accordance with applicable data protection regulations. All data were anonymized and stored securely, and testing was conducted in a controlled laboratory environment. From an ecological perspective, the study was performed in a setting without vehicle operation or emissions. The adjustable and reusable test rig minimizes environmental impact, and the findings may indirectly support more sustainable vehicle design by improving user acceptance of safety systems.

2

Theory

2.1 Lap belt geometry

According to UNECE Regulation No. 14 [22], a safety-belt is defined as a restraint system consisting of straps with a securing buckle, adjusting devices, and anchorage positions that can be placed on the interior of a vehicle. It is designed to limit occupant motion and reduce injury risk during a collision or sudden deceleration. Seat belts are commonly classified by lap belts, diagonal belts, and three-point belts, which are a combination of both. The geometry of a lap belt directly influences how it engages the pelvis and interacts with occupant tissues, emphasizing the importance of proper lap belt routing and fit [12].

The lap belt should lie low on the hips, over the bony pelvis at the anterior superior iliac spines (ASIS), and remain in contact with the lower abdomen and thighs [13]. This positioning prevents submarining, which is when the belt slides over the abdomen and transfers crash forces to soft tissues rather than the pelvic bones [14]. The bony pelvis is a ring-like structure that creates a strong base, connecting the legs and supporting the upper body [24]. The top edge of each hip bone, called the iliac crest, ends at the ASIS, which serves as a landmark for lap belt placement. Bone tissue is strong and resilient, with a collagen framework that absorbs energy together with a mineral matrix that resists deformation [25]. This allows the pelvis to protect internal organs and provide stable attachment sites for muscles. In contrast, soft tissues such as muscle and connective tissue are more deformable and viscoelastic, meaning the lap belt cannot rely on them to resist crash forces [26]. This underscores why proper lap belt fit over the bony pelvis is critical for minimizing injury risk during frontal impacts.

2.2 BMI and Anthropometry

Body mass index (BMI) and anthropometry are key factors influencing lap belt fit in vehicle occupants. BMI provides a general classification of weight status, while anthropometric measures such as waist, hip, and thigh circumferences capture the distribution of body fat and muscle. Together, these measures give a more complete picture of occupant body shape and how it can affect lap belt fit.

2.2.1 Body Mass Index

BMI is calculated using the formula:

$$\text{BMI} = \frac{\text{weight (kg)}}{\text{stature (m)}^2} \tag{2.1}$$

and is commonly used to categorize individuals into weight ranges that indicate potential health risks [27]. According to the National Institutes of Health, BMI classifications are as follows: below 18.5 kg/m^2 is underweight, 18.5–24.9 kg/m^2 is normal weight, 25–29.9 kg/m^2 is overweight, and 30 kg/m^2 and above is considered obese [28]. Overweight and obese individuals generally position the lap belt higher and more forward on the abdomen relative to the pelvis [16]. Based on quantitative measurements from a volunteer-based study, an increase in BMI of 20 kg/m^2 has been associated with the lap belt being positioned approximately 102 mm further forward and 94 mm higher relative to the pelvis, as well as substantially increased belt webbing length [16].

2.2.2 Body Composition

BMI is an indirect measure of body composition and does not fully capture variations in fat and muscle distribution. Waist circumference, hip circumference, and thigh circumference provide a more detailed representation of abdominal fat distribution for both men and women [29]. Hip and thigh circumference are positively associated with subcutaneous adipose tissue (SAT) in the abdomen and lower body, as well as with skeletal muscle mass [29]. SAT is the deepest layer of subcutaneous fat, lying beneath the skin and above the muscle [30]. Combining BMI with waist, hip, and thigh circumference provides a better understanding of body composition.

Research indicates that individuals with similar BMI may have markedly different tissue distributions, influencing lap belt positioning [31]. Based on the numerical study by Naseri et al. [7], forward positioning of the lap belt is associated with thicker layers of SAT, which alters the belt–pelvis interaction. The study further demonstrated that both the initial lap belt position and the lap belt angle relative to the pelvis influence this interaction mechanism. Furthermore, the combined effect of these factors is particularly pronounced for obese occupants, resulting in an increased risk of the lap belt sliding over the iliac crest during a frontal collision [7].

2.2.3 Posture

3D CT investigations have shown that seated posture affects pelvis orientation and belt–pelvis angle [12]. Slouched or reclined postures tilt the pelvis and modify the belt–pelvis angle, while belt–ASIS overlap is more strongly associated with anthropometry. In upright sitting postures, higher BMI increases thigh height while ASIS height remains relatively constant, reducing the ASIS–thigh distance and affecting belt–ASIS overlap [32]. When the posture is reclined, the lap belt shifts upward and rearward relative to the ASIS, reducing overlap and potentially increasing the risk of submarining.

2.3 Occupant behaviour

Occupant behaviour, including seat adjustment and posture choices influence the position of the lap belt. A field study of 127 drivers demonstrated that occupants adjust trunk-thigh angle, seatback inclination, and foot placement according to personal preferences, which are affected by age, sex, and stature [33].

2.3.1 Seat Adjustment Parameters

Parameters such as fore–aft position, seat height, and seatback angle affect lap belt geometry and its interaction with the occupant. Fore-aft seat position significantly influences occupant posture and lap belt interaction. Studies using multi-adjustable vehicle mock-ups have shown that when drivers sit further forward in the seat, their trunk–thigh angle increases and the trunk tends to recline more [34].

Seat height and backrest angle further influence lap belt fit by altering the occupant's pelvis orientation and thigh angle. Lower seat heights increase the thigh angle relative to horizontal, which can result in the lap belt sitting higher and more forward over the ASIS [6]. Similarly, a more reclined backrest tilts the pelvis rearward, changing the belt-pelvis angle and potentially reducing belt-ASIS engagement [12]. Together, these adjustments modify the relative geometry between the lap belt and the occupant, affecting both comfort and the risk of submarining in frontal collisions. Field measurements in passenger vehicles show that seatback angles average 25.1° with 95% of seats reclined less than 34° [4]. Fore-aft seat positions are on average 60 mm forward of full-rear, corresponding to roughly 28% of the total track length, with 87% of seats positioned rearward of the mid-track point. These distributions confirm that occupants frequently sit in positions that increase thigh angle and tilt the pelvis, showing the influence of seat adjustment parameters on lap belt fit and occupant safety.

2.4 Comfort in Vehicle Seating

Automotive seating is designed by considering safety, comfort, and aesthetics for the occupants. Comfort in the vehicle is often cited as the most important factor for occupant satisfaction, even surpassing other design considerations [9]. To prevent occupants from getting injured during vehicle crashes a good seat belt fit is important. However, due to discomfort the belt is sometimes misplaced which in turn increases the risk of severe injuries during crashes [5].

2.4.1 Definition of Comfort and Discomfort

Comfort is defined as the feeling of satisfaction and enjoyment, whereas discomfort is defined as the physical or mental uneasiness [19]. More recent research suggests that comfort and discomfort are not simply opposites and should therefore be treated on independent scales [20], [35]. They also mention that pure absence of discomfort may not result in comfort. Defining comfort in a seated position is complex, as it involves both physical sensations and psychological perceptions. Comfort is inherently subjective and can vary based on personal preference whereas discomfort in a seated position is less complex and easier to define and relate to [20]. It is typically described as a body's reaction to physical disturbances from the environment, such as pressure distribution or posture. It is also mentioned that discomfort increases with time on task and that it is often perceived identically by different people [20].

There is often a necessary trade-off between safety and comfort in seat design and the use of occupant restraint systems. Poor comfort can contribute to driver fatigue, potentially compromising overall vehicle safety [9], [36]. Achieving the optimal safety position, where the seat belt distributes forces evenly, can sometimes cause discomfort, particularly if the belt geometry does not match the occupant's anthropometry. In a study of drivers aged 75 and older, 90% found their seat belt comfortable, yet 21% repositioned it to improve comfort, with females being 7.3 times more likely to report discomfort [5]. Additionally, discomfort may lead to changes in posture (to relieve muscle fatigue) and increase the use of accessories such as seat cushions or belt pads, which can introduce slack into the restraint system further reducing the effectiveness of the seat belt in the event of a collision [5].

Seating comfort is generally categorized into static comfort, which is the occupant's experience during the initial period of sitting, and dynamic comfort, which relates to the experience of sitting during extended hours [36]. Static comfort is primarily determined by physical characteristics such as the geometry and material properties of the safety system. Dynamic comfort is influenced by how forces and vibrations are transmitted to the occupant [37]. Research indicates that a minimum of 30 minutes of discomfort is required to evoke a behavioural response in the driver [37].

2.4.2 Objective and Subjective Comfort

Regarding automotive development, comfort is evaluated using both subjective and objective methods to ensure robustness [35]. Data collection is generally categorized as qualitative and quantitative data. Qualitative data consists of descriptive, non-numerical information that addresses "how and why" questions, often covering perceptions, feelings, and emotions. In contrast, quantitative data is numerical and computed to measure specific variables [38]. Subjective or perceived comfort refers to the direct assessment of an occupant's feelings regarding the seating system. In this context, the overall comfort can be related to local discomfort which often manifests as irritation caused by improper belt routing [21]. The primary advantage of subjective measurement is that it directly addresses the user's perception [35].

Common instruments for collecting subjective measurements such as behaviours include questionnaires, interviews, and rating scales, such as Likert scales, which have been used in previous studies exploring seat comfort [39], [40]. The Likert scale is an effective and widely used instrument for measuring attitudes, perceptions, and opinions by providing a range of degrees of response to a given statement [41]. There are on-going discussions regarding which number of points is the most effective way of capturing perceptions. The five point scale is a widely used rating scale for this case and is supported by ergonomic and human factors research, which shows that a limited number of response options increases accessibility, reduces cognitive load, and facilitates consistent interpretation across participants [42], [43]. For example, Drury and Coury [42] demonstrated that a 5-point scale effectively captured seated comfort in laboratory settings. While larger scales (more than 7-points) can offer finer granularity, they may increase variability due to differences in individual perception of scale intervals [41]. Interviews are also a useful instrument when dealing with sensitive concepts where a more detailed answer is needed [38].

Objective comfort, on the other hand, utilizes physical measurements to evaluate the interaction between the occupant and the system. A common objective parameter is interface pressure distribution [35], and are generally less time-consuming to achieve reliable data compared to subjective assessments. However, a limitation is that objective methods measure physical quantities rather than comfort itself. Therefore, objective data is only valid for comfort evaluation if a correlation can be established between the physical measurement and the feeling of comfort [35].

2.5 Lap Belt Anchorage Positions

Lap belt anchorages are positioned to ensure occupant safety and comfort. Their locations are based on key seating reference points, such as the Hip-point (H-point) and Seating Reference Point (SgRP or R-point), and must comply with regulatory requirements like the FMVSS Standard No. 210 and the UNECE Regulation No. 14.

2.5.1 Seating Reference System

The H-point is the fundamental reference point for the occupant's seating posture. It represents the pivot point between the torso and the thigh [44]. The SgRP is a specific, unique H-point location designated by the manufacturer for each seating position. While an adjustable seat has many potential H-point locations along its travel path, only one is defined as the SgRP. The SgRP is critical because it serves as the origin for positioning other design tools, such as head clearance contours, and defines key vehicle dimensions such as legroom and shoulder room.

In an vehicle with fixed seats calculations for SgRP are simplified. An automotive seat is defined as a fixed seat if it lacks fore-aft and height adjustment mechanisms. Since a fixed seat lacks a travel path, the determination of the SgRP is simplified from a probabilistic calculation of an intersection point on a curve to a geometric verification. SAE J4002 states that fixed seats have only one H-point location, this H-point is the SgRP and therefore no further calculations are necessary [44]. Consequently, the position of the SgRP is defined by specific geometric dimensions relative to the vehicle or in the case of a test rig, the floor, and pedal reference points.

2.5.2 Regulatory frameworks

Lower seat belt anchorages are regulated to ensure that the lap belt is correctly positioned on the occupant and can provide effective restraint in a crash. Both FMVSS and UN/EU regulations specify how the lower anchorages shall be positioned, with particular focus on the angle between the belt and the SgRP, as this directly affects belt fit and load distribution. According to FMVSS Standard No. 210 [23], the requirements apply to lap belts and the lap portion of three-point seat belts in passenger cars. For all seat installations, the line from the SgRP to the nearest belt contact point at the lower anchorage shall extend forward at an angle between 30° and 75° relative to the horizontal. This requirement applies to both adjustable and non-adjustable seats. The same angle limits apply regardless of whether the belt runs over the seat frame or whether the anchorage is mounted directly to the seat structure. FMVSS also requires a minimum lateral distance of 165 mm between the two lower anchorages of the same seat belt.

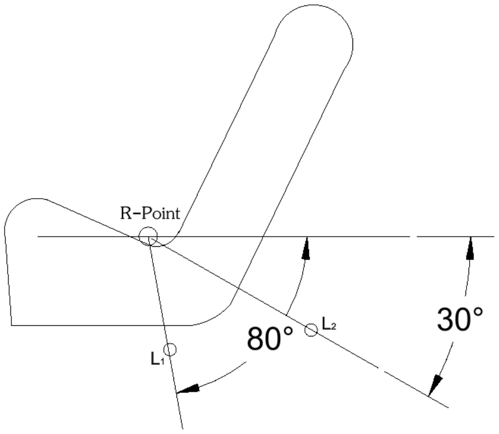


Figure 2.1: Definition of lower seat-belt anchorages represented as points L_1 and L_2 and the allowable anchorage angle ranges (30°–80°) relative to the R-point (SgRP), according to UNECE Regulation No. 14.

Under UNECE Regulation No. 14 [22], the lower anchorages for M1 vehicles (passenger cars) are defined by points L_1 and L_2, and their position is referenced to the seat R-point. The anchorage angles α_1 (non-buckle side) and α_2 (buckle side) are measured between the horizontal plane and lines connecting the R-point with the respective lower anchorages. For adjustable seats, these angle requirements must be fulfilled for all normal driving positions specified by the manufacturer. For front seats the buckle-side anchorage angle shall be between 45° and 80° and for the non-buckle-side between 30° and 80°, see Figure 2.1. In addition to angle requirements, UNECE Regulation No. 14 specifies a minimum lateral spacing of 350 mm between the two lower anchorages. For a single, non-interchangeable center rear seat, this distance may be reduced to 240 mm, provided that the seat center plane lies between the two anchorages and is at least 120 mm from each of them.

While regulatory frameworks define allowable anchorage positions based on geometric constraints, experimental studies highlight how variations in anchorage position influence the biomechanical interaction between the belt and the pelvis under loading conditions [8]. PMHS tests showed that moving the belt anchors forward, thereby reducing the belt-to-pelivs (Nyquist) angle (defined as the angle between the lap belt loading direction and the normal vector to the anterior surface of the iliac wing), which increased pelvic fracture tolerance and changed the fracture patterns. This configuration placed the lap belt lower on the pelvis and reduced loading at the ASIS. These findings indicate that belt angle and vertical position relative to the bony pelvis influence how forces are transferred during loading. Optimizing anchorage positions may therefore help reduce both the risk of severe iliac wing fractures and the likelihood of submarining.

2.6 Research gaps

Previous studies have examined how anthropometry and posture influence lap belt fit, and how belt geometry and lower anchorage configuration affect restraint performance and perceived comfort. However, these factors are typically studied separately. Few studies have investigated how user-preferred adjustments of the lower anchorage position, based on comfort, influence lap belt fit relative to the ASIS across different body types. As a result, there is limited understanding of how lap belt fit varies with occupant characteristics and sitting posture when lower anchorage positions are adjusted beyond regulatory limits. There is also limited knowledge of how variations in lower anchorage positions influence perceived comfort. Finally, little is known about how user-selected anchorage adjustments affect both fit and comfort in combination. Addressing these gaps forms the basis of this study.

3

Methodology

3.1 Study Design Overview

The study was structured to evaluate lap belt fit and perceived comfort under controlled laboratory conditions. First, a dedicated test rig was developed to represent a vehicle seating environment, allowing repeatable positioning of the seat belt system. This rig enabled precise control over key geometric parameters while minimizing variability that could influence lap belt fit. Following the test rig setup, a pilot study was conducted with a small sample of participants to validate the test procedures, measurement tools, and questionnaires. After refinement of the protocol from observations in the pilot study, the main volunteer study was carried out with a larger sample of adult participants, selected to reflect a diverse range of body types in the adult population. Anthropometric measurements, lower anchorage positioning, and subjective comfort assessments was collected for each participant in upright and reclined sitting positions. This enabled evaluation of relationships between occupant characteristics, sitting postures, belt fit, and perceived comfort. Finally, the data was analyzed using statistical methods, including, t-tests, correlation, and regression analysis. This was used to evaluate differences between seating conditions and participant groups and to identify relationships between occupant characteristics, belt fit, and perceived discomfort.

3.2 Test Setup

The test setup consisted of a rig replicating a vehicle seat, a reference point measured using the SAE H-point mannequin, a laser-based system and a 3D scanning tool. This setup enabled controlled evaluation of lap belt fit, occupant posture, and perceived comfort across different seating configurations.

3.2.1 Test Rig

The test rig, see Figure 3.1, was designed to represent a realistic vehicle seating environment while allowing precise control of geometric parameters relevant to lap belt fit and occupant posture. The rig consisted of the front seat of a mid-sized European sedan mounted on a rigid aluminum frame equipped with lockable wheels. The orientation of the X, Y, and Z axes relative to the seat is illustrated in the same figure. The rigid structure ensured stability during testing and prevented unintended displacement of the seat relative to the measurement system.

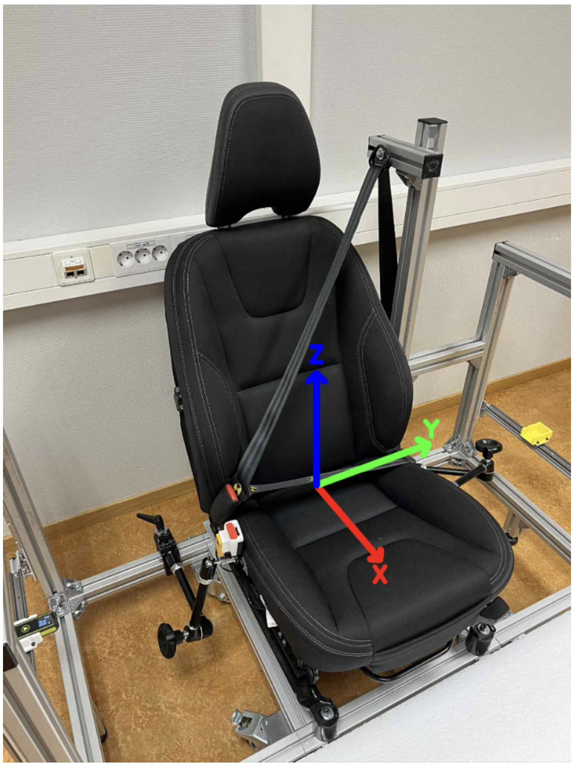


Figure 3.1: The test rig consisting of a front car seat mounted in a rigid steel frame, with X, Y, and Z coordinate directions relative to the rig.

This allowed controlled adjustment of selected seat and restraint system parameters known to influence occupant posture and lap belt geometry. These parameters included seat fore–aft position, seat height, seat cushion tilt, seatback recline angle, and seat belt anchorage locations. To reduce geometric variability and ensure reproducibility across participants, several parameters were fixed to standardized reference values, while others were varied to evaluate their influence on lap belt fit and perceived comfort. Table 3.1 provides an overview of the adjustable parameters available in the test rig, including their direction of adjustment and physical range.

Table 3.1: Overview of adjustable seat and belt system parameters in the test rig.

Parameter	**Adjustment Direction**	**Physical Range**
Seat fore–aft position	Longitudinal	220 mm total track length
Seat height	Vertical	20 mm
Seat cushion tilt	Rotation (front up/down) relative to horizontal	9.5°-15.5°
Seatback recline	Rearward rotation relative to vertical	-3°-63°
Lower belt anchorages	3D translation (X, Y, Z)	Adjustable via camera arms
D-ring position	Vertical position / routing	80 mm

3.2.1.1 H-Point

The H-point was established prior to all seat configuration adjustments using an SAE H-Point Machine with assistance from a test engineer at Autoliv. It served as the primary reference for all geometric definitions in the test rig. After positioning, the H-point was transferred to a fixed reference point on the seat structure, specifically the seatbelt buckle mounting bolt. The relative position between the H-point and this reference point was 71 mm in the X-axis, 252 mm in the Y-axis, and 155 mm in the Z-axis. All subsequent geometric measurements, including seat configuration and lap belt positioning, were defined within a three-dimensional coordinate system anchored to this reference.

3.2.1.2 Seat Height and Cushion Tilt

The seat height was set to its lowest position in accordance with the European New Car Assessment Programme (Euro NCAP) Frontal MPDB Test Protocol [45], which specifies that the front seat height should be adjusted to its lowest setting. Prior to the experimental testing, reference measurements were conducted in a real vehicle of the same model to reproduce this configuration in the test rig. During these measurements, the front seat cushion tilt was also set to its lowest position to obtain a well-defined and reproducible geometric reference. The vertical distance from the vehicle floor to the midpoint at the front of the seat was measured to be 283 mm in the lowest seat height position. This value was used to define the height of a rigid platform in the test rig representing the vehicle floor, ensuring that the seating environment closely replicated the geometry of the real vehicle.

Fixing the seat height to the lowest position allowed precise control of the seatback recline angle, as it was observed during setup that changes in seat height influenced torso orientation. This configuration provided a reproducible vertical reference for occupant posture. Its effect on thigh angle relative to the horizontal plane was also considered, as lower seat heights can cause the lap belt to sit higher and more forward over the ASIS, which can affect both belt fit and perceived comfort [6]. Using the lowest seat height therefore ensured consistent geometry while accounting for its influence on lap belt positioning and participant posture.

According to the Euro NCAP protocol, the front seat cushion tilt should correspond to the manufacturer's design position or, if undefined, be set to the mid position. In this study, the lowest cushion tilt was used during the reference measurements to obtain a clear geometric reference, as the mid cushion angle could not be reliably identified physically in the vehicle. During the participant tests, however, the cushion tilt was set to the mid position in accordance with the Euro NCAP specification, ensuring standardized seat geometry during the trials. The rigid platform in the test rig was constructed using two expanded polystyrene boards to represent the vehicle floor. In the test configuration, with the seat height in its lowest position and the cushion tilt set to the mid position, the resulting vertical distance was 285 mm, which defined the effective seating height used throughout the study.

3.2.1.3 Fore-Aft Position

The fore–aft seat position was kept constant throughout the study to provide a stable longitudinal reference for lap belt fit and occupant posture. Although previous research has shown that fore–aft position can influence trunk–thigh angle and torso orientation [34], it was intentionally fixed in this study to isolate the effects of lap belt anchorage positioning. This approach allowed for controlled comparisons between configurations while maintaining consistent participant posture and preserving realistic lap belt–pelvis interactions. It is important to note that, despite the fixed fore–aft and seat height settings, the impact on lap belt fit varies between participants due to differences in anthropometry. For example, a taller participant will have a different pelvis-to-seat relationship than a shorter participant, which may shift the lap belt relative to the ASIS. In the data analysis, inter-individual variations are addressed by measuring lap belt positions in three dimensions relative to the H-point and examining how belt geometry relates to each participant's anthropometric characteristics. This approach enables assessment of lap belt fit across a diverse participant sample while maintaining a standardized seat configuration.

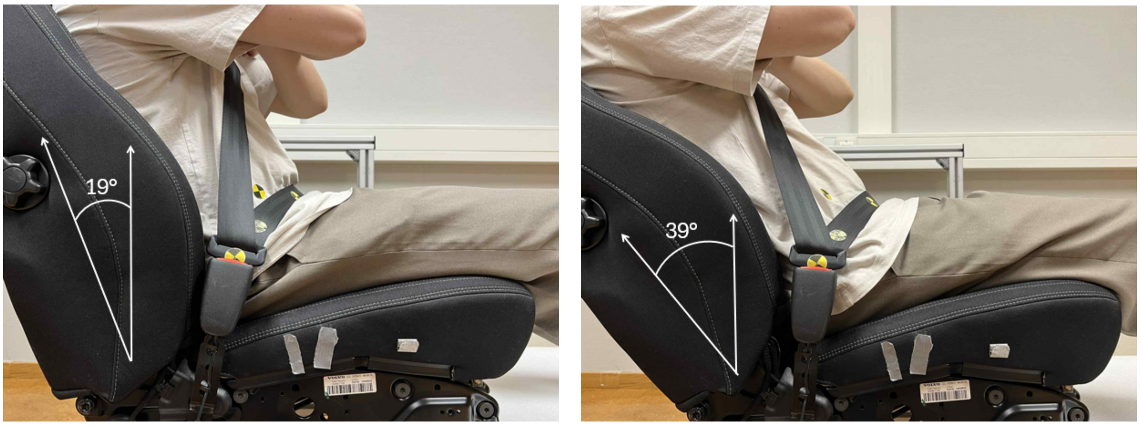
In accordance with the Euro NCAP Frontal MPDB Test Protocol [45], the front seat fore–aft position should be set to the mid position between fully forward and the 95th percentile rear position. If the seat cannot be locked at mid, it may be set to the first notch rearwards of mid. The total seat track length in the test rig was 220 mm, similar to measurements from a vehicle of the same model, and the mid position was therefore defined as 110 mm forward of the full-rear position. Following this approach, the fore–aft seat position in the test rig was set to this mid reference position, providing a standardized and reproducible seating configuration across all participants.

3.2.1.4 Seatback Recline

The seatback recline angle was adjustable while all other seat parameters remained fixed, allowing controlled variation of upper body posture without introducing additional geometric variability. The recline angles are defined based on the torso angle relative to vertical using an H-point reference system established with an SAE H-point manikin (see Section 3.2.1.1).

Two recline conditions were tested in this study. The first condition followed the Euro NCAP Frontal MPDB Test Protocol, where the front seat torso angle is set to the manufacturer's design position [45]. If no design position is provided, the angle is set to 25° from vertical. This standardized setting served as the reference configuration, representing typical occupant posture in conventional passenger vehicles. Field measurements indicate that 95% of vehicle seatbacks are reclined less than 34°, confirming that this configuration reflects common real-world seating [4].

The second condition examined a semi-reclined position with a seatback angle set to 45°, selected to represent a more relaxed seating position expected in future automated vehicle environments. This specific configuration is used in PMHS test setups, such as in the investigations conducted by Somasundaram et al. [46]. This condition was included to investigate occupant response under increased recline angles. The corresponding physical seatback inclinations measured relative to the seat structure were 19° for the 25° torso condition and 39° for the 45° semi-reclined condition, respectively, see Figure 3.2. Note that the values shown in the figure (19° and 39°) correspond to the physically measured seatback inclinations relative to the seat structure.



(a) 25° upright seatback.

(b) 45° semi-reclined seatback

Figure 3.2: Overview of the two seatback configurations used in the study.

3.2.1.5 Seat Belt System

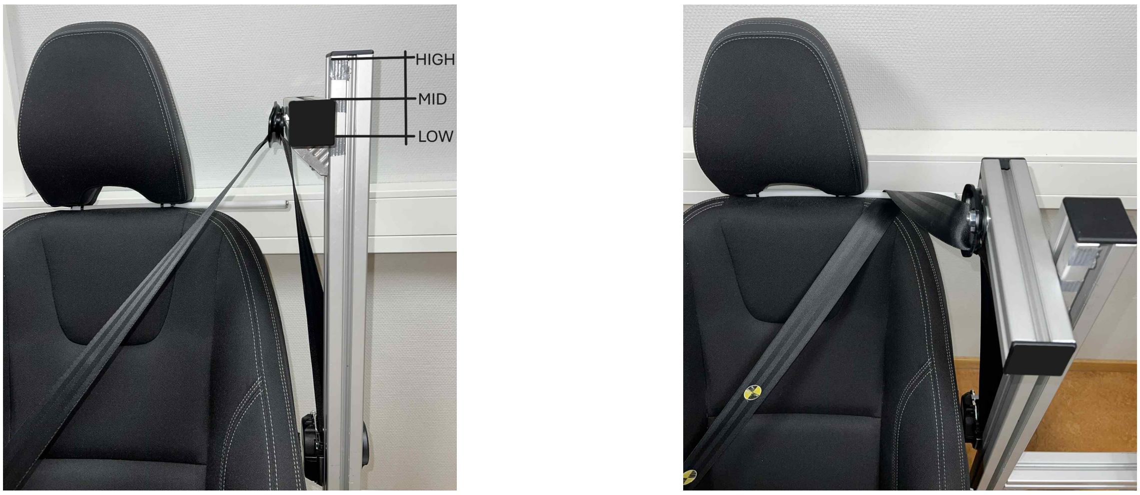
A standard automotive three-point seat belt system was integrated into the test rig. Two separate buckle configurations were used: a fixed manufacturer-installed buckle and an adjustable experimental buckle mounted on a movable structure. The manufacturer buckle (black) was the original buckle integrated into the seat. It is mechanically attached to the seat structure with a mounting bolt, see (a) in figure 3.3, and can rotate along its mounting path from the seat cushion up towards the seatback. It can also exhibit slight inward deformation when the belt is latched, depending on belt loading and routing. Due to this inherent mobility, the exact spatial position of the manufacturer buckle varies between participants and belt configurations, and its position was therefore recorded individually for each test condition.

In addition to this, an experimental buckle (white) was mounted on adjustable arms attached to the seat structure, see (a) in figure 3.3. The adjustable arm system allowed controlled three-dimensional positioning of the buckle within a defined range of motion relative to the mounting bolt of the manufacturer buckle. Specifically, the system allowed approximately 27 cm forward and 40 cm rearward movement in the X-direction, 58 cm outward and 23 cm inward (over the seat) in the Y-direction, and ±32 cm in the vertical (Z) direction. This provided sufficient flexibility to explore a wide range of buckle positions. Once the desired position was set, the adjustable arms were locked, fixing the entire assembly rigidly in place for evaluation. A corresponding lower anchorage was located on the opposite side of the seat (left side for the participant sitting in the seat), to maintain a consistent belt geometry.

(**a**) Right side

(**b**) Left side

Figure 3.3: Overview of the test rig showing both sides of the seat and the lower belt anchorage setup. The right side shows the manufacturer-installed buckle (black) and the adjustable experimental buckle (white) mounted on a movable arm structure. The left side shows the anchorage configuration from the opposite side.



(**a**) B-pillar installation (mid position), with high and low positions indicated (25° upright seatback).

(**b**) Belt-in-seat installation (45° semi-reclined seatback).

Figure 3.4: D-ring installation configurations used in the study.

For the upright position, a B-pillar installation was used, where the D-ring adjustment was defined using three discrete positions: a lower, mid, and upper position, as illustrated in Figure 3.4 (a). This was implemented to provide a controlled range of shoulder belt geometries. The D-ring was initially positioned in the mid configuration and could then be adjusted to the lower or upper position based on each participant's preference before being kept fixed to avoid influencing subjective responses. This prevented the shoulder belt from influencing perception of the lap belt. The D-ring adjustment range was defined by the lower position (-174, -260, 632) and the higher position (-174, -260, 712), relative to the H-point. The X-coordinate corresponded well with measurements from a reference vehicle. However, the Y-coordinate differed by approximately 80 mm compared to the reference vehicle, indicating that the D-ring was positioned 80 mm closer to the seat. This deviation was due to the pre-built structure of the test rig, which did not allow modification. The Z-coordinate matched the corresponding height of the reference vehicle, ensuring vertical alignment consistency with an actual car installation. During testing with the reclined seatback position, the B-pillar installation did not naturally align the shoulder belt along the participant's torso. To ensure proper belt routing, the D-ring was modified using a small hook attached to the seat frame, which guided the shoulder belt along a realistic path over the torso, as shown in Figure 3.4 (b). This setup was implemented to simulate a belt-in-seat installation.

3.2.1.6 Laser Measurement System

For geometric measurements, a laser-based measurement system was mounted directly to the test rig frame, as shown in Figure 3.5.

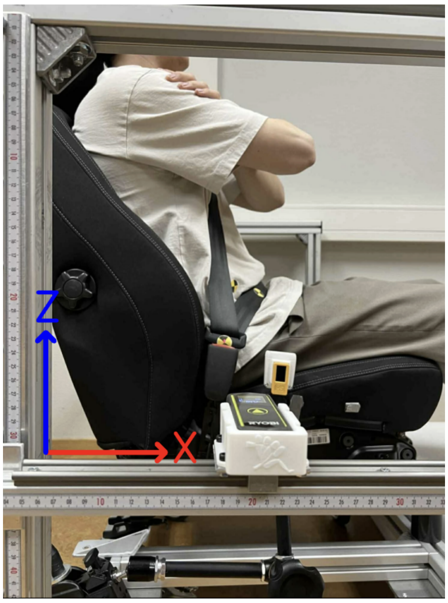


Figure 3.5: The laser measurement system consists of a movable laser that determines the depth (y-axis) and integrated rulers placed on the frame that captures the x- and z-coordinates). The figure shows the measurement of the buckle position.

The system consisted of a movable laser pointer used to measure depth (y-axis) at predefined anatomical landmarks and reference points, including the ASIS and lap belt anchorage locations. A RYOBI® laser distance meter, model number RBLDM20, was used in this study. The x- and z-coordinates were obtained manually by reading the corresponding positions on rulers integrated into the steel frame of the test rig. By combining the measured depth with the manually recorded frame coordinates, three-dimensional positions of each landmark could be determined. In addition to landmark localization, the system was used to obtain selected anthropometric dimensions that were difficult to measure reliably using conventional measurement tools.

3.2.2 Test Conditions

Testing was carried out in two sessions, with each session corresponding to a different seatback recline angle. In the first session, the seatback was set to its upright position, 25° from vertical. The second session used a semi-reclined seatback, which was set to 45° from vertical. Between the two sessions, while changing the seatback from upright position to the semi-reclined position, the shoulder belt had to manually be moved onto the hook attached to the seat frame. Within each session, participants experienced two predefined lower belt anchorage positions. The first corresponded to the manufacturer configuration, called Predefined 1 (P1), where the belt was buckled in the black-colored buckle, as shown in Figures 3.6 (a) and (d).

(a) Predefined 1 (25°) **(b)** Predefined 2 (25°) **(c)** User-preferred (25°)

(d) Predefined 1 (45°) **(e)** Predefined 2 (45°) **(f)** User-preferred (45°)

Figure 3.6: The first row represents the upright seatback position, and the second row represents the semi-reclined position. In each row, the three lower anchorage positions are shown: the predefined manufacturer-based position, a position 10 cm forward of this reference, and the participant selected position.

The second position, called Predefined 2 (P2), was positioned 10 cm forward, measured from the lower anchorage mounting bolt. In this position the belt was buckled in the white-colored buckle, as shown in Figures 3.6 (b) and (e). The position was set manually by the test leaders using the adjustable arm system and marked with tape to ensure repeatability across participants. The placement was selected so that the buckle position corresponded to the same general pitch and roll orientation as the manufacturer-installed buckle, while also keeping the upper edge of the buckle at approximately the same vertical level. Minor deviations could still occur because the two buckles were not identical in design.

This second position was included to represent a more extreme and non-standard belt routing condition compared to the manufacturer-recommended setup. The purpose was to expose participants to two distinctly different belt geometries, allowing evaluation of belt fit, comfort, and perceived safety across both a typical and a more extreme configuration. The choice of moving it 10 cm forward was partly motivated by the study by Hanggi et al. [8], which investigated the effect of anteriorly shifted lap belt anchor positions in PMHS tests. Their results showed that moving the lap belt anchors forward influenced pelvic fracture tolerance and altered fracture patterns, suggesting that anchor position is biomechanically relevant. Based on this, a 10 cm offset was selected to represent a clear deviation outside the regulatory belt anchor position range, while still remaining within a meaningful range.

To maintain comparable belt geometry on the left side of the seat, the lower anchorage was moved by the same distance in the X-direction as the buckle position and marked with tape. This adjustment was performed manually and exclusively in the longitudinal (X) direction, with no changes in other directions. This approach ensured a practical and time-efficient testing procedure while maintaining repeatability and consistency across participants. The movement is illustrated in Figure 3.7b.

(a) Right-side **(b)** Left-side

Figure 3.7: Illustration of the lower belt anchorage adjustments on the right (a) and left (b) sides of the seat. In (a), the longitudinal (X-direction) position of the experimental buckle is shown relative to the manufacturer reference mounting point, with the measured distance indicated. In (b) the lower anchorage position is placed at the manufacturer-mounted location, and the white line indicates the 10 cm forward position used for the second predefined configuration.

Further to that, each session included a self selected position of the lower belt anchorage, called user-preferred position. In this condition, the white experimental buckle was again used, and the participant's were allowed to adjust the anchorage within the movement range of the adjustable arm system to achieve the preferred belt position. Once the participant had selected a final position, the test leaders measured the distance between the mounting bolt of the manufacturer reference buckle and the user-preferred buckle position. The same distance was then applied to the left-side lower anchorage in the X-direction to preserve a comparable belt routing across the seat, which could be more or less than the previous 10 cm distance. Examples of user-preferred positions can be seen in figure 3.6 (c) and (f).

To enable clear identification of the configuration and of the participant during post-test data processing the corresponding identification number was written on sticky notes representing all six test setups. In the upright configuration the labels were formatted as 1_1_ID for image (a), 1_2_ID for image (b) and 1_3_ID for image (c) in figure 3.6. In the semi-reclined configuration, the same structure was used but instead with the prefix “2”, resulting in 2_1_ID for image (d), 2_2_ID for image (e), and 2_3_ID for image (f).

3.2.3 Clothing

Participants were instructed to wear a light-colored T-shirt and a pair of jeans when attending the test session. This clothing requirement was chosen to represent typical everyday clothing in order to simulate realistic seating conditions. Standardized clothing was not provided, as this would have increased the total duration of the test procedure due to the participants having to change clothes before and after the study. The light-colored T-shirt improved the visibility of the seat belt during measurements, photography, and 3D scanning, which facilitated more accurate identification of the belt position relative to anatomical landmarks. Jeans were requested to obtain a relatively consistent clothing thickness around the pelvis.

3.3 Data Collection

Data were collected to quantify anthropometric characteristics, lap belt fit, and perceived comfort, perceived safety, and usability in different test configurations. Objective measurements of body dimensions and lap belt positioning were combined with subjective assessments to enable a comprehensive evaluation of the relationship between occupant anthropometry, lap belt fit, and perceived discomfort.

3.3.1 Anthropometric Measurements

Participants anthropometric measurements were collected to assess lap belt fit and comfort. In addition, the ASIS were palpated and marked according to SS-EN ISO 7250-1:2017 [47], serving as a reference point. All standing measurements were performed according to the Swedish standard SS-EN ISO 7250-1:2017 [47], ensuring consistency. The measurements included hip breadth, waist, and thigh circumference on the right leg. Stature and body mass were not measured during the experimental session, as these parameters were provided by the recruitment company and used as inclusion and stratification criteria for participant selection.

To capture body dimensions most relevant to lap belt fit under realistic in-vehicle conditions, seated measurements were obtained with participants positioned in the test rig. Although the SS-EN ISO 7250-1:2017 standard specifies seated measurements on a conventional chair, these measurements were adapted to the vehicle context. This approach reflects the findings of previous research [48], which emphasized that standard anthropometric measurements obtained on flat surfaces do not fully represent an individual's posture in a car seat. These seated measurements focused on body dimensions most relevant for lap belt fit and posture. Hip breadth, thigh clearance, abdominal depth, and knee height were recorded in a test rig (25° recline, lowest seat height, mid cushion tilt) to capture pelvis orientation, thigh angle, and soft tissue distribution. Circumferences such as waist, hip, and thigh are difficult to measure directly in the test rig, therefore, these alternative measurements were selected to reflect similar aspects of body composition and geometry. By combining these anthropometric measures with a seated configuration, the study provides a realistic basis for assessing lap belt fit and potential risk factors such as belt displacement and comfort. The tools used in the measurements are shown in Figure 3.8.

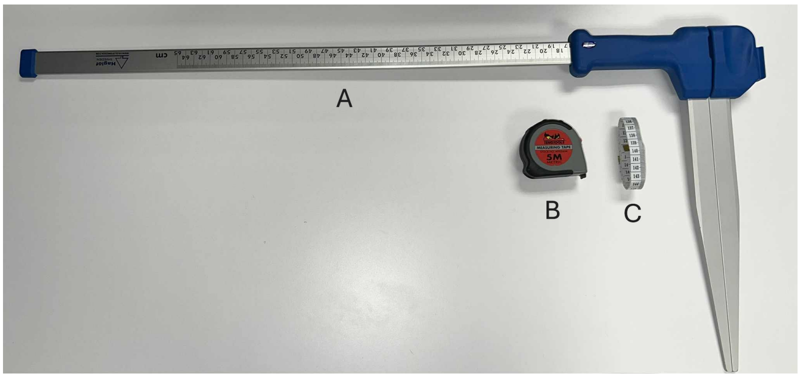


Figure 3.8: Anthropometric measurement tools used in the study. A: Large sliding caliper. B: Tape measure. C: Flexible measuring tape.

In addition, selected seated anthropometric dimensions that are difficult to obtain using conventional measurement tools were collected using a laser-based measurement system. Knee height was defined as the vertical position (Z-axis) of the knee relative to the floor. Thigh clearance was calculated as the vertical distance between the highest point of the thigh and the corresponding point on the seat directly below at the same X–Y coordinates. Abdominal depth was obtained as the distance between the most anterior point of the abdomen and the corresponding point on the seat surface posterior to it. This approach enabled precise, non-invasive measurements of seated anthropometry relevant to evaluating lap belt fit and body interaction. The combination of standardized standing measurements and seated measurements ensures that both general anthropometric and realistic in-vehicle geometry are captured. Table 3.2 provides an overview of the measurement instruments used for each anthropometric parameter.

Table 3.2: Anthropometric measurements collected, including the tools used.

Posture	Measurements	Tool
Standing	Iliac Spine Height right	Flexible measuring tape
	Waist circumference	Flexible measuring tape
	Hip Breadth	Large Sliding Caliper
	Thigh circumference right	Flexible measuring tape
Seated in the Test Rig	Abdominal Depth	Laser Measurement System
	Hip Breadth	Large Sliding Caliper
	Thigh Clearance	Laser Measurement System
	Knee Height	Tape measure

3.3.2 Lap Belt Fit Measurements

Lap belt fit was quantified by measuring the fore–aft and vertical position of the upper and rearward margin of the lap belt at the lateral location of the ASIS landmark, as illustrated in Figure 3.9.

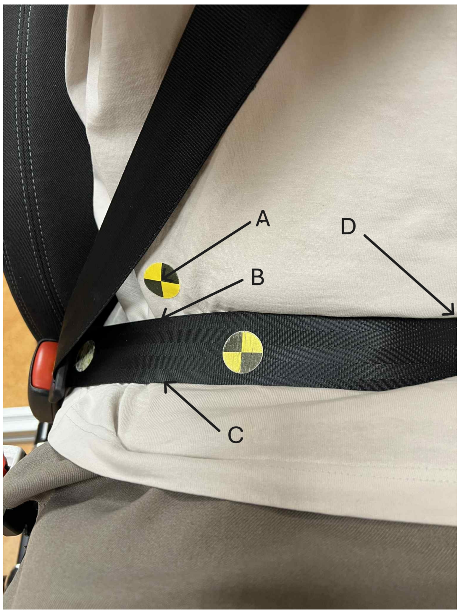
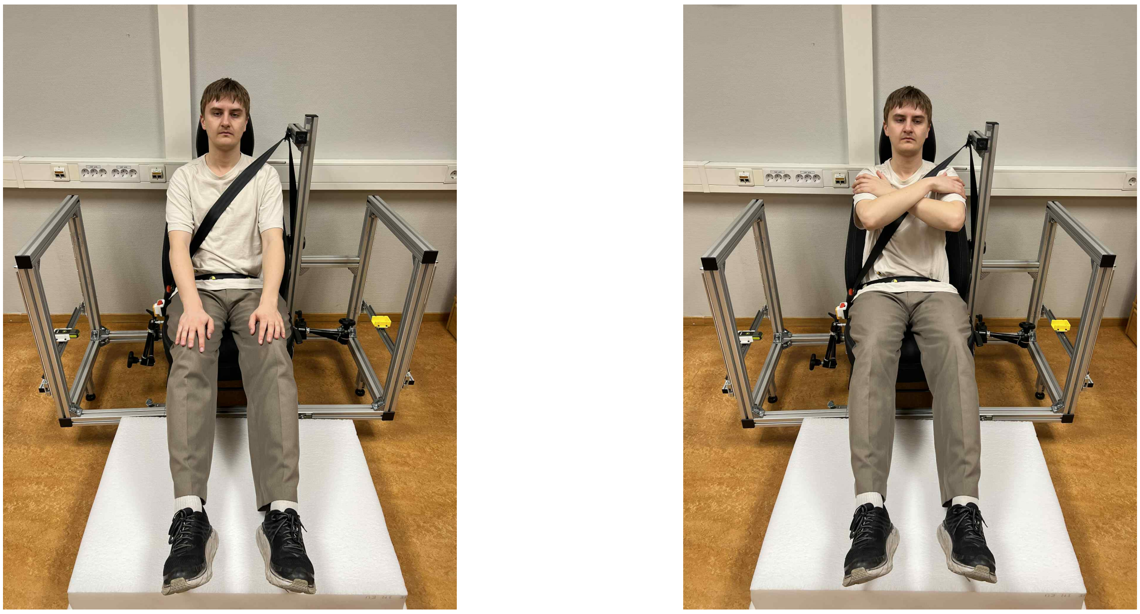


Figure 3.9: Overview of the measurements taken regarding ASIS and lap belt fit. A: Marked ASIS point. B: Upper edge of the lap belt. C: Lower side of the lap belt. D: Highest point of the lap belt edge.

Measurements were performed on the right side of the body. The reference point was defined at the same depth (Y-coordinate) as the palpated ASIS to ensure anatomical alignment with the bony landmark. Belt position was then expressed relative to this point in two directions: longitudinally (X-coordinate) and vertically (Z-coordinate). The X-coordinate represented anterior–posterior displacement with respect to the ASIS, while the Z-coordinate described the vertical position of the belt relative to the same landmark. This measurement approach was adopted to ensure consistency with previously established lap belt fit assessment methods, as described by Reed et al. [16]. In their methodology, lap belt fit is defined by the fore–aft and vertical location of the belt relative to the ASIS landmarks.

(a) Lateral view, hands on the lap

(b) Lateral view, arms raised



(c) Frontal view, hands on the lap

(d) Frontal view, arms raised

Figure 3.10: The first row shows the two different lateral photographs. The second row shows the two different frontal photographs.

To complement the coordinate-based measurements and to document belt routing visually, photographs were taken for each participant following the procedure described by Osvalder et al. [15]. Two GoPro® HERO10 cameras were used and mounted on tripods in fixed positions, and the same settings were used throughout the study. For each setup, two photographs were captured from a lateral and a frontal view with the participant's hands placed on their lap, see Figure 3.10. Two additional photographs were taken from the same views with the participant's arm raised to provide an unobstructed image of the lap belt routing. This procedure was repeated for all six unique setups, resulting in 24 photographs per participant.

To measure the correct placement of the lap belt buckle in the participant's user-preferred position more geometric measurements were captured. Besides the XYZposition of the buckle an inertial measurement unit (IMU) was used to capture the orientation of the lap belt buckle (Figure 3.11) . The sensor used was an M5StickC PLUS, an ESP32-based device equipped with a built-in 6-axis IMU. The IMU was attached to the white buckle and used to record its angular orientation in terms of pitch and roll. Pitch describes rotation about the lateral axis (Y-axis), corresponding to forward and backward tilting, this can be seen in figure 3.11a. Roll describes rotation about the longitudinal axis (X-axis), corresponding to side-to-side tilting, which can be seen in figure 3.11b. These measurements provided additional information on buckle orientation relative to the body.

(a) Pitch

(b) Roll

Figure 3.11: Illustration of the IMU sensor mounted on the lap belt buckle. (a) Pitch, with a reference angle of 0°, where forward tilting results in increasing angles and backward tilting results in decreasing angles. (b) Roll, with a reference angle of 90°, where inward tilting decreases the angle and outward tilting increases it.

In addition, three-dimensional surface data of the lap belt routing over the participant's abdomen and pelvis were collected using the 3D scanning system FARO® Freestyle 2 (see Figure 3.12).

Figure 3.12: FARO Freestyle 2 handheld 3D scanning system.

The Freestyle is a mobile, high-resolution 3D scanning device designed for rapid reality capture. It was selected due to its compact size, which allows effective maneuverability within the confined space of the testing rig. The scanner was connected to a smartphone running the FARO Freestyle application, enabling real-time visualization of the scanning process. A portable PC was connected to the system for data acquisition. After each completed scan, the data was saved to external storage and subsequently transferred to a laptop equipped with FARO Scene software for processing and management of the 3D scan data. Although the main analysis in this study focused on coordinate-based belt position measurements and questionnaire responses, the scan data provided a detailed geometric record that may support future analysis and modeling work.

3.3.3 Subjective assessment

The subjective data collection was organized in a structured sequence, beginning with a pre-test questionnaire designed to capture participants baseline characteristics. The full questionnaire is provided in Appendix A. Following this, participants were asked to evaluate the different test configurations using a structured interview approach. This method was chosen to ensure consistency across participants while still allowing both quantitative ratings and qualitative feedback, including descriptive comments about participant choices, which is recommended for collecting user requirements in human-centered design [49]. The subjective evaluation was divided into three main components: perceived comfort, perceived safety, and usability. These components are described in the following subsections, and the interview questions are presented in Appendix B.

3.3.3.1 Pre-test questionniare

In accordance with established methodological principles, the questionnaire was structured to progress from objective inquiries to closed-ended rating scales, ultimately concluding with open-ended questions. As noted by Cohen et al. [41], this sequencing captures baseline nominal data before transitioning into deeper explorations of participants subjective perceptions. The pre-test questionnaire first established participants standard exposure to vehicle seating by recording their travel frequency (days per week), average trip duration, and typical seating position (driver or passenger). To evaluate their baseline subjective experiences, participants rated their general sitting discomfort, ranging from 1 (No discomfort) to 5 (Extreme discomfort), and their perceived safety while driving and traveling as a passenger, ranging from 1 (Not safe at all) to 5 (Completely safe). Each of these Likert-scale evaluations was paired with an open-ended question, allowing participants to elaborate on the specific factors influencing their ratings. Additionally, binary (Yes/No) questions were utilized to identify any direct irritation caused by the seat belt and to determine if participants used aftermarket accessories (e.g., seat belt pads or cushions) while traveling. Finally, a question regarding general physical activity level was included to provide additional context regarding participant body composition, muscle mass, and potential differences in soft tissue distribution, which may influence both lap belt interaction and perceived seating comfort.

3.3.3.2 Comfort questions

To evaluate the participants overall perceived comfort, the assessment was divided into two distinct physical questions. Because comfort is inherently subjective, complex, and difficult to quantify directly, the study instead focused on capturing localized physical disturbances, specifically, level of perceived pressure and perceived discomfort. This approach aligns with previous findings indicating that discomfort is more readily defined by users and directly linked to physical environmental factors [20]. By measuring these specific variables, it is possible to better understand the underlying factors driving the participant's overall perception of the lap belt fit. Participants rated their perceived pressure and discomfort on separate five-point Likert scales, which were customized to the specific lap belt context based on established ergonomic methodologies [42], [43]. The scales ranged from 1 (No pressure / No discomfort) to 5 (Very strong pressure / Extreme discomfort). Utilizing independent scales for these metrics further supports the recognized ergonomic principle that comfort and discomfort represent independent perceptual dimensions rather than direct opposites [20], [35], allowing for a more nuanced analysis of the subjective feedback.

To further standardize interpretation and reduce individual differences in how participants map their sensations to numerical values, brief descriptive explanations were added to each point to contextualize the perceived pressure and discomfort in terms of lap belt fit [41]. For instance, the pressure scale ranged from 1 (No pressure) with intermediate descriptors as 2 (Slight pressure), 3 (Moderate pressure), and 4 (Strong pressure), up to 5 (Very strong pressure). The discomfort scale ranged from 1 (No discomfort), with intermediate descriptors as: 2 (Mild discomfort), 3 (Moderate discomfort), 4 (Significant discomfort) up to 5 (Extreme discomfort). This approach helps ensure that a given rating reflects a comparable experience across participants, rather than differing interpretations of what a mid-point value means.

To complement the Likert scales participants were asked to elaborate on their perceived physical comfort in the specific seating position. Here the participants could add comments and thoughts that otherwise is not captured by a singular rating, such as how the lap belt sits against the body or if other aspects affected their overall level of perceived comfort. The structured interview format made it possible to combine the rating scales with these open-ended comments, improving the interpretation of the numerical responses and providing a more detailed understanding of the participants experiences. This qualitative approach provided critical context for ratings that might otherwise appear identical across configurations, thereby revealing nuanced differences in the actual perceived experiences. For example a discomfort rating of "2" can vary between setups and between two participants based on their background and their way of reasoning.

Participants were also allowed to mark their perceived discomfort on a body map which gave more information for a detailed assessment of comfort and lap belt fit. While previous research has used standardized body discomfort scales with multiple zones to quantify discomfort across the whole body [43], the focus on lap belt fit involves only a limited number of contact areas. Therefore, a simplified body map was provided which included three predefined regions: the upper abdomen (red), lower abdomen (blue), and thighs (green) (see Figure 3.13). These regions were explained to the participants before the interview to ensure a consistent interpretation. All ratings were collected in a static seating condition to ensure that the responses reflected the participants subjective experience.

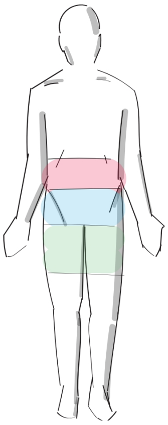


Figure 3.13: Simplified body map used for discomfort reporting.

3.3.3.3 Safety questions

To evaluate perceived safety, participants rated the statement "How safe do you perceive the seatbelt in this configuration" on a five-point Likert scale. The scale ranged from 1 (Not safe at all: *I would feel very unsafe using this seatbelt*), with intermediate descriptors as 2 (Slightly unsafe: *I notice some risks, but it's somewhat tolerable.*), 3 (Moderately safe: *I feel reasonably safe, but not fully confident.*), 4 (Safe: *I feel that the seatbelt would protect me well*) up to 5 (Completely safe: *I feel fully secure and confident using this seatbelt*). This question was followed by an open-ended question asking them to describe the reasoning behind their rating and their perceived level of safety. This follow-up question allowed participants to elaborate on the specific factors that made them feel safe or unsafe.

3.3.3.4 Usability questions

Participants were also asked (after physically interacting with the buckle) to rate how easy or difficult it was to: locate the buckle position, buckle the seat belt, and unbuckle the seat belt on a Likert scale ranging from 1 (Very easy) to 5 (Very difficult). Together, these questions provided insight into how different anchorage locations influenced participant perception beyond physical comfort. For the three questions regarding usability descriptive texts for each point were considered unnecessary, as the items were easier to interpret and therefore only the scale endpoints were labeled. Consistent with the other metrics, an open-ended question was included for participants to provide specific feedback regarding the buckle itself.

3.4 Pilot Study

A pilot study was carried out before the main volunteer study to assess whether the planned methods and procedures were feasible, clear, and practical. Defined as “a small-scale test of the methods and procedures to be used on a larger scale” [50], a pilot study aims to determine if the study can be conducted successfully, how it should be implemented, and whether any adjustments are needed [51]. This early evaluation allowed identification of potential issues with the test rig, measurement procedures, and questionnaire, as well as ensured that the protocol, instructions, and data collection could be applied correctly under controlled laboratory conditions. Observations included how well participants understood instructions, the ease and duration of completing the questionnaire, and any difficulties with belt positioning or measurements. Feedback collected during the pilot informed adjustments to the study design, supporting a safe and efficient execution of the main volunteer study.

The pilot study used the same setup and equipment planned for the main study. Both the upright and the semi-reclined seatback positions were tested. Three people took part in the pilot study and were chosen to cover a range of body sizes and shapes, to check that the test rig, measurement tools and belt adjustments worked for different body types. The first two participants only performed the key steps in one seatback position, such as D-ring adjustment. The third completed the full procedure, including seatback adjustment, belt positioning, recording belt coordinates and filling out the comfort questionnaire. None of the pilot participants were included in the main study and they were informed about the purpose and procedure and that participation was voluntary. Data on body measurements, belt fit, and questionnaire responses were collected to check that the equipment worked and that the questions were clear. The pilot study also gave a chance to practice measurements, such as marking anatomical points, 3D scanning, and recording belt geometry. Observations on instructions, questionnaire use, timing, and belt placement were used to improve the study protocol.

3.4.1 Modifications Following the Pilot Study

Based on the pilot study, several modifications were implemented to improve the clarity and efficiency of the main experimental protocol. First, the questionnaire was revised, as some questions were found to be difficult for participants to interpret consistently. The wording was therefore simplified and refined to improve clarity and reduce potential variability in responses. Second, the number of predefined anchorage positions was evaluated. Initial testing indicated that three predefined positions introduced unnecessary complexity without providing additional meaningful variation in participant responses. Consequently, the final study design was limited to two predefined anchorage positions, which was considered a more appropriate balance. Third, a more robust and repeatable method for identifying and locating the ASIS was developed. The ASIS position was re-identified for each test condition to ensure measurement consistency. This improved consistency in landmark identification and reduced inter-operator variability during measurements. Finally, to ensure a feasible procedure within the available testing time, it was decided to focus all measurements on the right side of the body only instead of doing bilateral measurements. This adjustment allowed the full protocol to be completed within a reasonable time frame while maintaining sufficient data quality for analysis.

3.5 Volunteer Study

Following the theoretical framework and preliminary observations, a structured volunteer study was conducted to evaluate lap belt fit and perceived comfort across varying body types.

3.5.1 Participants

A total of $n = 30$ participants were recruited for this volunteer-based study. The sample composition was designed to approximate the national adult BMI distribution in Sweden, based on statistics reported by SCB [52]. This approach was chosen to obtain a roughly normal distribution of participants across BMI categories, ensuring that the results could be generalized to the Swedish population.

Eligibility was assessed prior to study enrollment to ensure that participants could safely and comfortably complete the experimental protocol. Only individuals fulfilling all the following inclusion criteria were enrolled in the study: age 18 years or older; ability to sit independently and use a standard automotive seat belt; no medical conditions or injuries affecting normal seated posture; ability to remain seated for approximately two hours; ability to understand the study procedures and provide informed consent; and fluency in Swedish or English.

Participants were stratified across four BMI categories: underweight, normal weight, overweight, and obese. A balanced sex distribution was applied in the planned sample, with 15 women and 15 men. Within each BMI category, the number of women and men was determined using sex-specific BMI prevalence rates reported by SCB [52], see Table 3.3. To ensure an unbiased participant sample, recruitment was therefore conducted by an external research consultancy.

Table 3.3: Planned participant distribution across BMI categories and sex, based on Swedish national BMI prevalence data [52].

BMI category	BMI range	Total, % (n)	Women, % (n)	Men, % (n)
Underweight	< 18.5	2 (1)	2 (1)	1 (0)
Normal weight	18.5–25	46 (13)	51 (8)	40 (6)
Overweight	25–30	36 (11)	31 (4)	42 (6)
Obese	> 30	16 (5)	16 (2)	17 (3)
Total		**100 (30)**	**100 (15)**	**100 (15)**

All participants provided informed consent prior to participation. They were informed about the purpose of the study, the type of data collected, how the data would be used, and their rights under applicable data protection regulations. To ensure participant privacy, all collected data were anonymized. Each participant was assigned a unique identification number (e.g., ID_47), which was used throughout the study and in all datasets. No directly identifiable personal information was included in the analysis and the photographs were anonymized. The data were used exclusively for research and development purposes within automotive occupant safety. The collected participant data included basic demographic information (age and sex), body measurements (e.g., height, weight, and seated anthropometric dimensions), as well as subjective ratings of perceived comfort and safety for each test configuration.

To contextualize the participant sample, anthropometric reference data from `https://www.antropometri.se` based on Hanson et al. [53] were used post hoc. With 15 male and 15 female participants, reference percentiles (33rd and 66th) were used to stratify key anthropometric variables into three groups: below 33rd, 33rd–66th and above 66th percentile. This allowed assessment of whether participants were evenly distributed across the population range for each measure. The data in Table 3.4 were used to evaluate representativeness in terms of body size variability, checking whether each measure contained a roughly balanced number of participants within each sex. This analysis was purely descriptive and not used for inclusion or exclusion, but served as a validation of sample variability beyond BMI.

Table 3.4: Reference anthropometric percentiles for women and men based on Hanson et al. [53].

Measurement	**Women**		**Men**	
	33rd %ile	**66th %ile**	**33rd %ile**	**66th %ile**
Stature (body height) [mm]	1645	1702	1761	1821
Iliac spine height, standing [mm]	911	955	979	1024
Hip breadth, standing [mm]	361	380	350	374
Body mass (weight) [kg]	60	69	71	83

3.5.2 Test Procedure

Two test leaders were present throughout the procedure. One test leader was responsible for taking all physical measurements, asking questions, taking photographs from the side, and performing 3D scans. The other test leader recorded data in the spreadsheet, ensured that the protocol was followed, took photographs from the front, and assisted with measurements if needed. The same test leader consistently performed all physical measurements throughout the study to avoid inter-operator variability. The total test session took approximately 120 minutes, including preparation and post-test procedures. An overview of the test procedure is presented in Figure 3.14. The test rig, in which the test procedure was conducted in, can be seen in Figure 3.15.

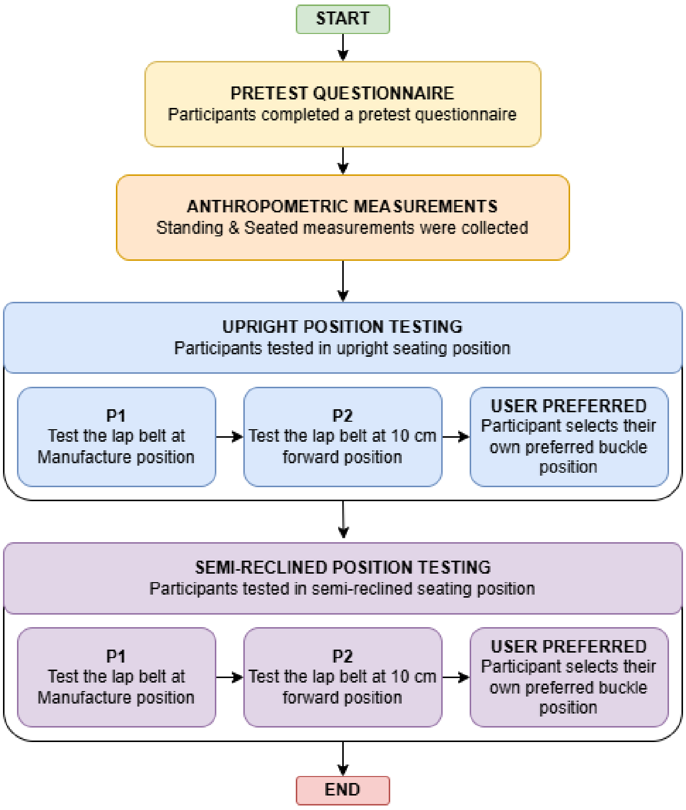


Figure 3.14: Flowchart illustrating the overall test procedure.

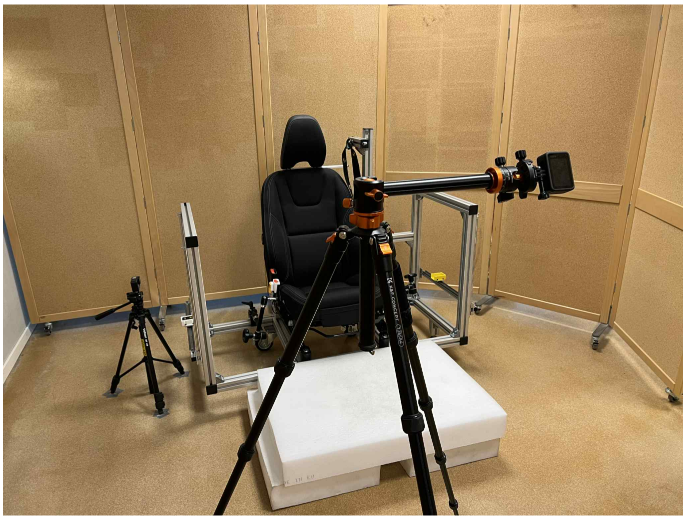


Figure 3.15: Overview of the test setup used during data collection.

Before each participant arrived, the test rig was checked to ensure that it was stable and locked in position. The seatback was set to its upright position and the lap belt anchorage were placed in the two pre-defined positions. The D-ring was set to its mid-position. All equipment required for the anthropometric measurements were prepared. This included the anthropometer, caliper, tape measures, Patrick markers, the FARO scanner, cameras, and the data collection forms.

Upon arrival, each participant was given a brief explanation of the study purpose and the test procedure. They were informed that this study aimed to evaluate lap belt positioning relative to the pelvis, as well as perceived comfort and safety across different seat and belt configurations. Prior to participation, all participants had completed the consent form. The participant first completed the pre-test questionnaire, see Appendix A, and then anthropometric measurements were carried out in the standing position. The ASIS on the participant's right side was palpated and marked as a reference point for the subsequent belt fit measurements. Note that, to ensure consistency across measurements, the location of the ASIS was re-verified by palpation at each measurement occasion. Furthermore, in order to reduce potential measurement error caused by SAT, gentle medial pressure was applied until contact with the ASIS was confirmed, and the corresponding depth was recorded to obtain the most accurate anatomical reference possible. After this, additional measurements were taken while the participant was seated in the test rig.

The test procedure was conducted in a fixed order to ensure consistency across participants and test configurations. Participants first evaluated P1, P2, and their user-preferred configuration in the upright seatback position. This exact progression was subsequently repeated for the semi-reclined position. A randomized order was not used, as the study design required participants to first experience the predefined belt anchorage positions before selecting their own preferred position. To further support this comparative structure, a systematic approach was integrated into the procedure to ensure consistent reference points across all configurations. Rather than evaluating each configuration in isolation, participants related their perceptions to previously experienced setups or everyday seating experience. For example, P2 was evaluated relative to P1, and the user-preferred position relative to both predefined configurations. A similar approach was applied in the semi-reclined condition. This continuous comparison provided a consistent basis for evaluation and enabled more nuanced feedback across configurations.

For the two predefined setups, P1 and P2, the participant was asked to sit in the test rig as he/she usually sits when traveling normally. They were then asked to buckle up, and adjust the shoulder belt and the lap belt somewhat to be placed optimally on their body. The test leaders then slightly tightened the lap belt by pulling the lower end of the shoulder belt softly to ensure that it was close to the body without introducing additional variability. To better reflect realistic in-vehicle behaviour, a secondary task was incorporated, allowing time-dependent postural adjustments to influence the responses. Previous observational research by Reed et al. [4] reported that interaction with hand-held devices, typically mobile phones, occurred in 26% of observed passenger frames (each frame representing approximately four minutes of travel time), making it one of the most common non-driving activities. Based on these findings, mobile phone use was selected as the secondary task to simulate a realistic passenger scenario. This was performed directly after the participant had buckled the belt and the time was set to two minutes per setup. The participant responded to questionnaire (see Appendix B), regarding perceived comfort, safety, and usability. The test leaders recorded the responses in the spreadsheet. The position of the belt relative to the ASIS was then measured, together with the corresponding belt coordinates and the position of the buckle. The position of the buckle was recorded using coordinates derived from a Patrick's marker placed on the buckle latch, reducing the influence of geometric variations in the buckle itself. Lastly photographs were taken before the participant unbuckled the belt.

After the two predefined belt anchor positions, P1 and P2, had been tested within a given seatback recline angle, the participant was asked to select their user-preferred lap belt anchorage position. Here, scenario-based questions were included to facilitate realistic engagement during the discomfort assessments. Participants were asked to evaluate belt positioning in both a conventional driving scenario with an upright seating condition and a future autonomous driving scenario with a more relaxed seating condition in a semi-reclined position. It has been shown that task-specific narratives help participants relate better to real-life contexts and provide more reliable subjective responses [49]. This approach aligns with participatory design principles that emphasize active user involvement in realistic use cases, which has been demonstrated to improve the reliability of subjective discomfort assessments [54]. After a short settling period, the participant was asked whether any further adjustment was desired. When a final preferred position had been established, the belt anchorage coordinates were recorded, followed by the same comfort, safety, and usability questions used in the predefined setups. In addition, to provide more feedback regarding the buckle placement participants were asked to describe why they choose to place it in that specific position. This addition provided deeper insight and revealed whether the participants prioritized physical comfort, perceived safety, buckle usability or other contextual factors while selecting ther preferred position. Lastly, lap belt position relative to the ASIS was measured, photographs were taken and a 3D scan was performed for the final preferred configuration.

3.6 Data Analysis

All data processing and statistical analyses were performed in MATLAB. Geometric transformations were used to map all measurements into a common H-point coordinate system, enabling consistent spatial comparison of belt and anthropometric data. Descriptive statistics, correlation analysis, regression models, and group comparisons were then applied to quantify relationships between anthropometric variables and subjective responses. Statistical significance was evaluated using a threshold of $\alpha = 0.05$. Since multiple statistical tests were performed, there is a risk of Type I errors (false positives). Therefore, the results should be interpreted with some caution, and consistent trends across analyses were considered rather than relying on individual p-values.

3.6.1 Visual analysis of belt positioning

Visual assessment of lap belt positioning was performed through manual annotation of image data to classify belt placement and identify potential usability issues. The classification procedure followed the approach described by Reed et al. [4], where belt position was evaluated relative to the pelvis and abdomen and categorised as either *on lap* or *on belly.* In addition to belt position classification, images were analysed for signs of belt folding and arm interference. Belt folding was defined as visible local deformation or buckling of the belt webbing, while arm interference was defined as cases where the upper limb obstructed or altered the belt path during positioning.

3.6.2 Belt position relative to ASIS

The position of belt landmarks was analysed relative to anatomical reference points in the XZ-plane. In particular, the ASIS was used as a primary anatomical reference. As illustrated in Fig. 3.16, the pelvis coordinate system and the definitions of upper and lower belt regions are shown to clarify the interpretation of the displacement measures used in subsequent analyses. The relative displacement between belt and reference points was computed component-wise as:

$$\Delta x = x_{belt} - x_{ref}, \quad \Delta z = z_{belt} - z_{ref} \tag{3.1}$$

where x represents the anterior–posterior direction and z the superior–inferior direction (see Fig. 3.16). Positive Δz values indicate that the belt is positioned superior to the reference point, whereas negative values indicate an inferior position.

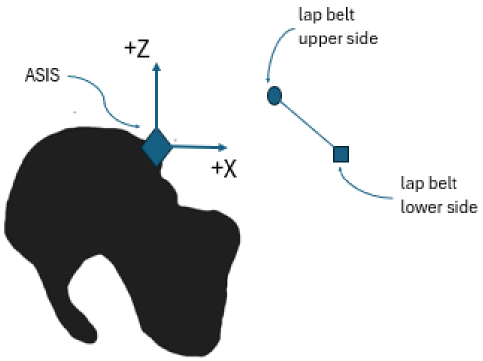


Figure 3.16: Pelvic coordinate system with ASIS marked as anatomical reference. The figure also illustrates the definition of upper and lower belt edges

For each experimental condition, the mean displacement across participants was calculated:

$$\overline{\Delta x} = \frac{1}{n}\sum_{i=1}^{n} \Delta x_i, \quad \overline{\Delta z} = \frac{1}{n}\sum_{i=1}^{n} \Delta z_i \tag{3.2}$$

This provides the average directional shift of the belt relative to the anatomical reference system and enables comparison between upper and lower belt positioning.

3.6.3 Conversion to H-point reference system

All measurements from the laser-based system were transformed into the H-point coordinate system. The transformation was based on a calibration between a fixed reference point on the seat structure (seat belt mounting bolt) and the H-point. This established a rigid relationship between the laser coordinate system and the H-point reference frame. The resulting rigid-body transformation was defined as:

$$\mathbf{r}_H = \begin{bmatrix} x - 277 \\ -y + 701 \\ -z + 325 \end{bmatrix} \tag{3.3}$$

3.6.4 Belt inclination

Belt inclination in the XZ-plane was computed after transformation to the H-point coordinate system. For each observation i, the inclination angle was defined as:

$$\theta_i = \tan^{-1}\left(\frac{z_{upper,i} - z_{lower,i}}{x_{upper,i} - x_{lower,i}}\right) \tag{3.4}$$

where $(x_{upper,i}, z_{upper,i})$ and $(x_{lower,i}, z_{lower,i})$ denote the spatial positions of the belt landmarks in the XZ-plane.

3.6.5 Statistical descriptors

For each variable, the mean and standard deviation were computed as:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{3.5}$$

$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2} \tag{3.6}$$

3.6.6 Correlation analysis

Relationships between anthropometric variables and biomechanical response variables were evaluated using Pearson's correlation coefficient. For each participant i, paired observations (x_i, y_i) were used to quantify linear associations between variables, where x_i represents an anthropometric measure and y_i represents a response variable such as belt displacement or positional change.

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}} \tag{3.7}$$

Pearson's correlation coefficient quantifies the strength and direction of a linear relationship between two continuous variables. The coefficient is dimensionless and bounded in the interval $[-1, 1]$, where values close to 0 indicate weak or no linear association, while values approaching -1 or $+1$ indicate strong negative or positive linear relationships, respectively. This property makes it suitable for evaluating whether systematic changes in anthropometric characteristics are associated with variations in responses, such as belt displacement or positional shifts.

In this study, correlation analyses were implemented in MATLAB using the built-in function `corr()`, which computes Pearson's correlation coefficient along with corresponding p-values for hypothesis testing. Pearson's correlation was explicitly used for all analyses. It is important to note that correlation analysis quantifies association rather than causation. Consequently, results are interpreted as measures of linear dependence and not as evidence of causal relationships, in accordance with established statistical guidelines [55]. Prior to interpretation, data were also inspected for outliers to ensure robustness of the results.

3.6.7 Regression analysis

Linear regression models were used to quantify relationships between response variables and anthropometric predictors. Both simple linear regression models and multiple linear regression models were applied. The general form of the multiple regression model is given by:

$$y_i = \beta_0 + \beta_1 x_{1,i} + \beta_2 x_{2,i} + \cdots + \beta_p x_{p,i} + \varepsilon_i \tag{3.8}$$

where y_i represents the response variable (e.g., belt displacement or buckle position), $x_{1,i}, \ldots, x_{p,i}$ represent the predictor variables, β_0 is the intercept, $\beta_1, \ldots, \beta_p$ are the regression coefficients, and ε_i is the error term. All regression analyses were performed in MATLAB using the built-in function `fitlm`, which estimates regression coefficients using ordinary least squares (OLS) and provides outputs including confidence intervals, p-values ,and coefficient of determination (R^2). Predicted values were obtained using the `predict` function for visualization of fitted relationships. Model performance was assessed using the coefficient of determination:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \tag{3.9}$$

where $\hat{y}_i$ is the corresponding predicted value from the regression model, $\bar{y}$ is the mean of the actual observed values, and n is the total number of observations. Regression analysis was used because it makes it possible to study how one or more variables are related to a continuous outcome and to use these variables to predict outcomes. The regression coefficients show the direction and strength of these relationships in an interpretable way. In addition, measures such as R^2 describe how much of the variation in the outcome is explained by the model, in line with standard statistical practice for linear models [56].

3.6.8 Independent samples t-tests

To compare mean differences between two independent groups, independent samples t-tests were used. The t-test is a standard statistical method for evaluating whether the means of two groups are statistically different and is widely applied in research for group comparisons [57]. In this study, participants were divided into two BMI-based groups: BMI group 1 (BMI < 25) and BMI group 2 (BMI ≥ 25). The independent samples t-test evaluates whether the observed difference in group means is larger than what would be expected due to random variation, using the t-distribution with degrees of freedom dependent on sample size. The test statistic is defined as:

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} \tag{3.10}$$

where $\bar{x}_1$ and $\bar{x}_2$ are the sample means of the two groups, s_1^2 and s_2^2 are the sample variances, and n_1 and n_2 are the corresponding sample sizes. The t-test assumes independence of observations and approximate normality within each group. Given that equal variances between groups could not be assumed, Welch's t-test was applied, which is the default implementation in MATLAB's `ttest2` function under unequal variance settings. In this study, the t-tests were implemented in MATLAB using the built-in function `ttest2`, where outcome variables (e.g., belt displacement measures) were compared between the two BMI groups.

3.6.9 Buckle positions and mounting bolt reconstruction

All buckle positions were defined in a two-dimensional coordinate system (x, z). Each buckle point was associated with a corresponding mounting bolt through a rigid kinematic transformation based on a fixed connector length $L = 22$ cm and a measured pitch angle θ. The pitch angle was defined at the buckle position and describes the orientation of the connector link in the xz-plane. The transformation follows a fixed local vector definition where the link direction is given by $(-\sin(\theta), \cos(\theta))$, such that a positive pitch rotates the link towards the negative x-direction. The mounting bolt positions were reconstructed using a planar rigid-body projection of the connector as:

$$x_{bolt} = x_{buckle} - L\sin(\theta) \tag{3.11}$$

$$z_{bolt} = z_{buckle} + L\cos(\theta) \tag{3.12}$$

where (x_{buckle}, z_{buckle}) are the measured buckle coordinates and L is the constant connector length. This formulation assumes that $\theta = 0°$ corresponds to a vertically aligned connector oriented along the positive z-direction of the measurement frame. The model therefore defines a direct forward kinematic mapping from each buckle position to its corresponding mounting bolt. Angular evaluation relative to the H-point reference was then performed in the xz-plane using:

$$\theta_H = \tan^{-1}\left(\frac{z - z_H}{x - x_H}\right) \tag{3.13}$$

where (x_H, z_H) denotes the H-point position. This enabled classification of buckle positions relative to the regulatory angular acceptance region defined between 30° and 80° in the xz-plane.

3.6.10 Qualitative analysis

To evaluate perceived comfort, usability, and safety across the six seat configurations, a mixed-methods approach was applied. Quantitative ratings were first summarized descriptively using frequencies and mean values, while qualitative follow-up comments were grouped by similarity. Participant preference was then determined by evaluating the quantitative and qualitative data together. Specifically, the change in metric ratings (such as perceived pressure or discomfort) was compared between a baseline (R_{base}) and an alternative configuration (R_{alt}), transforming subjective feedback into a standardized format. This comparative analysis was conducted when evaluating P1 in the semi-reclined condition against P1 in the upright condition, as well as when comparing P2 against P1 in both seating conditions. A similar comparison was not conducted for the user-preferred position due to its high variability; participant placements ranged widely between P1 and P2, making a standardized comparison unfeasible. The integration of these data points allowed participants to be classified into distinct categorical preference groups:

- **Preference for the alternative configuration:** Indicated by improved quantitative ratings (e.g., lower perceived discomfort) supported by positive qualitative feedback (e.g., “better perceived pressure distribution”).
- **Preference for the baseline configuration:** Indicated by worsened quantitative ratings supported by negative qualitative feedback (e.g., “increased perceived pressure on the thighs”).
- **No preference / Neutral:** Indicated by identical ratings between the two setups and comments reflecting no perceptible difference.

Data gathered from the pre-test questionnaire, including traveling frequency and average trip duration, were evaluated against subjective safety ratings, to enable analysis of prior travel habits and perceived safety. To complement the correlation analysis, participants were divided into categorical groups for independent-samples t-tests. For traveling frequency, participants were divided into two equally sized groups of ($n = 15$) participants each. These groups were categorized as either *Heavy Travelers*, defined as those traveling by car six or more days per week, or *Light Travelers*, defined as those traveling five or fewer days per week. The threshold was selected both for its conceptual relevance and because it produced balanced groups.

For trip duration, participants were divided into one group of ($n = 6$) participants, categorized as *Long Trip* travelers (45 minutes or more per trip), and a second group of ($n = 24$) participants, categorized as *Short Trip* travelers (less than 45 minutes per trip). This threshold was chosen to isolate participants whose habitual journeys approach or exceed one hour, as this group was considered likely to have greater exposure to the lap belt and may therefore hold more pronounced perceptions regarding its fit and safety. Even though the groups were distributed as uneven, which could lower the statistical power, it is believed that these results could show some further interesting perspectives of traveling habits versus perceived safety.

4

Results

4.1 Participants

Following recruitment, the final participant sample was established. The achieved distribution across BMI categories and sex is presented in Table 4.1. The sample consisted of 30 participants, with 15 women and 15 men. Participants ranged in age from 22 to 78 years, with a mean age of 47.7 years, covering a broad adult age span. No missing values were recorded for any of the reported variables and each participant completed the full set of anthropometric measurements. The measurements were conducted using standardized procedures, as described in Section 3.3.1.

Table 4.1: Final achieved participant distribution across BMI categories and sex.

BMI category	BMI range	Women	Men
Underweight	< 18.5	1	0
Normal weight	18.5–25	8	6
Overweight	25–30	4	6
Obese	> 30	2	3
Total		15	15

Standing and seated anthropometric characteristics are presented in Appendix C, including full distributions and correlation analyses. BMI showed strong positive correlations with key anthropometric measures in both standing and seated conditions, particularly waist circumference, hip breadth and abdominal depth.

To further contextualize the participant characteristics relative to a reference population, anthropometric measurements were compared to population-based percentile bands. Each measurement was categorized as below the 33rd percentile, between the 33rd and 66th percentile, or above the 66th percentile (Table 4.2). Overall, the distribution shows that participants are represented across all three percentile bands, although not uniformly across all anthropometric measures. Stature and iliac spine height are distributed across the full range of percentile categories for both female and male participants. Hip breadth shows a more central distribution, particularly among males, where a larger proportion falls within the 33rd–66th percentile range. Body mass exhibits a different pattern, with a relatively higher proportion of participants in the upper percentile band, especially among males. This indicates that while the sample covers a broad range of body sizes within the reference population, the distribution varies between different anthropometric dimensions.

Table 4.2: Participant distribution across anthropometric percentile bands relative to Hanson et al. [53].

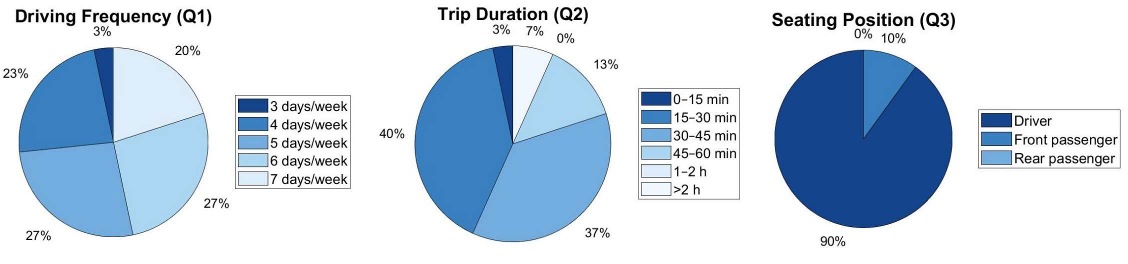
Measurement	<33rd %ile	33rd–66th %ile	>66th %ile
Female participants (n = 15)			
Stature (body height)	6	3	6
Iliac spine height	3	3	9
Hip breadth	7	3	5
Body mass (weight)	6	3	6
Male participants (n = 15)			
Stature (body height)	3	5	7
Iliac spine height	2	4	9
Hip breadth	2	8	5
Body mass (weight)	1	6	8

4.2 Pre-test Questionnaire

The pre-test questionnaire, presented in Appendix A (Questions Q1–Q13), was completed by all 30 participants. The questionnaire was used to characterize participants' typical travel habits, sitting comfort, perceived safety, discomfort from the seatbelt, use of comfort-related accessories and physical activity.

4.2.1 Travel Habits

Participants reported varying levels of driving exposure, see Figure 4.1. Driving frequency was most commonly 5–6 days per week, followed by 4 days per week and 7 days per week, with only one participant reporting 3 days per week. Trip durations were primarily distributed between 15–45 minutes, with fewer participants reporting shorter trips of 0–15 minutes or longer trips exceeding 45 minutes. The sample was predominantly composed of drivers, while a small proportion reported being front-seat passengers and no participants reported rear-seat usage.



(a) Driving frequency (Q1) **(b)** Trip duration (Q2) **(c)** Seating position (Q3)

Figure 4.1: Distribution of driving exposure variables from the pre-test questionnaire.

4.2.2 Sitting comfort

Overall, participants reported low-to-moderate discomfort while sitting in a car during a trip (Q4; Mean = 2.17, SD = 1.30, range = 1–5), indicating that most experienced relatively good seating comfort. Qualitative responses to Q5 further elaborated on the factors influencing seating comfort and were coded into four main categories. The most frequently reported theme was seat adjustment and ergonomics, followed by pressure-related comfort issues and individual physical constraints.

1. **Seat adjustment and ergonomics (n = 14)** Participants most commonly described seating comfort in terms of seat adjustability, including seat height, backrest angle, lumbar support and seat depth. Several responses emphasized the importance of achieving a balanced and stable driving posture.
2. **Pressure distribution and contact comfort (n = 6)** Several participants described discomfort related to pressure points, seat firmness or seat belt interaction with the body.
3. **Individual physical constraints (n = 5)** Participants related seating comfort to body size or physical limitations such as height or back-related issues.
4. **System-level driving experience (n = 3)** Some participants described comfort as an interaction between multiple vehicle components rather than isolated factors.

4.2.3 Perceived safety

Participants generally reported high perceived safety when using a seat belt, both while driving and as passengers. Ratings from Q6 and Q7 showed that participants, on average, felt safe in vehicle environments (driver: Mean = 4.17, SD = 1.09; passenger: Mean = 3.93, SD = 1.18; range = 1–5), although some variability in responses indicates that not all participants shared the same level of confidence. Qualitative responses to Q8 provided further insight into the factors shaping perceived safety and were grouped into five main themes.

1. **Proper belt fit and positioning (n = 18)** The most frequently reported factor influencing perceived safety was correct seat belt positioning and tension, particularly across the shoulder and hip regions. Participants emphasized that the belt should feel secure but not restrictive.
2. **Trust in seat belt systems and safety design (n = 7)** Few participants expressed trust in regulatory standards, vehicle safety systems and seat belt functionality as a basis for perceived safety.
3. **Vehicle and driving context (n = 6)** Perceived safety was also influenced by external factors such as vehicle type, traffic conditions, speed and road environment.
4. **Movement restriction and belt behaviour (n = 5)** Some participants associated safety with how the belt behaves during movement, including whether it retracts properly and maintains consistent tension.
5. **Personal experience and risk awareness (n = 4)** A smaller number of participants referred to personal experiences or risk-related events that influenced their perception of safety.

4.2.4 Discomfort from the seat belt

Reports of seat belt discomfort and related usability issues were relatively infrequent across the sample. For Q9 “Do you experience discomfort or irritation from the seatbelt while driving?”, four participants reported some level of discomfort, typically described as pressure or irritation around the hip region or interference from clothing, while the remaining participants reported no discomfort (one response was excluded due to “no driving license”). For Q10 “Do you experience discomfort or irritation from the seatbelt while riding as a passenger?”, 4 participants reported occasional discomfort or fit issues, mainly related to belt positioning or increased discomfort during longer trips, while the remaining participants reported no issues. It should be noted that two participants reported discomfort in both conditions, while the remaining positive responses were reported by different individuals.

4.2.5 Use of Accessories

Regarding use of comfort-related accessories, usage was generally low across both driving and passenger conditions. For Q11 “Do you use any accessories to increase comfort while driving?”, 2 participants reported using comfort-related aids such as neck support or ergonomic adjustments, while 27 participants reported no use (one response was excluded due to “no driving license”). For Q12, “Do you use any accessories to increase comfort while riding as a passenger?”, 2 participants reported using comfort-related accessories, while 28 participants reported no use. The reported accessories was neck support. One participant reported use in both conditions, while the remaining positive responses were reported by different individuals.

4.2.6 Physical Activity

Participants reported a wide range of physical activity levels (Q13). The mean activity level was 2.93 (SD = 1.46), with responses ranging from 0 to 5+ sessions per week (min = 0, max = 5+). Most participants reported moderate activity levels, with the largest proportion exercising 2–4 times per week (63.3%, n = 19). Lower activity levels (0–1 times per week) were reported by 23.3% (n = 7), while higher activity levels (5+ times per week) were reported by 13.3% (n = 4).

4.3 Visual analysis of belt positioning

This section presents the findings from the data collected during the testing phase, focusing on visual observations. Visual assessment of belt positioning was performed to classify whether the lap belt was positioned on lap or on belly, as well as to identify belt folding and occurrences of arm interference across all configurations.

Across all conditions, belt position was classified as either on lap or on belly. Examples of on lap and on belly belt positioning are shown in Figure 4.2. On belly positioning was observed in a minority of cases, with clear differences between configurations. In the upright position, on belly positioning occurred in 17% of cases for P1, and 3% for both P2 and the user-preferred condition. In the semi-reclined position, the occurrence increased to 27% for P1, 7% for P2, and 10% for the user-preferred condition. On belly positioning was observed in participants spanning a BMI range of approximately 17.9 to 37.8. Regarding sex, on belly positioning was observed in both male and female participants, with cases present in both groups.

(a) On lap (ID 72). **(b)** On belly (ID 52).

Figure 4.2: Examples of belt positioning in P1.

Arm interference, defined as cases where the upper limb obstructed or altered the shoulder belt path (e.g., when the shoulder belt interfered with the right arm, see Figure 4.3) was observed in approximately 7% of cases for P1 in the upright position and 3% for P1 in the semi-reclined position. When moving the lap belt anchor position forward, this interference became more pronounced. It now was observed in approximately 47% of cases in P2 for the upright and 43% in P2 for the semi-reclined position. When participants got to chose their user-preferred position the number of cases dropped again to being observed in approximately 13% of the cases in the upright and 10% of the cases in the semi-reclined position.

(a) Participant (ID 82), upright **(b)** Participant (ID 74), semi-reclined

Figure 4.3: Two examples of arm interference caused by altered shoulder belt geometry when the buckle is moved forward (Left: upright position, right: semi-reclined position).

Lap belt folding was observed in a limited number of participants and was unevenly distributed across the dataset. Across configurations, the occurrence of belt folding showed some variation in the upright position, with frequencies of 7% for P1, 10% for P2, and 13% for the user-preferred condition. In contrast, the semi-reclined condition showed a consistent occurrence of approximately 7% across all configurations. The highest frequency was recorded for participant ID 30 and ID 94, who together accounted for the majority of all observed cases. Both participants were male, with BMI values of 28.0 and 35.0. For these two participants, lap belt folding was consistently observed across multiple configurations and was associated with pronounced abdominal folds. In addition to these cases, isolated occurrences were identified in a small number of additional participants, including both male and female individuals, spanning a BMI range of approximately 20.0 to 37.8. An example of lap belt folding associated with an abdominal fold is shown in Figure 4.4, illustrating a representative case from participant ID 30.

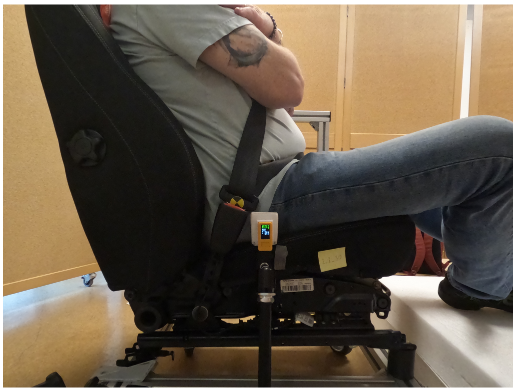


Figure 4.4: Example of lap belt folding associated with an abdominal fold during testing (participant ID 30).

4.4 Quantitative Results

Quantitative results are presented for the two seating conditions investigated in this study: a upright position and a semi-reclined position.

4.4.1 Upright position

The upright position was used to evaluate belt geometry, buckle position and anthropometric influences. All measurements were referenced to the ASIS coordinate system and subsequently transformed to the H-point coordinate system to ensure consistency across participants. The following subsections present belt geometry, displacement characteristics and relationships between anthropometric variables and belt positioning.

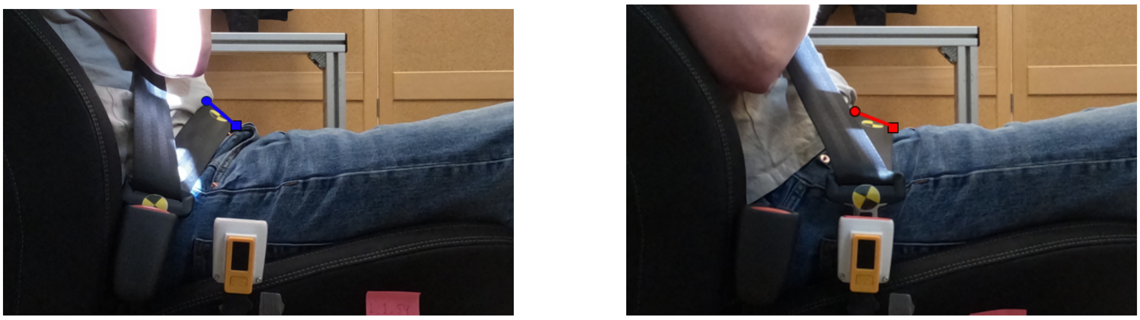
4.4.1.1 Belt geometry and displacement

Belt positions in the upright position were analysed relative to the ASIS reference system for P1, P2 and the user-preferred position. The D-ring anchorage position varied between participants, with two settings used: mid (n = 19) and low (n = 11). The mean belt displacement relative to the ASIS is summarized in Table 4.3. The results are reported separately for the upper and lower belt segments across the three experimental conditions. Both dx and dz components are presented as mean values with standard deviations. Positive values of dx indicate anterior (forward) displacement relative to the ASIS, whereas negative values indicate posterior displacement. Positive values of dz indicate superior (above) displacement relative to the ASIS, whereas negative values indicate inferior displacement. The user-preferred condition was excluded from all plots due to its substantially higher variability compared to P1 and P2, particularly reflected in large standard deviations (e.g. upper dx: 20.2 ± 120.8). This increased variability is likely explained by the individualized nature of the configuration, where participants actively adjusted the belt anchorage based on perceived comfort, leading to greater inter-individual differences in belt positioning. Including this condition would reduce visual clarity and hinder comparison between P1 and P2.

Table 4.3: Mean belt displacement relative to ASIS for upper and lower belt segments in the upright position across conditions. Positive dx indicates anterior displacement, and positive dz indicates superior displacement. Values are presented as mean ± standard deviation (mm).

	P1	P2	User-preferred
Upper dx	23.2 ± 37.1	54.6 ± 31.5	20.2 ± 120.8
Upper dz	11.3 ± 24.8	9.0 ± 27.0	11.5 ± 26.9
Lower dx	66.8 ± 38.1	98.4 ± 29.8	85.4 ± 43.8
Lower dz	-2.0 ± 24.6	7.8 ± 21.2	3.2 ± 25.4

An example of the belt positioning for an individual participant (ID 54) is shown in Figure 4.5. The figure illustrates the belt placement for P1 and P2. The visual comparison demonstrates how the forward shift of the anchorage point influences belt position and orientation.



(a) Predefined 1

(b) Predefined 2

Figure 4.5: Example of belt positioning for participant ID 54 in the upright position. The images illustrate the change in belt routing and positioning relative to the body.

The corresponding mean belt geometry for the two predefined configurations are shown in Figure 4.6. The plot illustrate the upper and lower belt segment positions in a ASIS-centered coordinate system, where the origin represents the ASIS landmark. The X-axis corresponds to the anterior–posterior direction and the Z-axis to the superior–inferior direction, both expressed in millimeters.

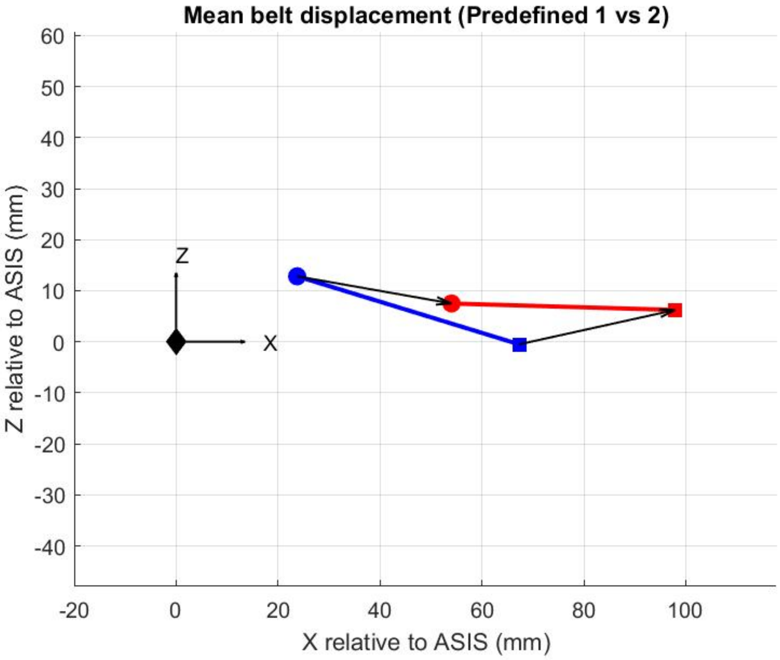


Figure 4.6: Mean belt displacement relative to the ASIS (Upright position). The blue line represents P1 and the red line represents P2.

The belt inclination, defined as the angle between the upper and lower belt points in the XZ-plane relative to the horizontal axis, can be derived from the belt geometry shown in Figure 4.6 for P1 and P2. The corresponding inclination angles were −102.8° for P1 and −33.9° for P2, indicating a substantially flatter belt orientation relative to the pelvis/ASIS following the anterior shift of the anchorage point. For the user-preferred condition, the inclination was −61.1°, lying between the two predefined configurations.

4.4.1.2 Anthropometric predictors of belt displacement for P1 & P2

A significant positive correlation was observed between BMI and the change in ASIS-to-belt distance between P1 and P2. This indicates that participants with higher BMI generally exhibited a larger increase in belt displacement relative to the ASIS when transitioning from P1 to P2, meaning that the belt moved further anteriorly and superiorly relative to the pelvis. The upper belt segment showed $r = 0.52$ ($p = 0.003$), while the lower belt segment showed $r = 0.57$ ($p = 0.001$). Figure 4.7 illustrates this relationship. In other words, higher BMI was associated with a larger increase in ASIS-to-belt distance from P1 to P2, indicating that the belt was positioned further away from the ASIS in P2 compared to P1.

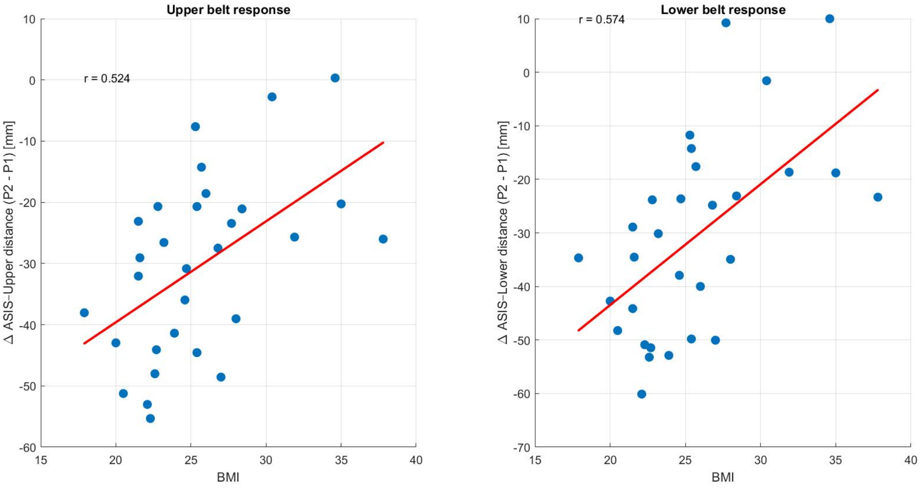
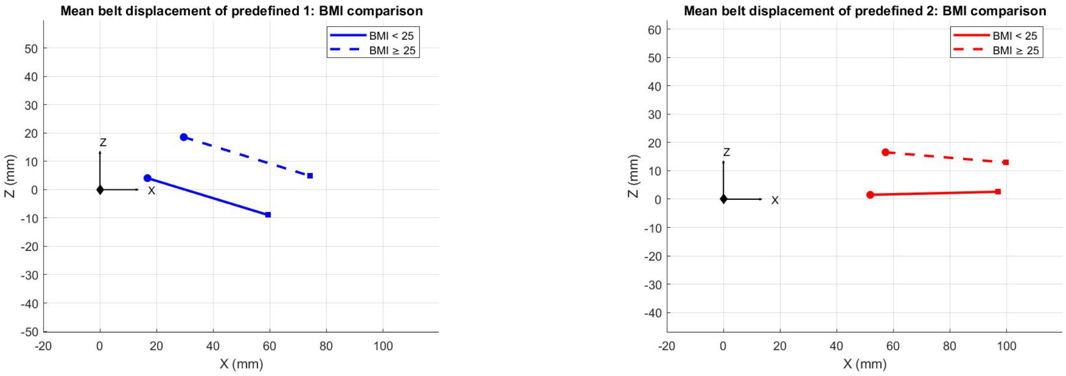


Figure 4.7: Relationship between BMI and change in ASIS-to-belt distance (P2 - P1) for upper and lower belt segments in the upright position.

Participants were divided into two BMI groups (< 25 and ≥ 25), and independent samples t-tests were performed on the change in ASIS-to-belt distance between P1 and P2. Significant group differences were observed for the upper ($p = 0.0021$) and lower belt segments ($p = 0.0010$). Absolute P1 and P2 positions were analysed to further characterise BMI-related effects. Strong correlations with BMI were observed for both predefined positions, particularly in the vertical (Z-axis) direction (P1: $r = 0.81$–0.84, P2: $r = 0.83$–0.84), indicating a strong dependence of vertical belt position on BMI. In the anterior–posterior direction, correlations were slightly higher for P1 ($r = 0.78$–0.80) compared to P2 ($r = 0.73$–0.74) across both belt segments. The mean belt displacement patterns for the two predefined belt configurations are illustrated in Figure 4.8.



(a) Predefined 1: comparison of belt segment displacement between BMI groups.

(b) Predefined 2: comparison of belt segment displacement between BMI groups.

Figure 4.8: Mean belt displacement relative to ASIS for BMI groups (< 25 and ≥ 25) across two predefined belt configurations in the upright position. Coordinates are expressed in millimetres in a ASIS-centered reference frame.

To investigate potential differences in belt displacement between males and females, a correlation analysis was performed between sex and the change in ASIS-to-belt distance. A moderate correlation was observed (r = 0.40, p = 0.028). A linear regression analysis showed that sex was a significant predictor when considered alone (p = 0.028), with higher belt displacement observed for male participants. When both BMI and sex were included in a multiple linear regression model, BMI remained a significant predictor (p = 0.003), while sex was no longer statistically significant (p = 0.095). The model explained 39.7% of the variance in belt displacement ($R^2 = 0.397$).

To further investigate the role of specific anthropometric variables beyond BMI, correlation and regression analyses were performed separately for standing and seated anthropometry. Pearson correlation analyses between anthropometric variables and belt displacement are presented in Table 4.4.

Table 4.4: Pearson correlation coefficients (r) and p-values between anthropometric variables and belt displacement for standing and seated conditions.

Variable (Standing / Seated)	Standing (r, p)	Seated (r, p)
Iliac spine height / Knee height	0.17, 0.39	0.18, 0.18
Waist circumference / Abdominal depth	**0.68, <0.001**	**0.59, <0.001**
Hip breadth	0.26, 0.16	**0.37, 0.048**
Thigh circumference / Thigh clearance	0.03, 0.89	**0.42, 0.022**

Waist circumference in the standing condition and abdominal depth in the seated condition showed the strongest correlations with belt displacement. In the seated condition, hip breadth and thigh clearance also showed statistically significant associations, while no significant relationships were observed for iliac spine height or knee height.

4.4.1.3 Anthropometric predictors of user-preferred buckle position

The user-selected buckle positions, all referenced to the mounting bolt, showed substantial variability, ranging from 48–243 mm in the X-direction, -19–69 mm in the Y-direction, and 114–211 mm in the Z-direction, indicating inter-individual differences in preferred buckle placement across all directions.

A positive correlation was observed between BMI and user-preferred buckle position in the X-direction (r = 0.348, p = 0.059), as shown in Figure 4.9. This indicates that participants with higher BMI tended to select a more forward buckle position, although the relationship did not reach statistical significance. A significant negative correlation was found between BMI and buckle position in the Y-direction (r = -0.612, $p < 0.001$), indicating that participants with higher BMI tended to position the buckle further outward from the seat. No significant relationship was observed between BMI and Z-position (r = 0.054, p = 0.779). The distribution of user-selected buckle positions relative to the predefined reference positions showed that 6 participants selected a position at or beyond P2, 12 participants selected a position between P1 and P2, and the remaining participants selected the same position as P1.

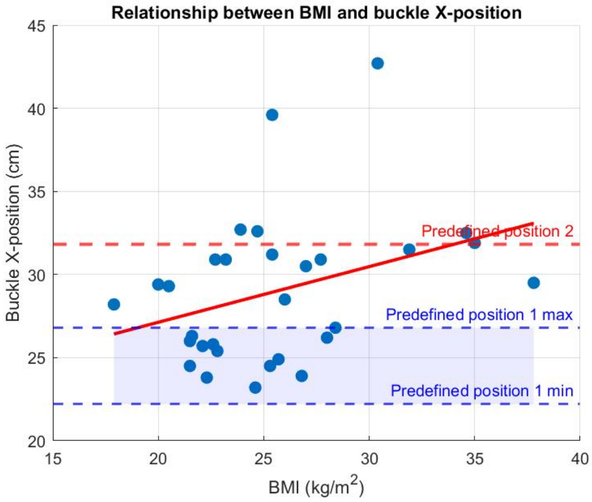


Figure 4.9: Relationship between BMI and buckle X-position in the user-preferred position in the upright position. Each point represents an individual participant, and the regression line illustrates the linear trend between variables. The red dashed line indicates P2, while the blue dashed lines represent the adjustable range of P1.

Correlations between standing anthropometric variables and user-preferred buckle position were analysed separately for each spatial direction, and the results are summarised in Table 4.5. Similarly, correlations between seated anthropometric variables and user-preferred buckle position are presented in Table 4.6.

Table 4.5: Pearson correlation coefficients (r) and p-values between standing anthropometric variables and buckle position in X, Y, and Z directions.

Variable	X (r, p)	Y (r, p)	Z (r, p)
Iliac spine height	-0.230, 0.221	0.055, 0.772	-0.079, 0.680
Waist circumference	**-0.711, <0.001**	**0.387, 0.034**	0.027, 0.889
Hip breadth	**-0.499, 0.005**	**0.376, 0.040**	0.193, 0.306
Thigh circumference	-0.180, 0.342	0.096, 0.615	-0.010, 0.960

Table 4.6: Pearson correlation coefficients (r) and p-values between seated anthropometric variables and buckle position in X, Y, and Z directions.

Variable	X (r, p)	Y (r, p)	Z (r, p)
Abdominal depth	**0.548, 0.002**	**-0.658, <0.001**	0.153, 0.419
Hip breadth	**0.380, 0.038**	**-0.551, 0.002**	0.103, 0.590
Thigh clearance	0.317, 0.088	**-0.458, 0.011**	0.237, 0.208
Knee height	0.183, 0.333	-0.336, 0.069	0.012, 0.951

In the standing condition, significant correlations were observed in the X- and Y-directions for waist circumference and hip breadth. No significant correlations were found for iliac spine height or thigh circumference, and no significant relationships were observed in the Z-direction. In the seated condition, significant correlations were identified for abdominal depth, hip breadth, and thigh clearance in the X- and Y-directions, whereas knee height was not statistically significant. Similarly, no significant correlations were observed in the Z-direction. Pitch angle had a median of 4.1° with a standard deviation of 8.3°. Roll angle had a median of 80.7° with a standard deviation of 9.3°. Pitch was positively correlated with BMI (r = 0.397, p = 0.030), as was roll (r = 0.490, p = 0.006).

4.4.2 Semi-reclined position

The semi-reclined position was used to evaluate belt geometry, buckle position and anthropometric influences under a more reclined seating configuration. All measurements were referenced to the ASIS coordinate system and subsequently transformed to the H-point coordinate system to ensure consistency across participants. The following subsections present belt geometry, displacement characteristics and relationships between anthropometric variables and belt positioning.

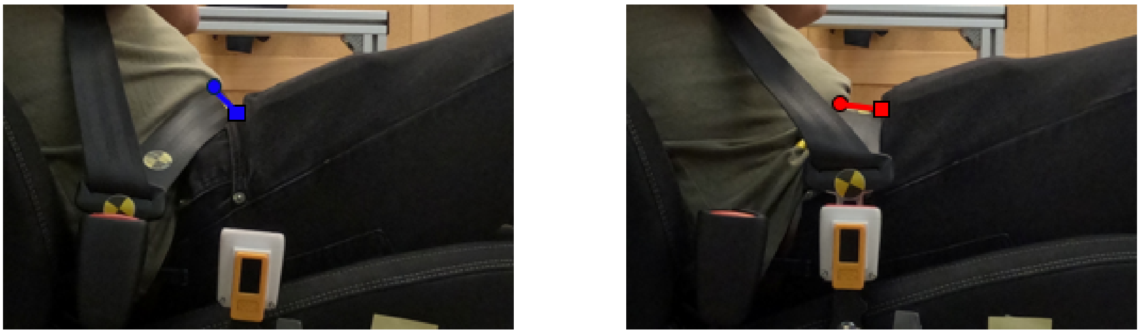
4.4.2.1 Belt geometry and displacement

The mean belt displacement relative to the ASIS is summarized in Table 4.7. The results are reported separately for the upper and lower belt segments across the three experimental conditions. Both dx and dz components are presented as mean values with standard deviations. Positive values of dx indicate anterior (forward) displacement relative to the ASIS, while negative values indicate posterior displacement. Positive values of dz indicate superior displacement relative to the ASIS, while negative values indicate inferior displacement.

Table 4.7: Mean belt displacement relative to ASIS for upper and lower belt segments in the semi-reclined position. Positive dx indicates anterior displacement and positive dz indicates superior displacement relative to ASIS. Values are presented as mean ± standard deviation (mm).

	P1	P2	User-preferred
Upper dx	13.9 ± 32.2	55.4 ± 18.2	39.2 ± 35.9
Upper dz	16.8 ± 25.7	14.2 ± 33.3	13.1 ± 27.6
Lower dx	56.5 ± 29.9	102.3 ± 22.0	83.8 ± 34.9
Lower dz	3.5 ± 25.3	8.6 ± 22.0	4.5 ± 25.8

An example of the belt positioning for an individual participant (ID 63) is shown in Figure 4.10. The figure illustrates the belt placement for P1 and P2. The visual comparison demonstrates how the forward shift of the anchorage point influences belt position and orientation.



(a) P1

(b) P2

Figure 4.10: Example of belt positioning for participant ID 63 in the upright position. The images illustrate the change in belt routing and positioning relative to the body.

The corresponding mean belt geometry for the two predefined configurations is shown in Figure 4.11. The plot illustrate the upper and lower belt segment positions in a ASIS-centered coordinate system, where the origin represents the ASIS landmark.

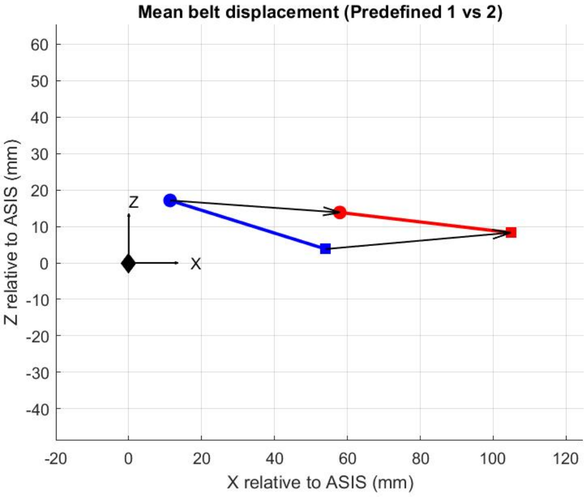


Figure 4.11: Mean belt displacement relative to the ASIS (Semi-reclined position). The blue line represents P1 and the red line represents P2.

The belt inclination, defined as the angle between the upper and lower belt points in the XZ-plane relative to the horizontal axis, changed from −126.1° in P1 to −43.9° in P2, indicating a substantially flatter belt orientation relative to the pelvis/ASIS following the anterior shift of the anchorage point. In the user-preferred position, the inclination was −109.1°.

4.4.2.2 Anthropometric predictors of belt displacement for P1 & P2

A correlation was observed between BMI and the change in ASIS-to-belt distance between P1 and P2 in the semi-reclined position. For the upper belt segment, the correlation coefficient was r = 0.438 (p = 0.016), and for the lower belt segment r = 0.366 (p = 0.047). Figure 4.12 shows the relationship between BMI and the change in ASIS-to-belt distance (P2 - P1) for both belt segments, with separate regression lines for upper and lower segments.

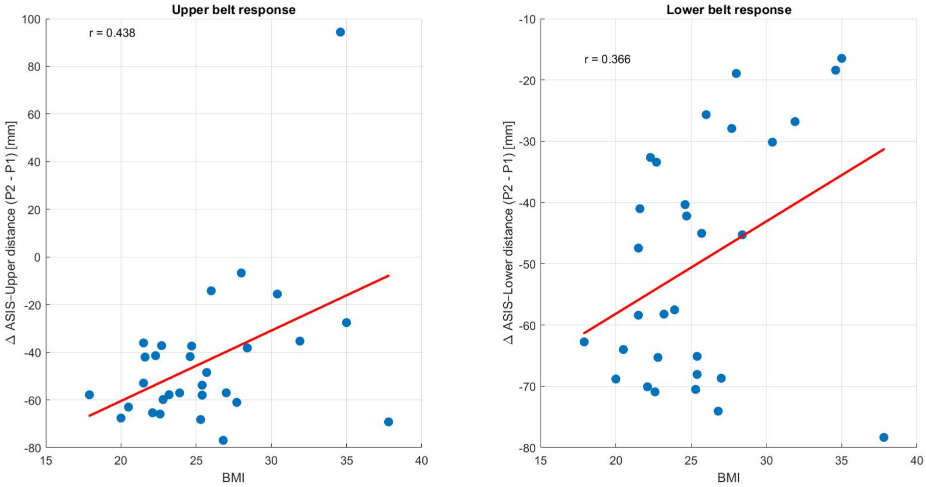
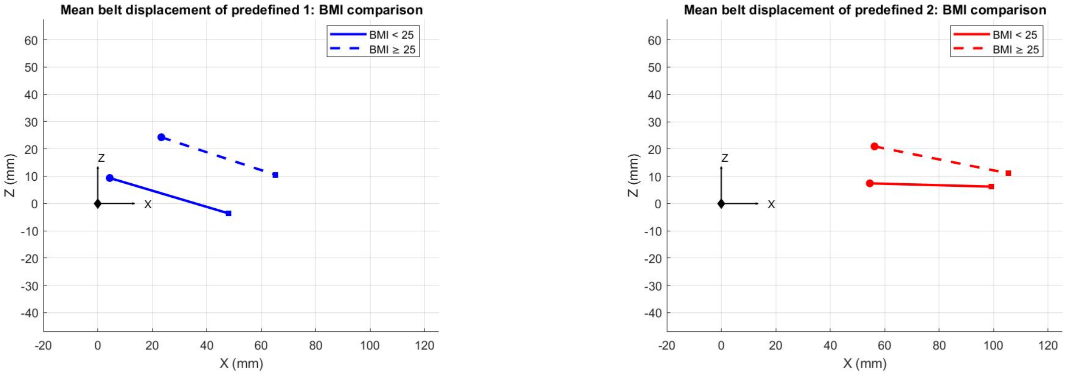


Figure 4.12: Relationship between BMI and change in ASIS-to-belt distance (P2 - P1) for upper and lower belt segments in the semi-reclined position.

Participants were divided into two BMI groups (< 25 and ≥ 25), and independent samples t-tests were performed on the change in ASIS-to-belt distance between P1 and P2. No statistically significant differences were observed between BMI groups for either belt segment (upper: $p = 0.154$; lower: $p = 0.209$). Mean values for BMI < 25 and BMI ≥ 25 were -5.222 and -3.573 for the upper segment, and -5.420 and -4.529 for the lower segment, respectively.



(a) P1: comparison of belt segment displacement between BMI groups.

(b) P2: comparison of belt segment displacement between BMI groups.

Figure 4.13: Mean belt displacement relative to ASIS for BMI groups (< 25 and ≥ 25) across two predefined belt configurations in the semi-reclined position.

Both P1 and P2 showed statistically significant correlations with BMI in both the X- and Z-axes when evaluated independently. In the vertical (Z-axis) direction, consistently strong correlations were observed for both predefined positions (P1: $r = 0.82$ to 0.87; P2: $r = 0.81$ to 0.87). In the anterior–posterior direction (X-axis), positive correlations with BMI were observed for both P1 and P2. The correlation coefficients were higher in P1 (r = 0.58–0.61) compared to P2 (r = 0.44–0.58) across upper and lower belt segments. The mean belt displacement patterns for the two predefined belt configurations are illustrated in Figure 4.13.

No statistically significant association was found between sex and belt displacement in the semi-reclined position (r = 0.27, p = 0.144), and it also was not a significant predictor in the regression model (p = 0.144). In the multiple regression model including BMI and sex, neither variable reached statistical significance (BMI: p = 0.094; sex: p = 0.306), and the model explained 16.8% of the variance in belt displacement ($R^2 = 0.168$).

Table 4.8: Pearson correlation coefficients (r) and p-values between anthropometric variables and belt displacement in the semi-reclined position.

Variable (Standing / Seated)	Standing (r, p)	Seated (r, p)
Iliac spine height / Knee height	0.000, 1.000	0.143, 0.450
Waist circumference / Abdominal depth	**0.446, 0.014**	0.332, 0.073
Hip breadth	0.142, 0.455	0.270, 0.148
Thigh circumference / Thigh clearance	0.128, 0.500	0.277, 0.139

Correlation analyses between anthropometric variables and belt displacement in the semi-reclined position are presented in Table 4.8. In the standing condition, a statistically significant correlation was observed for waist circumference (r = 0.446, p = 0.014), while no significant correlations were found for hip breadth, iliac spine height, or thigh circumference. In the seated condition, none of the anthropometric variables showed statistically significant correlations with belt displacement.

4.4.2.3 Anthropometric predictors of user-preferred buckle position

The user-selected buckle positions in the reclined condition, all referenced to the mounting bolt, showed substantial variability, ranging from 19–193 mm in the X-direction, -14–61 mm in the Y-direction, and 102–241 mm in the Z-direction, indicating inter-individual differences in preferred buckle placement across all axes.

A significant positive correlation was observed between BMI and buckle position in the X-direction (r = 0.481, p = 0.007), as shown in Figure 4.14. A significant negative correlation was found between BMI and buckle position in the Y-direction (r = -0.376, $p < 0.041$). Finally, a significant correlation was observed between BMI and buckle position in the Z-direction (r = 0.486, p = 0.006). The distribution of user-preferred buckle positions relative to the predefined reference positions showed that 2 participants selected a position beyond P2, 13 participants selected a position between P1 and P2, 11 participants selected a position within the range of P1, and 4 participants selected a position below P1.

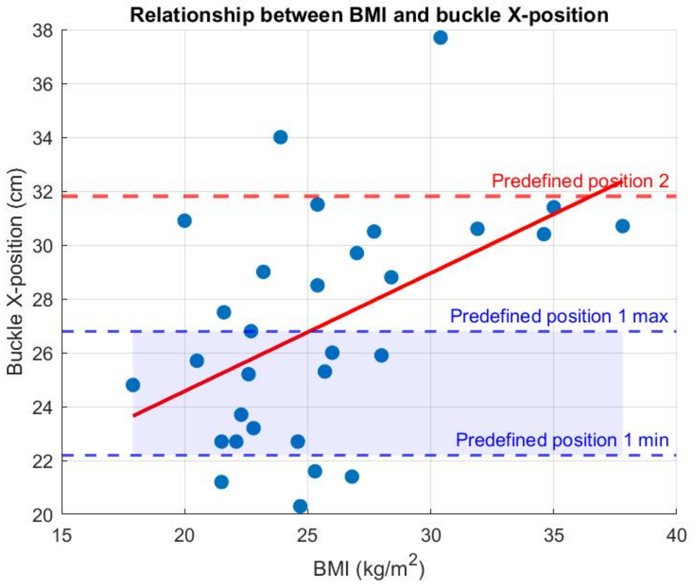


Figure 4.14: Relationship between BMI and buckle X-position in the user-preferred position in the semi-reclined position. Each point represents an individual participant, and the regression line illustrates the linear trend between variables. The red dashed line indicates P2, while the blue dashed lines represent the adjustable range of P1.

To further investigate relationships between anthropometric variables and buckle position, Pearson correlation analyses were performed separately for standing and seated anthropometry. The results are shown in Tables 4.9 and 4.10.

Table 4.9: Pearson correlation coefficients (r) and p-values between standing anthropometric variables and buckle position in X, Y, and Z directions in the semi-reclined position.

Variable	X (r, p)	Y (r, p)	Z (r, p)
Iliac spine height	-0.277, 0.139	0.142, 0.453	-0.151, 0.426
Waist circumference	**-0.409, 0.025**	**0.388, 0.034**	**0.419, 0.021**
Hip breadth	**-0.567, 0.001**	**0.465, 0.010**	0.247, 0.189
Thigh circumference	-0.120, 0.527	0.227, 0.228	0.253, 0.177

Table 4.10: Pearson correlation coefficients (r) and p-values between seated anthropometric variables and buckle position in X, Y, and Z directions in the semi-reclined position.

Variable	X (r, p)	Y (r, p)	Z (r, p)
Abdominal depth	**0.503, 0.005**	**-0.413, 0.023**	**0.503, 0.005**
Hip breadth	**0.475, 0.008**	**-0.568, 0.001**	0.265, 0.157
Thigh clearance	**0.432, 0.017**	**-0.423, 0.020**	0.355, 0.054
Knee height	0.253, 0.177	-0.340, 0.066	-0.032, 0.868

In standing anthropometry, significant correlations were observed for waist circumference and hip breadth in the X- and Y-directions. No significant correlations were observed in the Z-direction. In seated anthropometry, significant correlations were observed for hip breadth, abdominal depth, and thigh clearance in the X- and Y-directions. No significant correlations were observed in the Z-direction. Pitch angle had a median of 0.3° with a standard deviation of 7.9°. Roll angle had a median of 79.9° with a standard deviation of 8.6°. Lap belt buckle orientation showed positive correlations with BMI for both pitch ($r = 0.310$, $p = 0.096$) and roll ($r = 0.327$, $p = 0.078$), although these correlations were not statistically significant.

4.5 Regulatory Framework Compliance

The regulatory compliance analysis was based on lower seat belt anchorage angle requirements defined in FMVSS 210 and UNECE Regulation No. 14, both specifying an allowable angular range relative to the horizontal plane (SgRP/R-point reference). For the present analysis, a unified acceptance range of 30°–80° in the xz-plane relative to the H-point was used to represent the overlapping regulatory envelope.

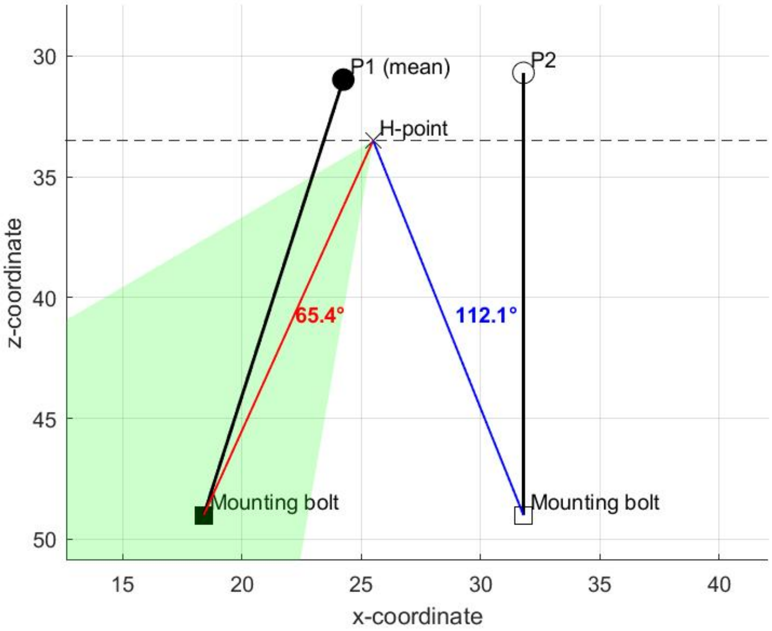


Figure 4.15: Regulatory acceptance envelope in the xz-plane relative to the H-point for both seating conditions. The green region represents the angular range 30°–80°. P1 corresponds to the mean of all manufacturing buckle positions (black). P2 represents the measured buckle position (white). The manufacturing reference bolt represents the measured mounting point in the test rig, and the additional reference bolt is aligned vertically with P2.

Figure 4.15 shows the regulatory acceptance region together with the belt geometry used as a common reference for both seating conditions. P1 represents the mean value of all manufacturing buckle positions in the upright position (black markers). For the semi-reclined position, the corresponding mean position was located at x=21.5 and z=30.7. However, since the regulatory framework is defined relative to the fixed manufacturing mounting bolt, the resulting angular evaluation remains unchanged between the two seating conditions. P2 represents the measured buckle position (white marker). The manufacturing reference mounting bolt position corresponds to the measured attachment point in the test rig configuration, while the additional reference bolt is defined vertically aligned with P2 at the same z-level as the original manufacturing reference.

It should be noted that both FMVSS 210 and UNECE Regulation No. 14 are originally defined for upright seating conditions and assume a nominal occupant posture aligned with the H-point reference. No explicit regulatory criteria exist for reclined seating configurations. As a result, the same angular acceptance limits are applied here to the semi-reclined position in order to enable comparative analysis, rather than to represent a validated regulatory requirement for reclined conditions.

4.5.1 Upright position

Figure 4.16 shows the distribution of all user-preferred buckle positions together with their corresponding reconstructed mounting bolts in the xz-plane.

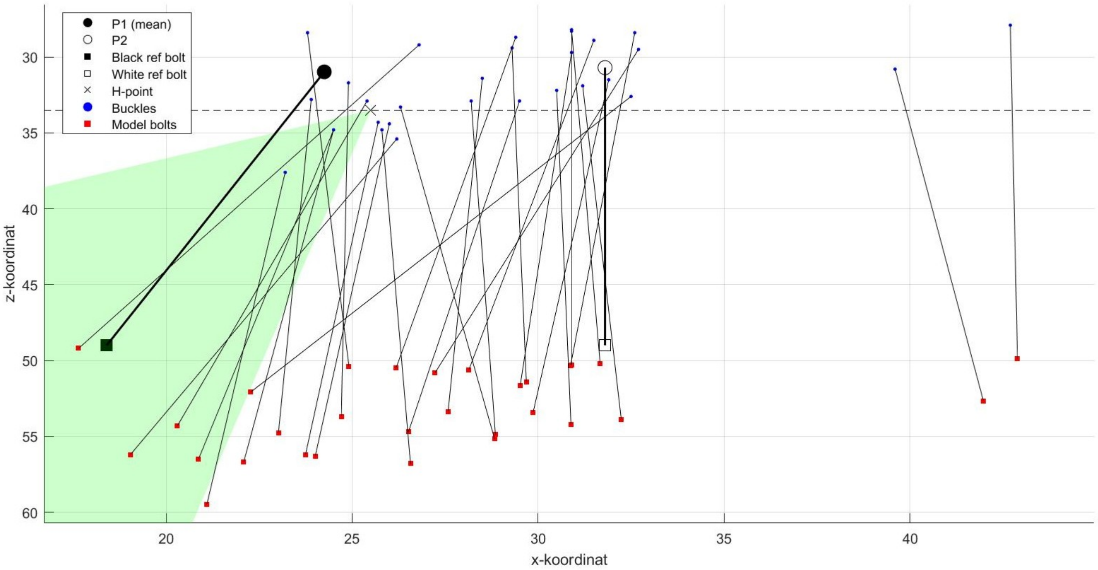


Figure 4.16: Regulatory compliance analysis in the xz-plane for the upright position. Blue markers represent the measured buckle positions from all participants, while red markers indicate the corresponding reconstructed mounting bolt positions. Each buckle position is connected to its reconstructed mounting bolt via a rigid link. The green shaded sector represents the regulatory acceptance region defined by angular limits of 30°–80° relative to the horizontal reference passing through the H-point.

All user-preferred buckle positions were analysed within a common xz-plane coordinate system. Each buckle position was treated in its original measurement frame, and the corresponding mounting bolt position was reconstructed individually using a rigid kinematic link model with fixed length $L = 22$ cm and a pitch-dependent orientation. This approach preserves the original spatial configuration of the measurements while enabling direct comparison of all reconstructed points relative to the defined regulatory acceptance region. The results show that **the majority of participants (86.7%) selected positions outside the regulatory acceptance region**, while only 4 participants (13.3%) remained within the specified limits.

4.5.2 Semi-reclined position

The same analysis approach was applied to the semi-reclined position. All user-preferred buckle positions were analysed within a common xz-plane coordinate system, and the corresponding mounting bolt positions were reconstructed using the same rigid kinematic link model with fixed length $L = 22$ cm and pitch-dependent orientation. This ensures consistency between seating conditions and allows direct comparison of reconstructed configurations relative to the same regulatory envelope. Figure 4.17 shows the distribution of all user-preferred buckle positions and their corresponding reconstructed mounting bolts for the semi-reclined position.

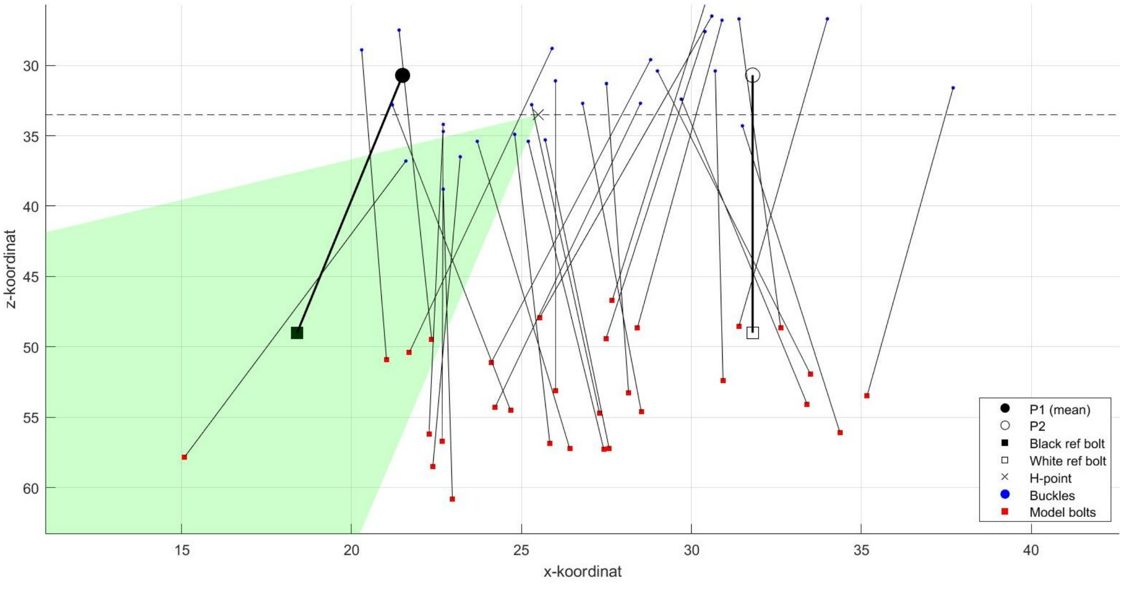


Figure 4.17: Regulatory compliance analysis in the xz-plane for the semi-reclined position. Black markers represent the measured buckle positions from all participants, while red markers indicate the reconstructed mounting bolt positions. Each buckle position is connected to its reconstructed mounting bolt via a rigid link. The green shaded sector represents the regulatory acceptance region defined by angular limits of 30°–80° relative to the horizontal reference passing through the H-point.

The results show that **the majority of participants (86.7%) selected positions outside the regulatory acceptance region**, while only 4 participants (13.3%) fall within the specified limits.

4.6 Qualitative Results

Results are presented with quantitative Likert scale ratings on perceived comfort, perceived safety, and usability together with qualitative feedback gathered from interviews.

4.6.1 Upright position

This section describes the subjective evaluations from the participants that were collected in the upright position.

4.6.1.1 Perceived Discomfort and Pressure

P1 yielded the highest mean perceived pressure (1.57 ± 0.86), while discomfort was lower (1.17 ± 0.59). In P2, the pressure score decreased (1.27 ± 0.52), whereas the discomfort score increased to (1.40 ± 0.67). When participants were allowed to select their own position, discomfort scores dropped to the absolute minimum (1.00 ± 0.00), see Table 4.11.

Table 4.11: Frequency of participant responses (n = 30) for lap belt pressure (Q1) and discomfort (Q2), which was rated with a 5-point likert scale (1 = No pressure/No discomfort, 5 = Very strong pressure/Extreme discomfort).

Configuration	**Measurement**	**1**	**2**	**3**	**4**	**5**	**Mean ± SD**
P1	Q1: Pressure	20	8	1	1	0	1.57 ± 0.86
	Q2: Discomfort	26	3	0	1	0	1.17 ± 0.59
P2	Q1: Pressure	23	6	1	0	0	1.27 ± 0.52
	Q2: Discomfort	20	9	0	1	0	1.40 ± 0.67
User-preferred	Q1: Pressure	23	4	3	0	0	1.33 ± 0.66
	Q2: Discomfort	30	0	0	0	0	1.00 ± 0.00

Qualitative data in P1 showed that many participants (n = 16) reported that the lap belt felt normal, describing it as “seamless” or barely noticeable. However, a notable group (n = 8) reported that the lap belt sat awkwardly, chafed or exerted pressure on the stomach and hips. Additionally, a few participants (n = 6) noted that while the lap belt was acceptable, the shoulder belt caused annoyance by disturbing the right arm, sitting too high, or chafing against the neck. For P2, many participants (n = 14) noted that the lap belt had a positive shift of perceived pressure away from the stomach and onto the thighs or hips, which was frequently described as a more even and comfortable pressure distribution (e.g., “The pressure has moved from the stomach to the thighs with a lower pressure overall” [ID_176]).

Another interesting result from the feedback for P2 was that there were two main reasons for the higher discomfort score. First, some felt a perceived lack of safety; for instance, participant ID_30 reported a discomfort level of 4, noting that the belt did not sit tightly around the hips and felt “less safe”. Second, higher discomfort was caused by right-arm interference from the shoulder belt (n = 8), which was discussed before in Section 4.3. Participants noted that the altered belt geometry made the shoulder belt “feel almost like an armrest”. One example of this occurrence can be seen in previous Figure 4.3 (a)). Finally, for the user-preferred position, several participants ($n = 9$) reported feeling little to no pressure from the lap belt. Although the overall rated pressure for this configuration was higher than in P2, qualitative feedback indicated this was perceived positively; participants felt that moving the lower anchorage closer to P1 achieved an optimal, more embracing fit. Furthermore, the user-preferred adjustment removed the major problems with annoyance of the shoulder belt chafing against the neck in P1 and the right-arm interference experienced in P2. Only two participants still felt annoyance from the shoulder belt (one with neck chafing and with the right arm interference).

To visualize and compare the preference for P2 against P1 regarding perceived discomfort and pressure, subjective ratings and qualitative feedback from all participants (n = 30) were analyzed and interpreted. The analysis showed that nearly half of the participants (47%) preferred P2 over P1 and conversely, 20%, preferred P2 less. This subset was divided into two distinct groups: those who preferred the position less due to unfamiliarity with the forward lap belt placement (7%), and those who experienced increased perceived pressure on the thighs (13%). The remaining participants (33%) reported no preference, indicating that there was no perceptible difference between the two setups. This distribution can be seen in Figure 4.18. One thing to be noted is that this analysis regarded only the participants perceived discomfort and pressure from the lap belt. Including feedback and rating related to the previous mentioned arm interference due to the shoulder belt fit would have reduced the preference for P2 somewhat.

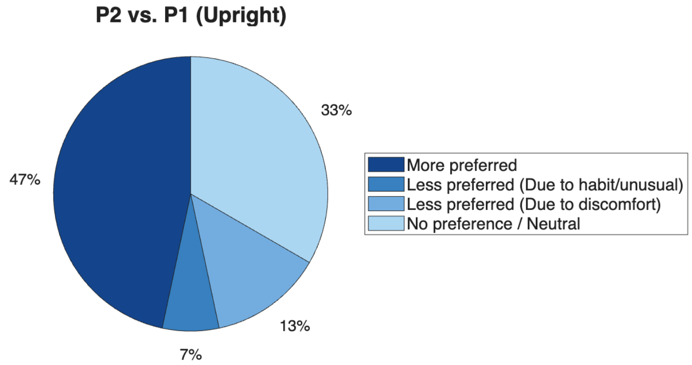


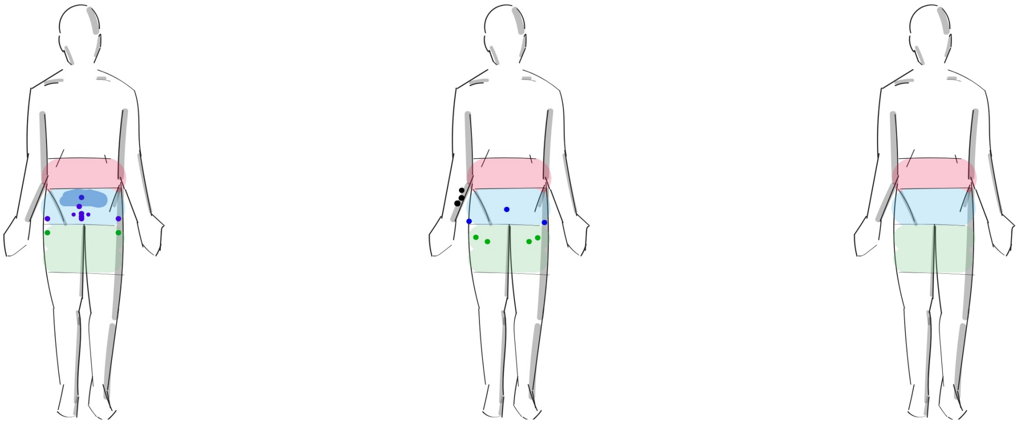
Figure 4.18: Distribution of participant preference for P2 compared to P1, regarding perceived pressure and comfort.

Correlation analyses were conducted to investigate the relationship between participant demographics, anthropometric measurements, and their subjective preference for P2. Preference was numerically scored (1 = Liked more, 0 = Neutral, -1 = Liked less). Overall, no statistically significant correlations were found across the variables ($p > 0.05$). However, weak negative trends were observed regarding midsection dimensions. Waist circumference ($r = -0.313$, $p = 0.093$) and abdominal depth ($r = -0.287$, $p = 0.124$) exhibited the strongest negative correlations, but was not statistically significant, see Table 4.12.

Table 4.12: Pearson correlation coefficients (r) and p-values between standing and seated anthropometric variables and preference for P2.

Variable (Standing / Seated)	**Standing (r, p)**	**Seated (r, p)**
Iliac spine height / Knee height	0.045, 0.815	-0.112, 0.556
Waist circumference / Abdominal depth	-0.313, 0.093	-0.287, 0.124
Hip breadth	-0.007, 0.973	-0.013, 0.947
Thigh circumference / Thigh clearance	-0.123, 0.517	-0.170, 0.368

To further visualize the physical experience across the three lap belt anchorage positions, participants marked areas of bodily discomfort or annoyance on a standardized body map. Figure 4.19 presents the composite markings for P1, P2, and user-preferred position. A note here is that the plotted marks may under represent the total extent of discomfort, as participants tended to mark only the most pronounced areas rather than every minor annoyance noted verbally.



(a) P1 **(b)** P2 **(c)** User-preferred

Figure 4.19: Participant-reported areas of discomfort or annoyance plotted on a body map across the three seating configurations (upright position).

In P1, a subset of all participants (27%; 5 females, 3 males) documented their discomfort on the body maps, placing 11 specific marks and shading one broader area. These marks were primarily concentrated around the stomach, the hips, and outer thighs. When transitioning to P2, the overall frequency of visual reporting remained similar (23%; 4 females, 3 males) with a few marks near the hips and outer thighs but the most notably was that two males and one female explicitly marked their right arm. In the user-preferred position, zero participants plotted any points.

For further analysis, a t-test was conducted of previous mentioned shoulder belt interference. In P1, more females was affected and was close to being statistical significant (5 females, 1 male; $p = 0.072$), while BMI did not significantly differ from the rest of the participants ($p = 0.883$). For P2, the sex disparity disappeared (4 females, 4 males) but instead participants who found the shoulder belt obstructive had a significantly lower average BMI (22.6) compared to the rest of the participants (26.7), ($p = 0.034$). Also, these participants had significantly smaller seated measurements in abdominal depth ($p = 0.032$) and thigh clearance ($p = 0.041$). Furthermore, their standing waist circumference showed a strong trend toward significance ($p = 0.099$), see Table 4.13 (P1) and Table 4.14 (P2) for more results.

Table 4.13: T-test results comparing anthropometric variables between those who experienced shoulder belt annoyance in P1 and the rest of the participants. The mean values are measured in [cm].

Posture	**Variable**	**Mean (Annoyed)**	**Mean (Rest)**	***p*-value**
Standing	Iliac spine height	100.8	100.4	0.913
	Waist circumference	91.4	94.9	0.656
	Standing hip breadth	38.6	36.6	0.200
	Thigh circumference	56.6	55.7	0.719
Seated	Abdominal depth	28.0	28.7	0.826
	Seated hip breadth	44.0	41.5	0.226
	Thigh clearance	13.0	12.6	0.524
	Knee height	55.1	55.4	0.887

Table 4.14: T-test results comparing anthropometric variables between those who experienced shoulder belt annoyance in P2 and the rest of the participants. The mean values are measured in [cm].

Posture	**Variable**	**Mean (Annoyed)**	**Mean (Rest)**	***p*-value**
Standing	Iliac spine height	100.3	100.6	0.908
	Waist circumference	85.9	97.2	< 0.100
	Standing hip breadth	35.6	37.5	0.160
	Thigh circumference	53.6	56.7	0.141
Seated	Abdominal depth	24.3	30.1	**0.032**
	Seated hip breadth	40.1	42.7	0.154
	Thigh clearance	11.8	13.0	**0.041**
	Knee height	54.7	55.5	0.629

4.6.1.2 Perceived Safety

Perceived safety was highest in P1 (4.50 ± 0.63) and in the user-preferred position (4.30 ± 1.02). Conversely, P2 introduced a notable drop (3.57 ± 1.25), with some participants rating it as “Not safe at all” (Min = 1) (see Table 4.15).

Table 4.15: Frequency of participant responses ($n = 30$) for perceived safety (Q5). It was evaluated with a 5-point Likert scale (1 = Not safe at all, 5 = Completely safe).

Configuration	**Measurement**	**1**	**2**	**3**	**4**	**5**	**Mean ± SD**
P1	Q5: Perceived safety	0	0	2	11	17	4.50 ± 0.63
P2	Q5: Perceived safety	3	1	11	6	9	3.57 ± 1.25
User-preferred	Q5: Perceived safety	1	1	3	8	17	4.30 ± 1.02

Based on qualitative feedback for P1, feelings of safety were heavily driven by habit and an inherent trust ($n = 16$). Participants noted the belt sat exactly where expected, providing a subconscious certainty that it would protect them. Another group ($n = 7$) focused on the physical fit, generally finding the position tight and comfortably enclosed. A final subset ($n = 7$) emphasized that perceived safety was also influenced by external circumstances and general vehicle trust, noting that a seatbelt alone does not guarantee absolute safety. For P2, a large group of participants ($n = 16$) perceived the lap belt as less safe and commented that they had a reduced sense of physical embrace or that it felt unusual (e.g., "Does not really sit against the body, feels like I can move sideways" [ID_24]). Another group ($n = 9$) noted that the lap belt still sat good and that they felt safe due to them "feeling" the belt on the body, (e.g., "It sits where it should be placed" [ID_58]). Depending on where and how the participants placed their user-preferred lower anchor position, the qualitative feedback varied a bit. A majority of the participants ($n = 17$) believed that this position again yielded a high perceived safety due to the belt sitting closer to the body and embracing it more, compared to P2. However, still a notable group ($n = 7$), felt not safe at all or less safe than P1, noting that the lap belt sat loose or citing: "I still have a belt but don't believe it would have helped in a crash" ID_94. This was probably due to these participants adjusting their lower anchorage position to a more forward position or closer to P2.

To visualize and compare preference for P2 against P1, regarding perceived safety, subjective ratings together with qualitative feedback from all the participants ($n = 30$) was analyzed and interpreted. It showed that a clear majority (63%) preferred P2 less. A portion of participants (30%) reported no preference. Finally, a minority (7%) actually preferred P2 regarding perceived safety. The distribution is illustrated in Figure 4.20.

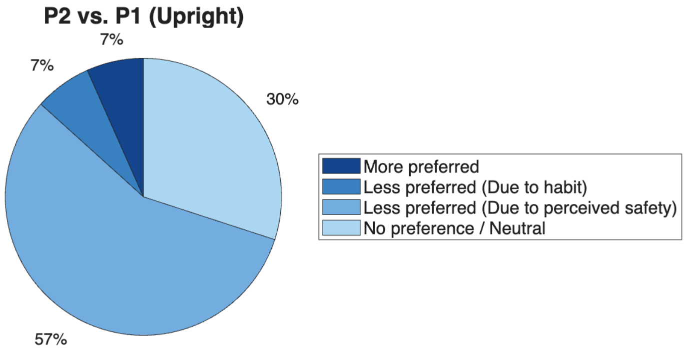


Figure 4.20: Distribution of participant preference for P2 compared to P1, regarding perceived safety.

Due to previous findings suggesting that participants felt less safe in P2 it was evaluated if traveling habits influenced this. Travel data, gathered from the pre-questionnaire (see Figure 4.1), was analyzed against safety ratings using both Pearson correlation and independent-samples t-tests. A Pearson correlation analysis revealed no significant linear relationship between the number of days traveled per week and safety ratings ($r = -0.053$, $p = 0.780$). Average trip duration showed a weak negative correlation ($r = -0.304$), suggesting a trend where longer trips correspond to lower safety ratings, though this did not reach statistical significance ($p = 0.102$), see Table 4.16. Participants were then divided into categorical groups based on their travel frequency and average trip duration for further investigation (see the groups in previous Section 3.6.10). T-tests revealed no significant difference in safety ratings based on weekly traveling frequency ($p = 0.400$). However, a statistically significant difference was found for trip duration ($p = 0.017$), with *Long Trip* participants reporting notably lower safety ratings ($M = 2.50$) compared to *Short Trip* participants ($M = 3.83$), see Table 4.17.

Table 4.16: Pearson Correlation: Impact of Travel Habits on Safety Rating in P2.

Travel Metric	r	p
Days per Week	-0.053	0.780
Trip Duration	-0.304	0.102

Table 4.17: T-Test Analysis: Impact of Travel Habits on Safety Rating in P2.

Metric	**Category (Definition)**	**Mean Rating**	**p-value**
Days per Week	Heavy ($\geq$ 6 days)	3.36	0.400
	Light ($\leq$ 5 days)	3.75	
Trip Duration	Long ($\geq$ 45 min)	2.50	**0.017**
	Short (< 45 min)	3.83	

4.6.1.3 Perceived Usability

P1 presented some higher rated difficulty compared to the other setups. Comparing the ratings of P2 to P1 shows a slight improvement in the ease of buckling (1.23 ± 0.50) and unbuckling (1.20 ± 0.41). While the mean score for locating the buckle remained similar (1.43). When participants were allowed to select their own position, usability scores reached near-perfect levels across all three metrics, see Table 4.18. Qualitative feedback for P1 showed that this position offered standard usability and that the buckle sat where expected based on habit. However, a few participants ($n = 4$) found it difficult to locate and fasten the belt. They noted that the standard placement sat too far back, requiring them to twist their upper body, a problem worsened by the buckle's color blending in with the seat. For P2, many participants ($n = 19$) noted that the forward placement, combined with the buckle's color, made it easier to visually locate and physically operate without twisting the torso (e.g., "Easier to find because it is further forward and is white colored. I see it right away" [ID_30]). A smaller group ($n = 8$) expressed that the forward placement felt unnatural, sometimes resulting in a higher difficulty rating. Lastly, for the user-preferred position several participants ($n = 10$) felt that this position gave high accessibility and visibility and that the buckle overall was very easy to handle, mainly due to a more forward position. A few participants ($n = 3$) felt that it was a position they were not used to and that it therefore was more difficult find and operate.

Table 4.18: Frequency of participant responses ($n = 30$) for locating the buckle (Q7), buckling the belt (Q8) and unbuckling the belt (Q9). They were evaluated with a difficulty rating with a 5-point scale (1 = Very easy, 5 = Very difficult).

Configuration	**Measurement**	**1**	**2**	**3**	**4**	**5**	**Mean ± SD**
P1	Q7: Locating buckle	20	7	3	0	0	1.43 ± 0.68
	Q8: Buckling belt	24	3	3	0	0	1.30 ± 0.65
	Q9: Unbuckling belt	25	2	3	0	0	1.27 ± 0.64
P2	Q7: Locating buckle	21	6	2	1	0	1.43 ± 0.77
	Q8: Buckling belt	24	5	1	0	0	1.23 ± 0.50
	Q9: Unbuckling belt	24	6	0	0	0	1.20 ± 0.41
User-preffered	Q7: Locating buckle	28	1	1	0	0	1.10 ± 0.40
	Q8: Buckling belt	29	1	0	0	0	1.03 ± 0.18
	Q9: Unbuckling belt	29	1	0	0	0	1.03 ± 0.18

To visualize preference for P2 against P1, regarding usability, subjective ratings together with qualitative feedback from all the participants ($n = 30$) was analyzed and interpreted. It showed that a majority (53%) preferred P2 over P1. Conversely, 27%, of the participants preferred P2 less, mainly due to habit. The remaining participants (20%) reported no preference and found P2 just as easy to use as P1. The distribution is illustrated in Figure 4.21.

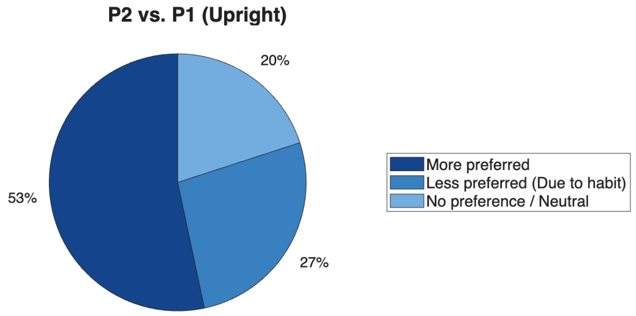


Figure 4.21: Distribution of preference for P2 compared to P1, regarding ease of finding the buckle, as well as buckling and unbuckling the belt.

4.6.1.4 Qualitative feedback for the user-preferred position

Interpretation of the qualitative feedback indicated that the vast majority of participants ($n = 26$) considered their user-preferred position to provide the best overall fit among all tested setups or being equally good (some participants chose their user-preferred position close to or in the exact same position as P1 or P2). However, rather than converging on a single universal placement, individuals adjusted the position based on differing priorities to achieve what they considered optimal. As shown in Figure 4.22, the primary motivations for their specific adjustments fell into three main categories: perceived safety, usability and ergonomics, and perceived physical comfort. Despite this variation in reasoning and final placement, allowing users to tailor the system to their specific needs resulted in high overall satisfaction. Still, a small minority ($n = 4$) preferred the previous positions. This was primarily because moving the lower anchorage forward to achieve reduced perceived discomfort and pressure (closer to P2) felt unfamiliar, or because their manual attempts to recreate the perceived safety baseline in P1 failed to achieve the exact same placement.

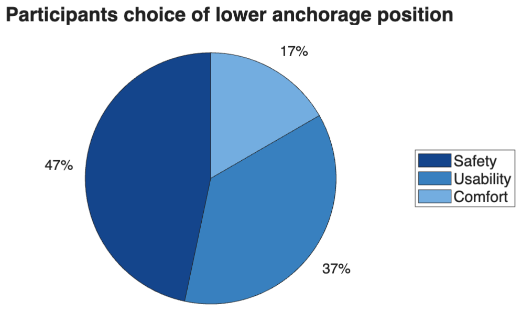


Figure 4.22: Distribution of participant's primary motivations for determining their user-preferred position in the upright position.

Out of the 30 participants, the largest group of participants (47%) based their adjustment primarily on safety. These individuals commented that they positioned the lap belt anchor closer to the body to find a balance between appropriate perceived pressure and secure restraint. Another group (37%) prioritized the practicality of operating the buckle. These participants positioned the buckle slightly forward for visual accessibility and to allow a more natural movement of the arm, effectively reducing torso twisting. Despite choosing a more forward placement, some participants found the change temporarily confusing due to habits of reaching backward for the standard buckle. The final group (17%) focused on physical comfort and adjusted the buckle to eliminate perceived pressure points, ensuring that the belt did not press uncomfortably against sensitive areas, such as the lower part of the stomach.

4.6.2 Semi-reclined position

This section describes the subjective evaluations for the semi-reclined position.

4.6.2.1 Perceived Comfort

Similar to the upright position, P1 produced the highest mean perceived pressure (1.63 ± 0.76) and discomfort (1.33 ± 0.66), while the user-preferred position achieved the lowest possible discomfort score (1.00 ± 0.00). For P2 however, the pressure score achieved the lowest rating of all positions (1.13 ± 0.00), see Table 4.19. The qualitative feedback regarding P1 showed that some participants ($n = 10$) appreciated the more relaxed seating and noted that the belt felt less intrusive. Another group ($n = 8$) felt unusual or that the new reclined position felt weird (e.g., "Feels unusual with the back, would not have traveled like this as a passenger" [ID_13]). One interesting aspect from the qualitative feedback was that, similar to the upright position, a large group of participants ($n = 13$) noted interference and annoyance from the shoulder belt. Feedback regarded a higher felt pressure from the shoulder belt, pressing more against the shoulder and the neck and one instance of right arm interference.

Table 4.19: Frequency of participant responses ($n = 30$) for lap belt pressure (Q1) and discomfort (Q2). Ratings were evaluated with 5-point scales (1 = No pressure/No discomfort, 5 = Very strong pressure/Extreme discomfort).

Configuration	Measurement	1	2	3	4	5	Mean ± SD
P1	Q1: Pressure	16	9	5	0	0	1.63 ± 0.76
	Q2: Discomfort	23	4	3	0	0	1.33 ± 0.66
P2	Q1: Pressure	26	4	0	0	0	1.13 ± 0.35
	Q2: Discomfort	24	5	1	0	0	1.23 ± 0.50
User-preferred	Q1: Pressure	24	4	2	0	0	1.27 ± 0.58
	Q2: Discomfort	30	0	0	0	0	1.00 ± 0.00

To get a visualization of preference for P1, regarding perceived pressure and comfort, in the semi-reclined compared to the upright position ratings and qualitative feedback for all participants ($n = 30$) was analyzed and interpreted. One group (33%) preferred the semi-reclined P1 more. A larger group of participants divided into two smaller groups preferred it less: one (17%) due to the seat-back angle, and another (23%) due to increased lap belt pressure. The remaining group (27%) were neutral or uncertain. Preferences are illustrated in Figure 4.23. Similar to the upright is that the analysis regarded only the participants perceived discomfort and pressure from the lap belt and not from the shoulder belt.

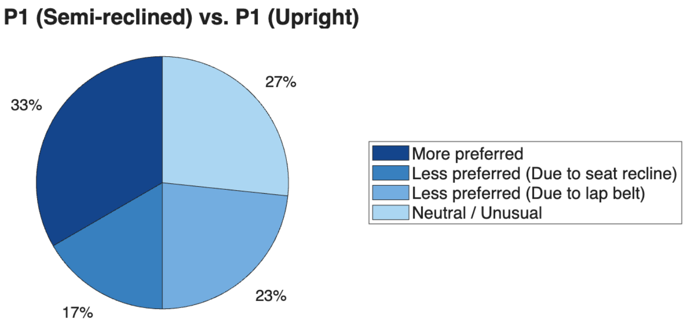


Figure 4.23: Comparison of participant preference regarding perceived comfort for P1 in the semi-reclined position compared to P1 in the upright position.

Qualitative feedback for P2 showed that a large group of participants ($n = 15$) highlighted that moving the buckle forward shifted perceived pressure away from the stomach and hip bones into a more tolerable resting posture. The more forward position also removed the major problems that participants reported regarding pressure on the shoulder and the neck. However, as seen in the upright position, moving the buckle forward in the semi-reclined position introduced right-arm interference with the shoulder belt for some participants ($n = 7$), (see previous Figure 4.3 (b) for example of the shoulder belt interference).

In the user-preferred position, feedback revealed that the placement itself together with a semi-reclined seatback angle gave an overall comfortable experience. Some participants ($n = 4$) mentioned that they placed the lower anchorage further forward and lower to get the lap belt pressure more on the thighs and not on the stomach which previously made the participants rate the pressure higher in P1. Similar to the upright position the overall rated pressure was higher than in P2, but qualitative feedback indicated this was perceived positively due to having the lower anchorage closer the body resulted in a more embracing fit. Furthermore, similar to the upright position, the user-preferred adjustment removed almost all reported annoyance from the shoulder belt regarding chafing against the neck in P1 and the right-arm interference experienced in P2.

To visualize and compare preference for P2 against P1, regarding perceived comfort and pressure, subjective ratings together with qualitative feedback from all the participants ($n = 30$) was analyzed and interpreted. The results showed that a large majority (73%) preferred P2 over P1 in the semi-reclined position. A small group reported a less favorable experience: one participant (3%) due to the semi-reclined position and one (3%) due to pressure distribution. The remaining six participants (20%) were neutral, see Figure 4.24 for the distribution. Similar to previous analysis is that it regarded only the participants perceived discomfort and pressure from the lap belt, and not from the shoulder belt.

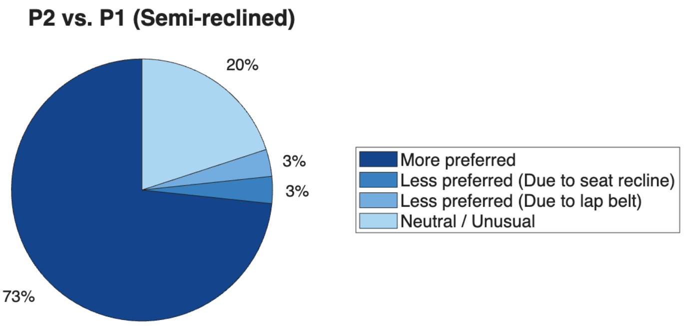


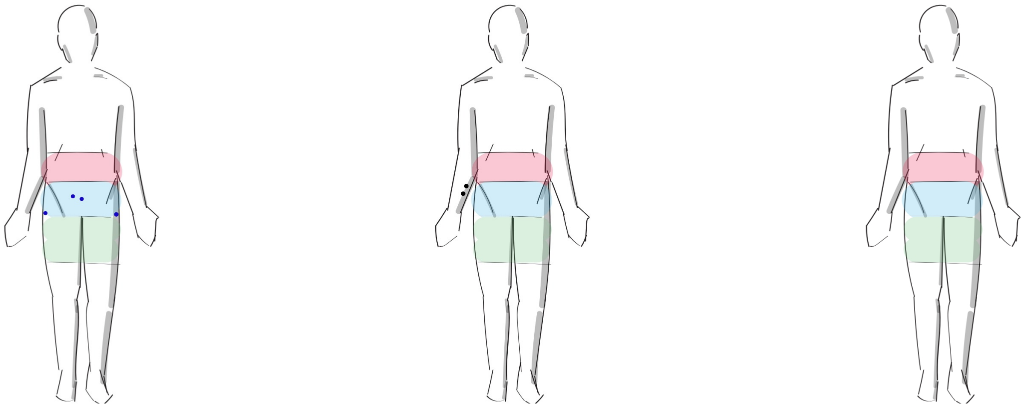
Figure 4.24: Distribution of participant preferences regarding perceived comfort comparing P2 to P1 in the semi-reclined position.

Correlation analyses were conducted to investigate the relationship between participant demographics, anthropometric measurements, and their subjective preference for P2 in the semi-reclined position. Preference was numerically scored (1 = Liked more, 0 = Neutral, -1 = Liked less). Two statistically significant positive correlations emerged at the semi-reclined position: knee height ($r = 0.369$, $p = 0.045$) and iliac spine height ($r = 0.422$, $p = 0.020$). Full correlation results are presented in Table 4.20.

Table 4.20: Pearson correlation coefficients (r) and p-values between standing and seated anthropometric variables and preference for P2 (semi-reclined position).

Variable (Standing / Seated)	**Standing (r, p)**	**Seated (r, p)**
Iliac spine height / Knee height	**0.422, 0.020**	**0.369, 0.045**
Waist circumference / Abdominal depth	0.155, 0.413	0.163, 0.390
Hip breadth	0.238, 0.206	0.140, 0.459
Thigh circumference / Thigh clearance	0.118, 0.535	0.116, 0.541

To further visualize the physical experience at the semi-reclined position, participants again marked areas of discomfort on the body map, see Figure 4.25. As with the upright position, the plotted marks may under represent the total extent of discomfort, as participants tended to mark only the most pronounced areas.



(a) P1 **(b)** P2 **(c)** User-preferred

Figure 4.25: Reported areas of discomfort plotted as dots on body maps across all lap belt anchorage positions with the semi-reclined seatback angle.

In P1, 10% of all participants (n = 3; 2 males, 1 female) placed a total of four marks, all localized around the midsection and outer hips, consistent with the pattern observed in the upright position. For P2, the number of participants marking discomfort dropped to 7% ($n = 2$; both female), placing two marks in total. Both marks were located on the right arm, directly reflecting the reported shoulder belt arm obstruction. As in the upright position, no participant marked any discomfort in the user-preferred position.

A similar t-test analysis conducted in the upright position of shoulder belt interference was conducted in the semi-reclined position as well. For P1, 13 participants reported annoyance (7 males, 6 females), while 7 participants reported annoyance in P2 (3 males, 4 females). In P1, no anthropometric variable reached statistical significance. In P2, participants reporting annoyance tended to have smaller body dimensions, with waist circumference approaching significance (mean 83.79 cm vs. 97.37 cm; $p = 0.058$). These results are summarized in Tables 4.21 and 4.22.

Table 4.21: T-test results comparing anthropometric variables for participants who experienced shoulder belt annoyance in P1 in the semi-reclined position. The mean values are measured in [cm].

Posture	Variable	Mean (Annoyed)	Mean (Rest)	p-value
Standing	Iliac spine height	101.19	99.94	0.611
	Waist circumference	94.96	93.62	0.831
	Standing hip breadth	37.15	36.88	0.830
	Thigh circumference	54.85	56.71	0.323
Seated	Abdominal depth	29.49	27.82	0.504
	Seated hip breadth	42.35	41.79	0.740
	Thigh clearance	12.58	12.71	0.816
	Knee height	55.62	55.06	0.718

Table 4.22: T-test results comparing anthropometric variables for participants who experienced shoulder belt annoyance in P2 in the semi-reclined position. The mean values are measured in [cm].

Posture	Variable	Mean (Annoyed)	Mean (Rest)	p-value
Standing	Iliac spine height	99.79	100.70	0.753
	Waist circumference	83.79	97.37	0.058
	Standing hip breadth	36.43	37.17	0.615
	Thigh circumference	55.79	55.93	0.947
Seated	Abdominal depth	25.50	29.47	0.169
	Seated hip breadth	41.64	42.15	0.793
	Thigh clearance	12.21	12.78	0.379
	Knee height	54.14	55.65	0.401

4.6.2.2 Perceived Safety

Interestingly, in the semi-reclined position, the user-preferred position was perceived as the safest (4.07 ± 1.01), outperforming P1 (3.73 ± 1.14) (see Table 4.23). P2 consistently resulted in the lowest feelings of security across both seat back recline angles.

Table 4.23: Frequency of participant responses ($n = 30$) for perceived safety (Q5) in the semi-reclined position. The question was evaluated with a 5-point scale (1 = Not safe at all, 5 = Completely safe).

Configuration	**Measurement**	**1**	**2**	**3**	**4**	**5**	**Mean ± SD**
P1	Q5: Perceived safety	0	6	6	8	10	3.73 ± 1.14
P2	Q5: Perceived safety	3	1	13	7	6	3.40 ± 1.16
User-preferred	Q5: Perceived safety	1	0	8	8	13	4.07 ± 1.01

Qualitative feedback for P1 one group of participants ($n = 15$) felt that they were unsafe, that the belt was less embracing and that they could get hurt if a crash wore to happen in the more reclined position (e.g. “In a crash, do I slide under the belt?” [ID_129]). Another large group ($n = 13$) reported that they still felt safe in the semi-reclined position and that the belt embraced them (e.g. “Preconceived knowledge of having the belt on makes me feel safe” [ID_75]). To get a visualization of preference for P1 in semi-reclined position against P1 in the upright position, regarding perceived safety, ratings and qualitative feedback for all participants ($n = 30$) was analyzed and interpreted. The analysis showed that a minority (7%) actually preferred the semi-reclined baseline, noting the belt sat tightly and instilled a higher sense of safety. One group (10%) preferred the semi-reclined position less due to reduced embracing of the belt and another group (40%) preferred it less due to the seatback recline angle itself. A final group of participants (43%) remained neutral, feeling their safety was unchanged. This distribution is illustrated in Figure 4.26.

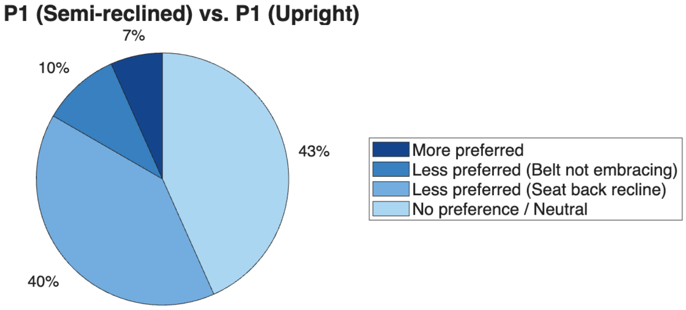


Figure 4.26: Comparison of participant preference regarding perceived safety for P1 in the semi-reclined position compared to P1 in the upright position.

The qualitative feedback for P2 showed that one group of participants ($n = 16$) felt very unsafe due to that the belt sat wrong or didn’t embrace them enough and also due to the seat-back recline (e.g., “Nothing holding the person down in the seat it feels like, will slide under” [ID_94]). A smaller group ($n = 4$) reported that they still felt safe, similar to in P1 for the semi-reclined, the simple knowledge of the belt being located on the body makes you feel safe. Lastly, similar to previous positions, the feedback for the user-preferred position highlighted that some participants ($n = 5$) still felt less safe due to the more semi-reclined position. However, the overall perceived safety was rated higher from the participants in the user-preferred position. To visualize and compare preference for P2 against P1, regarding perceived safety, subjective ratings together with qualitative feedback from all the participants ($n = 30$) was analyzed and interpreted. It showed that a small group (23%) preferred P2, appreciating that the lap belt sat slightly further down on the body. Another group (33%) perceived P2 to be less safe, mainly due to the more forward position being less embracing. Lastly, a somewhat larger group (43%) remained neutral or felt equally safe as in P1, see Figure 4.27 for the full distribution.

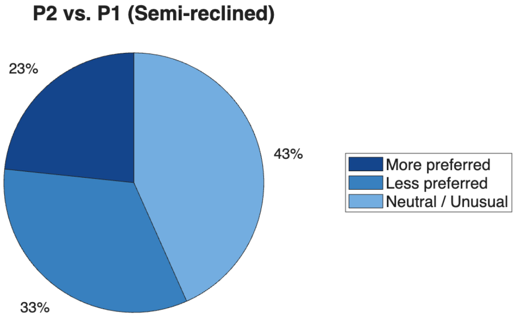


Figure 4.27: Distribution of participant preference for P2 compared to P1, regarding perceived safety.

The notably lower perceived safety observed for P1 in the semi-reclined position compared to the upright position prompted a further investigation into whether traveling habits influenced this perception, mirroring the analysis conducted for P2 in the upright position. The drop is reflected in the rating distributions: in the upright position, 28 of 30 participants assigned a safety rating of 4 or 5, whereas in the semi-reclined position this fell to 18 participants, with six participants rating safety as low as 2. The same travel metrics were then evaluated to determine whether this perception was driven by traveling experience. A Pearson correlation analysis revealed no significant relationship between either days traveled per week ($r = -0.106$, $p = 0.578$) or average trip duration ($r = -0.082$, $p = 0.668$) and perceived safety ratings for the semi-reclined position when evaluating P1. For P2, similar to P1, no significant relationship was found (see Table 4.24).

Table 4.24: Pearson Correlation: Travel Habits vs. Safety Ratings in P1 & P2.

Position	**Travel Metric**	r	p
P1	Days per Week	-0.106	0.578
	Trip Duration	-0.082	0.668
P2	Days per Week	0.194	0.303
	Trip Duration	-0.234	0.212

Independent-samples t-tests confirmed this pattern for both positions (see Table 4.25). Neither travel frequency nor trip duration produced a statistically significant difference in perceived safety ratings for either P1 or P2 at the semi-reclined position. Notably, the negative trend for trip duration in the forward position (long trips: $M = 2.83$, short trips: $M = 3.54$) is consistent in direction with the equivalent finding at the upright position ($r = -0.304$, $p = 0.102$), suggesting a weak recurring tendency for longer-trip travelers to perceive the forward position as slightly less safe compared to the short-trip travelers group.

Table 4.25: T-Test Analysis: Impact of Travel Habits on Safety Ratings in P1 & P2.

Position	Metric	Category	Mean Rating	*p*-value
P1	Days per Week	Heavy ($\geq$ 6 days)	3.64	0.692
		Light ($\leq$ 5 days)	3.81	
	Trip Duration	Long ($\geq$ 45 min)	3.83	0.815
		Short ($<$ 45 min)	3.71	
P2	Days per Week	Heavy ($\geq$ 6 days)	3.50	0.667
		Light ($\leq$ 5 days)	3.31	
	Trip Duration	Long ($\geq$ 45 min)	2.83	0.187
		Short ($<$ 45 min)	3.54	

4.6.2.3 Perceived Usability

Similar to the upright position, P1 was rated having the highest difficulty in the semi-reclined position, with some participants assigning maximum difficulty ratings of 5. In P2 accessibility was notably improved across all metrics, bringing usability scores closer to the highly rated user-preferred position, where locating the buckle (1.17 ± 0.46) was perceived as the easiest task overall, see Table 4.26.

Table 4.26: Frequency of participant responses ($n = 30$) for locating the buckle (Q7), buckling the belt (Q8) and unbuckling the belt (Q9). The questions were evaluated with a 5-point Likert scale (1 = Very easy, 5 = Very difficult).

Configuration	Measurement	1	2	3	4	5	Mean ± SD
P1	Q7: Locating buckle	13	11	4	1	1	1.87 ± 1.01
	Q8: Buckling belt	16	11	2	0	1	1.63 ± 0.89
	Q9: Unbuckling belt	16	12	1	0	1	1.60 ± 0.85
P2	Q7: Locating buckle	24	5	1	0	0	1.23 ± 0.50
	Q8: Buckling belt	24	3	1	2	0	1.37 ± 0.85
	Q9: Unbuckling belt	26	2	1	1	0	1.23 ± 0.68
User-preferred	Q7: Locating buckle	26	3	1	0	0	1.17 ± 0.46
	Q8: Buckling belt	24	3	2	1	0	1.33 ± 0.76
	Q9: Unbuckling belt	25	4	1	0	0	1.20 ± 0.48

Qualitative feedback for P1 revealed that a group ($n = 13$) of participants found it more difficult to locate and buckle the belt in the semi-reclined position compared to the upright position. Because the occupant was more reclined, the buckle in P1 was more hidden, forcing participants to raise their upper body or awkwardly twist their torso to search for it (e.g., “Need to raise the upper body to find the buckle” [ID_304]). Furthermore, the reclined angle introduced spatial conflicts, with users noting that their arm hit the seat when reaching backward. To get a visualization of preference for P1 in semi-reclined against P1 in the upright position, regarding usability, ratings and qualitative feedback for all participants ($n = 30$) was analyzed and interpreted. This showed that half of the participants (50%) reported increased difficulty and that a substantial portion (40%) remained neutral, feeling that standard usability was maintained. Only a small fraction (10%) found the semi-reclined P1 inherently easier to use than the upright position, see Figure 4.28.

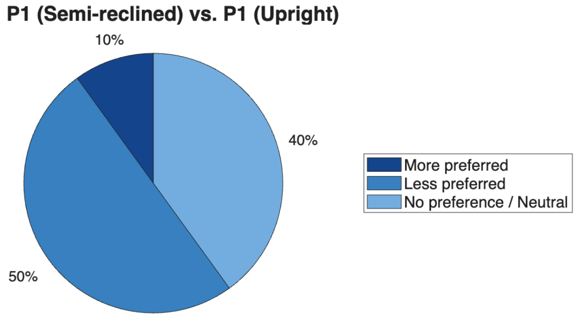


Figure 4.28: Comparison of participant preference regarding usability for P1 in the semi-reclined position compared to P1 in the upright position.

The qualitative feedback for P2 revealed that one group of participants ($n = 13$) praised this forward placement for eliminating the need to twist and raise their bodies while reclined. The buckle was also more visible and that the buckle ended up "more naturally in the hand" [ID_49]. A smaller group ($n = 4$) still had problems with the arm hitting the seat when reaching for the buckle as well as visibility. Lastly, feedback for the user-preferred position showed that overall participants find their chosen position easy to locate and handle, with some participants ($n = 4$) finding it a bit more difficult to locate and operate, mainly due to the reclined position forcing them to raise their upper body and that the buckle was located too close to the seat. To visualize and compare preference for P2 against P1, regarding usability, subjective ratings together with qualitative feedback from all the participants ($n = 30$) was analyzed and interpreted. The analysis showed that a large group (53%) preferred P2 and found it easier to locate and operate. Conversely, a smaller group (13%) found P2 less preferable. The remaining participants (33%) reported no distinct preference, finding no substantial difference in usability between the two setups, see Figure 4.29 for the full distribution.

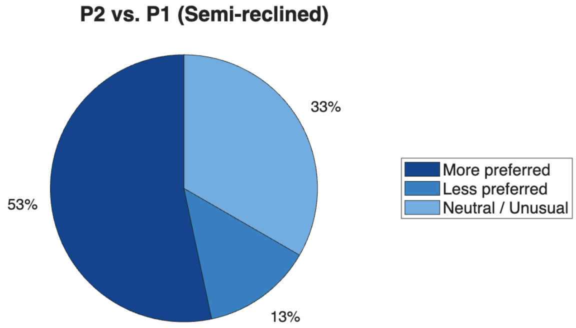


Figure 4.29: Distribution of participant preference for P2 to P1, regarding perceived usability.

4.6.2.4 Qualitative feedback of the choice for the user-preferred position

The qualitative feedback regarding the user-preferred placement in the semi-reclined position revealed highly individualized preferences falling into the same three categories as for the upright position: perceived safety, usability & ergonomics and physical comfort (see Figure 4.30). Notably, the distribution of primary motivations shifted compared to the upright position, reflecting how the reclined position fundamentally changes the lap belt interaction.

Out of the 30 participants, the largest group (47%) focused primarily on physical comfort, a reversal from the upright position. These participants actively adjusted the anchor to eliminate pressure points and find the most restful configuration, with several describing their chosen position as perfect. A recurring theme was the successful avoidance of shoulder belt interference with the arm, which had been a prominent issue in the predefined positions. A second group (37%) prioritized perceived safety. Many in this group moved the buckle back toward P1 to ensure that the belt embraced the body and tightened securely around the hips. However, a persistent subgroup (17%), of the second group, reported feeling somewhat unsafe regardless of where they placed the belt, suggesting that for these participants, the inherent geometry with the semi-reclined position created a sense of insecurity that no buckle adjustment could fully resolve. The smallest group (17%), reduced from 37% at the upright position, prioritized usability and ergonomics. These participants sought placements that were visually accessible and required minimal arm movement to operate. Despite optimizing for reach, some still noted that the reclined position introduced new ergonomic challenges, describing the buckle as feeling “too close to the body” or requiring them to lift their neck from the headrest to locate it. The full distribution of primary motivations is shown in Figure 4.30.

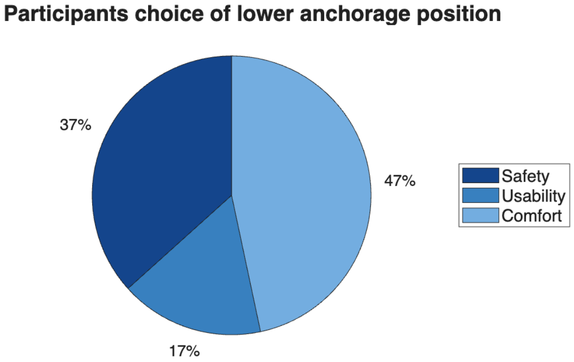


Figure 4.30: Distribution of participant’s primary motivations for determining the user-preferred lap belt anchor placement at the semi-reclined position.

5

Discussion

5.1 Anthropometric and postural influences on lap belt positioning

The presented results show that lap belt fit is influenced by both occupant anthropometry and seatback recline angle, although this influence differs between the vertical belt placement (i.e., the height of the lap belt relative to the ASIS) and the anterior–posterior belt positioning (i.e., the forward or rearward location of the belt relative to the pelvis). A central finding is the consistently strong relationship between BMI and the vertical location of the lap belt relative to the ASIS across both seating configurations. Participants with higher BMI generally showed a more superior belt position, indicating that increased body size and soft tissue thickness shift the belt upward relative to the pelvis. This trend was observed in both the upright and semi-reclined positions, suggesting that vertical belt placement is primarily governed by overall body geometry rather than seatback recline angle alone. These findings are consistent with previous research showing that occupants with higher BMI tend to position the lap belt higher relative to the pelvis due to increased abdominal soft tissue thickness [7], [16].

An additional observation from the visual analysis was the occurrence of lap belt folding, primarily associated with increased abdominal soft tissue and more common among participants with higher BMI. Interestingly, belt folding was observed in both upright and semi-reclined conditions, despite the expectation that a reclined posture would stretch the abdomen and reduce fold formation. However, although the abdominal geometry became more posteriorly oriented in the reclined position, this change was not sufficient to eliminate the local soft tissue interaction responsible for folding. This suggests that belt folding depends primarily on local anthropometric characteristics, particularly abdominal soft tissue distribution, rather than being mitigated by seatback recline alone. The higher occurrence of folding in male participants in the present study may therefore be linked to differences in body composition and fat distribution rather than sex itself, which is consistent with previous findings showing that observed sex-related differences in belt positioning are largely explained by underlying anthropometric variation rather than sex alone [5], [15]

In contrast to the vertical belt position, the anterior–posterior belt position appears to be more sensitive to seat reclination. BMI shows strong associations with anterior–posterior belt displacement in the upright seating condition, but these relationships weaken in the semi-reclined condition. The reduction in Pearson correlation coefficients by approximately 0.20–0.30 suggests that seat reclination alters pelvis orientation and redistributes soft tissue and thereby modifying the belt–pelvis interaction. Similar effects of seatback recline angles on belt routing and belt–ASIS overlap have previously been reported in CT-based investigations of seated occupants [12], [32]. As a result, BMI becomes a weaker predictor of forward belt displacement in more reclined seating conditions.

When comparing P1 and P2, the Pearson correlations between BMI and anterior–posterior belt displacement are slightly lower for P2 in both seating configurations. In the upright condition, the correlations are reduced by approximately 0.05–0.07 for P2 compared to P1, which may indicate a minor stabilizing effect of the forward anchorage position on belt displacement. One possible explanation is that a more forward buckle position alters the belt routing relative to the pelvis, resulting in a more direct belt path with reduced wrap around the abdomen. This may reduce the extent to which variations in soft tissue thickness influence the resulting belt displacement. However, the differences between the configurations are relatively small and overlapping, meaning that neither anchorage configuration consistently reduces anthropometric influence on belt displacement compared to the other. These findings suggest that BMI alone is insufficient to fully explain belt displacement and should therefore be interpreted together with local anthropometric measures when evaluating lap belt fit.

In addition to the predefined anchorage configurations, the user-selected buckle positions provide further insight into how lap belt geometry evolves when occupants are allowed to adjust the system based on perceived comfort. The results show substantial inter-individual variability in the user-selected buckle positions, ranging from 48–243 mm, 19–69 mm, and 114–211 mm in the X-, Y-, and Z-directions, respectively, in the upright condition, and from 19–193 mm, 14–61 mm, and 102–241 mm in the semi-reclined condition. The results show that the user-selected positions are generally located between P1 and P2 for both seating configurations, indicating that participants tend to adopt an intermediate belt geometry rather than fully following either predefined condition.

From a geometric perspective, the user-selected buckle positions and the predefined configurations define a consistent ordering of mean belt displacement relative to the ASIS across both seating conditions. In the upright position, the upper belt segment shows mean anterior displacements of 23.2 mm (P1), 54.6 mm (P2), and 20.2 mm (user-selected), while the lower segment shows 66.8 mm, 98.4 mm, and 85.4 mm, respectively. In the semi-reclined position, the corresponding values are 13.9 mm (P1), 55.4 mm (P2), and 39.2 mm (user-selected) for the upper segment, and 56.5 mm, 102.3 mm, and 83.8 mm for the lower segment. Overall, P2 consistently results in the most anterior belt position, while P1 represents the least anterior configuration. The user-selected condition lies between these two predefined configurations in most cases, particularly in the semi-reclined position. This indicates that occupant-selected adjustments produce a moderated belt geometry within the range defined by the predefined anchorage positions. The spread of user-selected positions further indicates substantial inter-individual variability, with some participants selecting positions closer to P1 or P2. This variability is consistent with differences in anthropometry and local body–belt interaction, and is reflected in the observed anthropometric correlations, where larger participants tend to select more forward and outward buckle positions.

The relationship between BMI and local anthropometric measures provides context for interpreting the dataset structure. BMI is considered a global measure for body size rather than a descriptor of local body geometry or tissue distribution. In this context, strong correlations such as waist circumference in the standing condition ($r = 0.87$) and abdominal depth in seated position ($r = 0.84$) indicate that BMI captures both overall body size and soft tissue distribution. However, previous research indicates that lap belt fit is primarily governed by local geometry at the pelvis and abdomen, rather than global body size alone [16]. When related to belt displacement, a more selective relationship is observed between anthropometric measures and belt displacement. For anthropometric measurements obtained in the standing position, only waist circumference shows a statistically significant association ($r = 0.68$). For seated anthropometric measures, abdominal depth ($r = 0.59$), thigh clearance ($r = 0.42$), and hip breadth ($r = 0.37$) are all significantly associated with belt displacement. These variables more directly reflect the local geometry that governs lap belt fit and interaction with the pelvis and surrounding soft tissues. In contrast, in the semi-reclined condition these relationships are substantially weakened, with only a moderate association for waist circumference ($r = 0.446$) in standing anthropometry and no significant associations for seated measures. This suggests that changes in pelvic orientation alter the geometric relationship between the belt and local anthropometric features, reducing their predictive value for belt displacement.

In addition to these correlation-based differences, a consistent geometric effect was observed in the vertical position of the lower belt segment. The lower edge of the lap belt is positioned slightly higher in the vertical direction (dz) for P2 compared to P1, and this trend is present in both the upright and the semi-reclined position. In the upright position, lower dz increases from -2.0 mm (P1) to 7.8 mm (P2), while in the semi-reclined position it increases from 3.5 mm to 8.6 mm. Although the magnitude of the increase is modest, the direction of the shift is consistent. This effect can be explained by the geometric relationship between belt routing and thigh orientation. In both upright and semi-reclined position, the thighs are inclined upward relative to the seat pan. For the majority of participants (approximately 90%), the lower edge of the belt is in contact with the thighs in P1, and this contact is maintained when the buckle is moved 10 cm forward (P2). As a result, the belt remains in contact with the same anatomical structure rather than changing support surface. When the buckle is displaced forward, the belt path shifts anteriorly along the body while remaining in contact with the thighs. Since the thighs are inclined, this anterior movement places the belt at a higher position along the same surface. The observed increase in vertical position is therefore a direct consequence of the belt following the slope of the thighs rather than a change in anthropometric interaction. The consistency of this effect across seatback recline angles suggests that it is primarily governed by seat geometry rather than anthropometric variation. However, the magnitude of the shift is likely influenced by seat design parameters such as seat pan angle and cushion geometry, which together determine thigh inclination.

Overall, these results indicate that lap belt positioning emerges from the combined influence of anthropometry, seatback recline angle, and seat geometry. While BMI is consistently associated with vertical belt position, its relationship with anterior–posterior displacement is strongly dependent on seatback recline angle and is mediated by local anthropometric features. This indicates that BMI acts as a broad metric for body geometry rather than a direct predictor of belt–body interaction. These effects are directly relevant for subsequent assessment of submarining risk and safety implications.

5.2 Submarining-related geometric conditions

The observed variations in lap belt fit across anthropometry, seatback recline angle, and belt anchorage position provide insight into geometric conditions that have previously been associated with submarining in dynamic crash scenarios. Since the present study is based on static measurements, it does not allow any direct evaluation of injury risk or dynamic restraint performance. Instead, the results are interpreted in relation to previously identified mechanisms describing belt–pelvis interaction under loading conditions [14], [16].

A key mechanism described in the literature is the ability of the lap belt to maintain engagement with the bony pelvis, particularly the ASIS, during crash loading. When the belt is positioned higher relative to these landmarks, load transfer is more likely to occur through soft abdominal tissues rather than the pelvis. Such geometric configurations have previously been associated with submarining events in dynamic studies, where the belt migrates upward over the iliac crest [14]. In the present study, higher BMI was consistently associated with an elevated vertical belt position relative to the ASIS. While this does not indicate risk in itself, it corresponds to a geometry that is consistent with previously reported conditions of reduced pelvic engagement under loading. This provides a qualitative link between the observed static belt position and submarining-related configurations in the literature.

Seatback recline angle further influences this relationship by altering pelvic orientation. The reduced association between anthropometric measures and anterior–posterior belt position in the semi-reclined condition indicates that pelvic rotation modifies the belt–pelvis geometry. Previous research has shown that posterior pelvic rotation can reduce belt engagement with the ASIS and alter the belt loading path relative to the pelvis [12], [32]. These findings suggest that reclined seating may represent a less favourable geometric condition for stable belt–pelvis interaction.

The influence of belt anchorage position appears comparatively limited in the present static measurements. The small differences observed between P1 and P2 suggest that forward anchorage slightly modifies baseline belt geometry but does not substantially change the relationship between anthropometry, seatback recline angle, and belt position. In comparison to seatback recline angle and occupant geometry, this indicates that anchorage adjustment plays a secondary role in shaping the static belt–body configuration observed in this study. However, previous experimental work by Hanggi et al. [8] has shown that changes in lower belt anchorage position can influence pelvic response under dynamic loading conditions, including altered fracture patterns and differences in load distribution. Their findings indicate that even relatively small geometric changes in belt anchorage may become relevant when load is applied, highlighting a potential link between static geometry and dynamic response.

Overall, the results do not quantify submarining risk, but identify geometric configurations that have previously been associated with submarining in dynamic crash studies. In particular, combinations of higher BMI and semi-reclined position correspond to belt–body configurations with reduced pelvic engagement. These findings should therefore be interpreted as static geometric observations, rather than indicators of injury risk.

5.3 Lap belt pressure distribution and perceived comfort

In the upright position, nearly half of the participants preferred P2 over P1, despite P1 already producing low levels of perceived pressure and discomfort. The preference for P2 was primarily driven by a reduction in abdominal pressure and a redistribution of load toward the hips and thighs. The low baseline discomfort reported in P1 is notable in this context: it indicates that participants began the comparison from a position they generally found acceptable, rather than one they were actively seeking relief from. The fact that a meaningful proportion still preferred P2 under these conditions suggests that occupants are sensitive to subtle improvements in belt fit, and that a lap belt perceived as comfortable in absolute terms may nonetheless be improved upon. This was further reflected in participant responses, where many noted, despite having rated P1 favorably, that the belt could be positioned more naturally against the body in P2, pointing to a latent preference that the standard configuration had not fully captured. This aligns with the general ergonomic understanding that discomfort is strongly related to localized pressure concentrations and tissue distortion [20], a principle that becomes particularly relevant when standard belts apply pressure to sensitive soft tissue regions such as the abdomen. The redistribution could also be interpreted as a more favorable engagement of the bony pelvis, where load is transferred away from compressible abdominal tissue toward more load-bearing structures. However, the results also show that this effect is not universally beneficial. A few participants ($n = 4$) instead reported increased thigh discomfort, indicating that the same geometric adjustment can shift the discomfort problem rather than solve it.

A similar pattern was observed in the semi-reclined position, where overall pressure and discomfort ratings remained low across all configurations, though P1 again produced the highest mean values. Comparing P1 in the semi-reclined and the upright position revealed a divided response where one third of participants found the semi-reclined position more comfortable while 40% commented on it being less favorably. This divergence suggests that seat back recline alone introduces variability in belt–body interaction that cannot be attributed solely to lap belt geometry, as pelvic rotation and soft tissue redistribution under recline differ considerably between individuals [20]. The transition to P2 in the semi-reclined position produced a considerably stronger and more consistent preference than was observed in the upright condition, with 73% of participants favoring P2 over P1. This could be explained by that in a reclined position, the pelvis tends to posteriorly rotate, which moves the abdomen further into the belt's load path. By moving the anchorage point forward therefore amplifies the benefit of redistributing pressure away from the abdomen toward the thighs, an effect that is less pronounced when the occupant is seated upright and pelvic tilt is already more neutral. Qualitative feedback reinforced this interpretation, with several participants noting that the adjusted position felt sustainable for longer journeys.

The preference for P2 was further supported by correlation analyses, which revealed two statistically significant anthropometric predictors in the semi-reclined position: iliac spine height ($r = 0.422$, $p = 0.020$) and knee height ($r = 0.369$, $p = 0.045$). Neither variable reached significance in the upright condition. These moderate positive correlations indicate that in a semi-reclined posture, participants with greater iliac spine heights and longer legs show a significantly stronger preference for P2 over P1. Although no further analysis was conducted to confirm the exact mechanism, one plausible explanation could be that the forward anchorage position accommodates this specific anthropometry better, thereby reducing perceived pressure and discomfort.

Even though the primary focus of this study was lap belt fit, qualitative feedback revealed secondary effects experienced from the shoulder belt. In the upright P1 configuration, shoulder belt discomfort primarily manifested as neck chafing, particularly among female participants, which aligns with previous research indicating higher discomfort reporting rates for women [5]. Similarly, in the semi-reclined P1 setup, feedback showed that participants were annoyed by the top of the shoulder belt chafing the neck and in addition there was reported increased pressure on the shoulder and neck. However, this additional mentioned annoyance was likely an artifact of the temporary belt-in-seat installation for the semi-reclined position. Because the routing mechanism was positioned unusually close to the upper body, it might have generated a localized pressure that may not accurately represent the geometry of a standard vehicle design. When shifting the anchorage position forward the majority of all complaints regarding neck chafing and shoulder pressure were eliminated, resulting in an improved upper-body fit for most participants. However, this modification introduced a secondary trade-off and discomfort: moving the anchor position forward in both the upright and semi-reclined positions caused arm interference from the shoulder belt. This interference is strongly linked to anthropometric factors, specifically, a smaller abdominal depth and waist circumference, reduced thigh clearance, as well as lower BMI. A plausible explanation to this is the lack of soft tissue standoff; participants with larger abdomen might naturally push the shoulder belt outward, creating clearance for the arm. For smaller individuals, the belt follows a more direct path causing it to intersect the arm's natural resting position. Ultimately, these findings highlight the observed variability in shoulder belt fit across different body types and demonstrates that lap belt geometry cannot be considered in isolation; changes of the lower anchorage position inherently affect the entire restraint system's interaction with the occupant.

Another interesting aspect regarding the arm interference observed in P2 was that the visual prevalence of shoulder belt obstruction was notably higher than the subjective reporting of discomfort. Visual analysis confirmed that the shoulder belt physically interfered with the right arm in approximately 47% of upright cases and 43% of semi-reclined cases. However, qualitative feedback indicated that only 27% of the participants reported this interference as a source of annoyance or discomfort in the upright position and 23% of participants in the semi-reclined position. Because the t-test analyses were based exclusively on the subset of participants who actively gave feedback of their discomfort, the resulting statistical correlations, such as the significant links between arm interference and lower BMI, smaller abdominal depth, or reduced thigh clearance, may not fully represent the broader group experiencing the physical belt contact. However, this discrepancy can likely be explained by several factors. First, tolerance to belt contact is highly subjective; some participants may have adapted to the obstruction, viewing it as a neutral physical contact rather than an active nuisance. Second, because participants were explicitly instructed to focus their evaluations on the lap belt, some may have consciously ignored the upper body interference, assuming feedback on the shoulder belt was outside the scope of the assessment. Finally, as noted earlier, smaller individuals with less soft tissue standoff may experience a more direct, flush belt path that rests against the arm without creating significant focal pressure. This suggests that the qualitative feedback captures only those individuals who were distinctly bothered by the shoulder belt, rather than everyone who experienced physical interference, which could explain the results from the t-test analyses.

When evaluating the user-preferred position a consistent pattern emerges in both the upright and the semi-reclined positions: discomfort ratings dropped to the absolute minimum (1.00 ± 0.00), demonstrating a clear occupant preference for self-adjustment to mitigate physical belt interference. One explanation to this could be qualitative feedback suggesting that adjustability empowers users to actively eliminate localized issues; for instance, the neck chafing, shoulder pressure, and right-arm interference from the shoulder belt that inflated discomfort scores in P1 and P2 were almost entirely resolved in the user-preferred position. Another interesting result was that the user-preferred position produced slightly higher perceived pressure than P2 (however lower than P1) in both recline conditions (upright: 1.33 ± 0.66 vs. 1.27

± 0.52; semi-reclined: 1.27 ± 0.58 vs. 1.13 ± 0.35), despite achieving lower discomfort. This suggests that a moderate degree of belt-body contact may be perceived positively when the occupant has actively chosen the position, possibly because the sensation of the belt sitting closer to the body reinforces a sense of security and control. The combination of this secure, embracing fit and the resolution of previous shoulder belt interference issues could explain why all thirty participants rated the user-preferred position as causing “No discomfort”. This suggests that occupants actively optimize belt placement based on personal perception of comfort, reinforcing that perceived comfort is strongly influenced by local anthropometric characteristics rather than global body size alone. This is consistent with previous findings demonstrating that individuals with similar overall body size can vary significantly in body composition and local geometry [31], which explains why occupants of the same global body size still experience different belt interactions.

Overall, the findings indicate that moving the lap belt anchorage position forward influences both lap belt fit and comfort primarily through redistribution of perceived interface pressure rather than complete elimination of discomfort. However, this redistribution extends beyond the lap belt itself and affects shoulder belt routing as well, creating a clear ergonomic trade-off between abdominal pressure reduction, thigh loading, neck clearance, and arm mobility. This reinforces the idea that comfort and discomfort should not be treated as simple opposites [20], [35]. Instead, they represent independent perceptual dimensions, where reducing discomfort in one area does not necessarily improve overall comfort. The present results demonstrate this, as improvements in abdominal comfort were often accompanied by new discomfort in either the thighs or upper body regions, depending on seatback recline angle and anthropometry. From a design perspective, this supports the view that restraint systems inherently involve trade-offs between multiple body regions rather than a single global optimum.

5.4 Perceived safety and psychological factors

In the upright position, participants strongly preferred P1 in terms of perceived safety. This preference appears to be primarily driven by familiarity and learned expectations of how a seatbelt should feel during use. In P1, the tighter lap belt position produced a stronger sensation of body “containment”, which participants interpreted as increased safety. For P2, local pressure was reduced which improved perceived comfort, but simultaneously weakened the perceived sense of restraint, highlighting a disconnect between physical load distribution and subjective safety perception. The reliance on familiar belt sensation was further reinforced by habitual exposure to standard restraint configurations. While traveling frequency did not significantly influence responses, it was significantly shown that participants with longer trip durations rated P2 as less safe compared to those with shorter trip durations. This suggests that repeated exposure to a specific belt geometry establishes a perceptual baseline for restraint tightness, which in turn shapes safety judgment.

The transition to a semi-reclined position introduced a broader shift in perceived safety across all participants. In this configuration, P1, previously perceived as highly safe in the upright condition (Mean = 4.50), was no longer trusted to the same extent (Mean = 3.73). Participants expressed concerns about sliding underneath the lap belt, reflecting increased perceived vulnerability due to changes in body orientation. Even though the safety aspects were not physically measured and tested during this study previous studies suggest that reclined seating alters belt angle and reduces overlap with the pelvis, increasing a higher risk of submarining, which in turn decreases occupant safety [12], [32]. Interestingly, the disparity in perceived safety ratings between P2 and P1 narrowed considerably when participants were reclined. In the upright posture, participants showed a strong preference for P1 over P2 (a difference in means of 0.93). However, in the semi-reclined position, this rating gap shrank to 0.33. Furthermore, the perceived safety of P2 remained relatively stable between the upright (Mean = 3.57) and semi-reclined (Mean = 3.40) positions. This indicates that moving the belt to a more forward position does not negatively affect perceived safety as sharply when reclined as it does when sitting upright. Instead, the recline angle itself appears to be the dominant factor driving the overall drop in safety perception for the semi-reclined position. Unlike in the upright position, prior traveling experience had no observable effect, suggesting that the lack of familiarity with reclined seating, rather than prior experience, is the dominant factor shaping safety perception in the semi-reclined position.

When looking at the user-preferred position it can be seen that this position yielded comparatively high perceived safety ratings in both recline conditions (Mean = 4.30 for upright and 4.07 for semi-reclined), outperforming P2 in both positions and even surpassing P1 in the semi-reclined condition. A result of this is that while moving the lower anchorage forward may aid usability and better load distribution in the semi-reclined position, it negatively impacts user trust in the restraint system. This pattern suggests that when occupants can adapt the lower anchor to a location they find natural, both the physical fit of the belt and its perceived sense of restraint are better maintained. Ultimately, these findings indicate that perceived safety is strongly influenced by psychological interpretation of belt–body interaction rather than purely mechanical restraint conditions. Even when a modified geometry may improve load distribution or comfort, it may be perceived as less safe if it deviates from expected sensory feedback. This supports the idea that subjective evaluation of restraint systems is shaped by both anthropometry-driven belt interaction and learned expectations of belt behaviour, particularly in configurations with different seatback recline angles.

5.5 Usability and buckle accessibility

The results show that the forward buckle position (P2) generally improved usability across both seatback recline angles, particularly with respect to locating and operating the belt. In the upright position, a majority of participants preferred P2, primarily because the buckle fell within a more direct line of sight and required less rearward trunk rotation to reach. In P1, several participants reported relying on habit rather than visual search, suggesting that the standard position aligns with learned interaction patterns. A smaller group preferred P1 due to familiarity with the conventional layout, indicating that usability is shaped not only by geometric accessibility but also by learned expectations. This indicates that usability is influenced not only by geometric accessibility, but also by learned interaction patterns developed through repeated exposure to conventional vehicle interiors. However, the present findings indicate that this effect was secondary, as most participants reported improved ease of locating and operating the buckle in P2. Analyzing the results from the user-preferred position shows that it reached near-perfect scores (means ranging from 1.03 to 1.10). This suggests that personalized buckle placement offers a meaningful ergonomic benefit, as it allows occupants to position the buckle in accordance with their individual reach envelope and natural hand trajectory.

In the semi-reclined position, usability challenges associated with P1 became more pronounced. As the seat reclines, the buckle is pushed further out of view and became fully hidden for some participants. This forced occupants to twist their torso or lift their upper body, actions that disrupt the intended comfort of the reclined position. In this context, P2 acts as a critical ergonomic improvement. By maintaining the buckle within a natural line of sight and reach, it allows operation without the participant rising their upper body and breaking the reclined posture, resulting in lower difficulty ratings across all usability measures. This suggests that small forward changes in anchorage position can partially compensate for posture-induced reductions in reachability. However, some participants still reported difficulties in P2, particularly related to insertion angle and occasional interference with arm movement against the seat structure. This points to a design challenge: while a forward anchor position successfully addresses the primary issues of reach and visibility, the geometric orientation of the buckle head may require further optimization to align with the altered downward arm trajectories that occupants naturally adopt when reclined. The user-preferred position again yielded the lowest difficulty ratings overall, reinforcing the pattern observed in the upright condition and further highlighting the ergonomic value of personalized buckle placement.

Overall, the findings support that usability is governed by the interaction between buckle geometry and seatback recline angle rather than buckle position alone. Changes in anchorage position modify reach distance and visual accessibility, while seatback recline angle determines the effective range of upper-body movement. This combined effect explains the observed improvements in usability with the buckle being moved forward, particularly in the semi-reclined position. The consistently lower ratings of the user-preferred position across both recline angles suggest that while a standardized forward position offers meaningful improvement over the conventional layout, individual variation in anthropometry and anchor placement means that a degree of adjustability may be necessary to achieve optimal usability across a wider population.

5.6 Regulatory Compliance and User Behaviour

The results from the regulatory compliance analysis reveal a clear mismatch between user-preferred buckle positions and the defined regulatory frameworks [22], [23]. Only 4 participants (13.3%) preferred positions were located within the allowable angular range of 30°–80°, while the majority (86.7%) fell outside the defined limits. It is important to emphasize that the plotted buckle positions represent user-preferred placements, where participants were explicitly instructed to position the buckle in a way that maximized perceived comfort. The resulting distribution therefore reflects natural user behaviour.

A notable observation is that this compliance outcome remains consistent between the upright and semi-reclined positions. Since the regulatory requirement is defined relative to the fixed mounting bolt of the lower anchor position, variations in user seatback recline angles have limited influence on the evaluated angles. This indicates that the governing constraint is primarily dictated by anchorage geometry rather than seating configuration, suggesting that the observed mismatch is inherent to the system design rather than posture-dependent behaviour.

To understand this mismatch, it is necessary to consider how users actually select buckle positions. The anthropometric analysis showed that user-preferred positions are systematically influenced by body geometry, particularly in the lateral and vertical directions. While BMI showed limited direct influence on horizontal placement, local anthropometric variables, such as hip breadth, abdominal depth, and waist circumference, demonstrated consistent relationships with how users adjust the buckle. These findings indicate that users actively compensate for their individual body shape in order to achieve a more favorable lap belt fit. This behaviour is consistent with the variability in anthropometric characteristics observed in the participant sample, where individuals were distributed across low, middle, and high percentile bands for key body dimensions. This spread in body morphology likely contributes to the systematic variation in user-selected buckle positions.

This behaviour is further clarified by the subjective evaluations, which provide insight into the underlying decision-making process. Across both seating configurations, the user-preferred position consistently resulted in the lowest reported discomfort (mean = 1.00), demonstrating that participants were highly effective in identifying positions that minimized physical annoyance. However, qualitative feedback also shows that buckle positioning is not determined by perceived comfort alone; participants simultaneously considered perceived safety and usability when selecting their preferred placement. This revealed a clear spatial trade-off: positioning the lower anchor closer to the body generally provided a greater sense of safety due to an enhanced feeling of enclosure, whereas moving it further forward improved perceived comfort and usability. Specifically, moving the buckle forward reduced localized pressure and the need for upper body rotation, while also improving load distribution and accessibility. However, perceived safety also acted as a limiting factor; excessively forward positions were sometimes rejected due to a feeling of looseness or reduced restraint effectiveness. Because a single position cannot perfectly maximize all these criteria at once, no single parameter can account for optimal satisfaction across the entire participant group. Instead, individuals weighed these factors based on their own priorities.

Note that these adjustments are not random but follow systematic trends linked to occupant geometry. For example, larger abdominal depth and hip breadth were associated with shifts in buckle position that likely reduce local pressure and improve perceived comfort. However, these same adjustments tend to move the effective belt path away from the angular region defined by the regulatory framework [22], [23]. This creates a consistent directional deviation rather than isolated outliers, explaining why the majority of participants fall outside the acceptance region.

Taken together, the results highlight a fundamental conflict between ergonomic preferences and regulatory requirements. Users consistently select buckle positions that optimize perceived comfort, usability or perceived safety, but in doing so, often move outside the prescribed angular limits. This suggests that the current regulatory framework, while based on safety considerations, does not fully account for natural variation in human body geometry or real-world interaction behaviour. From a design perspective, this indicates a need to consider how belt system geometry can better accommodate user-driven positioning behaviour, while still taking regulatory constraints into account.

5.7 Methodological limitations

A potential source of variability in the present study relates to the identification and measurement of the ASIS reference point. The ASIS was manually palpated on the participant's body surface and marked prior to each measurement. However, the accuracy of this procedure depends on individual anatomical differences, particularly variations in soft tissue thickness. This introduces both random variability and a potential systematic bias, as the thickness of adipose tissue may cause a consistent offset between the measured surface location and the underlying bony landmark. This is consistent with previous findings showing that soft tissue distribution, especially in individuals with higher BMI, can lead to deviations when estimating anatomical landmarks from surface measurements [16]. In such cases, skin-based landmark identification may not fully correspond to the underlying bony pelvis, which is critical for accurately assessing lap belt interaction.

To reduce this uncertainty, pressure was applied toward the underlying bone during measurement in order to minimize the influence of soft tissue and approximate the bony landmark as closely as possible. This approach was used as an alternative to more precise motion capture digitisation systems, such as a FaroArm, which were not available in the present study. In previous work, algorithm-based and BMI-dependent correction models have been proposed to compensate for this type of offset and improve the estimation of pelvis-related reference points [16]. In the present study, no such computational correction was applied, and the ASIS position was instead estimated through manual palpation and local compression of soft tissue. The applied method was therefore intended to approximate the underlying bony landmark while maintaining experimental feasibility.

To minimize the risk of marker displacement, the ASIS position was re-measured prior to each measurement. The variability between repeated measurements was generally small across all directions, with differences typically on the order of a few millimetres. The observed variation was of similar magnitude in all directions, indicating no clear dominance of error in the depth direction. Across repeated measurements, the variability ranged up to 4–7 mm in individual cases, while typical differences were around 1–2 mm. This can be interpreted as an estimate of the measurement repeatability of the ASIS localization in the present study.

In addition to measurement-related uncertainties, the experimental design may introduce bias related to the fixed ordering of test conditions. The predefined buckle positions were presented in a non-randomized sequence, with the manufacturer-defined position (P1) always evaluated first, which may have influenced participant responses in several ways. This could have established a cognitive baseline for the participants of what is perceived as the “correct” or expected belt placement, potentially leading to anchoring bias in which subsequent evaluations of alternative positions are judged relative to prior experience rather than independently. The influence of ordering is most evident in the user-preferred condition, which was always evaluated last. By this point, participants were fully familiar with the buckle location, the range of available positions, and the interaction characteristics of each configuration. The consistently superior ratings observed for the user-preferred position may therefore partly reflect a practice or familiarity effect rather than a genuine ergonomic advantage of the chosen placement. Although the sequential design was necessary to enable meaningful comparison between configurations and to support the user-preferred selection process, the absence of randomization should be considered when interpreting the results.

It is also important to consider that the findings reflect short-term exposure to the belt configurations. The present study captures initial perceptual responses under static conditions, where participants primarily evaluate immediate perceived perceptions of pressure, comfort, and safety. A previous study showed that it is essential for research on vehicle seat comfort to consider the element of time and that comfort significantly decrease after 30 minutes of traveling by car [36]. More previous research has shown that discomfort over time can lead to behavioural adaptations such as belt repositioning [5], or involuntary posture changes [37], which in the end could have changed the results of the study. Although a short adaptation period including a secondary task was included during the study to allow participants to settle into the seating position, this does not replicate prolonged exposure. As a result, the observed responses likely represent early-stage perceptual evaluations rather than stabilized user behaviour.

Furthermore, while the primary objective of this study was to evaluate lap belt fit in relation to anthropometrics, the fixed geometry of the shoulder belt introduced unintended confounding effects. For several participants, the shoulder belt caused localized discomfort, such as chafing against the neck or obstructing the right arm. Although participants were explicitly instructed to decouple their assessment and focus solely on the lap belt, subjective perceptions of comfort are inherently holistic; annoyance from the upper body inevitably influenced their overall ratings. More critically, this interference likely affected the user-preferred buckle placements as well. In an attempt to alleviate upper-body discomfort or to forcibly improve the shoulder belt routing, participants may have selected lap belt anchorage positions that they would not have otherwise chosen. Had the shoulder belt been adjustable, or excluded from the test entirely, the resulting user-preferred lap belt configurations might have differed significantly. Consequently, while evaluating the restraint system as a complete three-point assembly was a deliberate choice to maintain ecological validity, the fixed shoulder belt's influence on lap-specific subjective ratings and geometric preferences should also be considered when interpreting these findings.

Another aspect is that the D-ring in the upright configuration was mounted approximately 80 mm closer to the seat centerline than the corresponding position in a reference vehicle, due to structural constraints of the test rig. This deviation may have influenced shoulder belt routing and contact geometry in ways that do not fully reflect a real vehicle installation, therefore feedback regarding discomfort related to the shoulder belt for the upright position should be interpreted with this in mind. Similarly, the shoulder belt arrangement in the semi-reclined configuration, where a hook attached to the seat frame was used to guide the belt along a realistic torso path, represents an approximation of a belt-in-seat installation rather than a direct replication of one. While this setup was designed to preserve the intended geometric relationships of the restraint system, the resulting belt routing and contact pressure distribution may differ from those produced by a fully integrated belt-in-seat system, and the same interpretive caution therefore applies to shoulder belt findings in the semi-reclined condition.

A further limitation concerns the statistical power of subgroup analyses conducted throughout the study regarding qualitative results. Several comparisons were based on groups that emerged organically from the data rather than being defined with adequate sample sizes in mind. This applies both to the trip duration grouping used to assess the influence of travel habits on perceived safety (*Long Trip* ($n = 6$) and *Short Trip* ($n = 24$)) and to the subgroups of participants reporting shoulder belt interference in the upright and semi-reclined positions, where group sizes ranged from approximately seven to eight participants. In both cases, the considerable imbalance between groups reduces statistical power and increases the risk that observed effects, whether significant or non-significant, do not fully reflect true population-level differences.

A final limitation concerns the design of the body map used during the interviews to assess perceived discomfort. The map utilized color-coded regions, with the upper abdomen being represented by a red color, the lower abdomen by a blue color and thighs by a green color. Because red is commonly recognized as a warning color or a signal of danger, this design choice may have inadvertently introduced a subconscious response bias. Specifically, it might have visually biased participants to interpret the upper abdomen as a “wrong” or unsafe area, potentially deterring them from placing their discomfort markings in that specific zone. To mitigate this risk, a preferred approach could have been to use neutral colors and objective labels, such as “Region A, B, and C,” to ensure that the map did not influence participant feedback.

5.8 Suggestions for future work

Future work should investigate how the observed geometric and anthropometric relationships influence occupant kinematics under dynamic crash loading. While the present study focused on static belt fit and subjective evaluations, it remains unclear how these geometric differences translate into real-world safety performance. Dynamic sled testing or simulations using validated human body models (HBM) are therefore necessary to assess how variations in belt positioning affect load paths and the risk of submarining and injury. In particular, the interaction between seatback recline angle, belt geometry and inertial loading should be examined to determine whether the trends observed in static conditions persist under realistic crash scenarios.

As part of the study, 3D body scans were collected using a FARO Freestyle scanner. These datasets provide a strong foundation for future work involving more detailed geometric analysis and simulation-based modeling. The scan data capture local body contours and belt routing geometry with substantially higher spatial resolution. This enables a more refined analysis of how local geometric features influence belt–body interaction. A natural extension of this work is the integration of the 3D scan data into human body model simulations. By mapping individual participant geometries onto computational models, it becomes possible to evaluate how variations in anthropometry and seat back recline influence belt loading and occupant kinematics during crash events. Such simulations could be used to investigate how differences in body shape alter belt routing. This would also allow exploration of subject-specific responses, rather than relying on simplified or average anthropometric representations.

Another direction for future work is to further study the interaction between the lap belt and the shoulder belt. The current study kept the shoulder belt geometry fixed, but the results indicate that shoulder belt interference had a substantial influence on perceived comfort and usability. To address this, a more integrated investigation is needed where both lap and shoulder belt geometries are varied simultaneously. This would enable the identification of design trade-offs and potential optimization strategies that account for the full restraint system rather than its individual components. Conversely, to establish a pure baseline for lower-body restraint preferences, future experimental designs could also isolate the lap belt entirely. By temporarily removing the shoulder belt during static evaluations, researchers could eliminate upper-body confounding factors, allowing for a strictly isolated assessment of how anthropometrics dictate lap belt placement and perceived comfort. However, while this isolated approach would yield specific geometric data without upper-body disturbances, any resulting design guidelines would ultimately need to be validated within a complete three-point system to ensure compliance with vehicle safety regulations.

The present study was conducted with a sample of 30 participants, which provided sufficient power for overall group comparisons but limited the conclusiveness of subgroup analyses. As discussed in the methodological limitations, several findings, including the influence of trip duration on perceived safety and the anthropometric predictors of shoulder belt interference, were based on considerably small and unbalanced groups. Future studies should therefore aim for larger and more demographically diverse samples to improve statistical power and enable more robust subgroup comparisons. A larger participant pool would also increase the likelihood of capturing sufficient representation across anthropometric extremes, which is particularly important for understanding how belt fit varies across the full population rather than within a narrow range of body sizes. Future work should also investigate the extent to which the fixed test order influenced participant responses. A counterbalanced or fully randomized design, in which the order of both buckle positions and seatback recline angles is varied across participants, would allow assessment of whether the observed differences reflect genuine ergonomic effects or are partly attributable to the sequence in which configurations were experienced.

In addition, future work could explore adaptive or personalized restraint system concepts. The results indicate that user-preferred lower anchorage positions often deviate from standard configurations, highlighting a mismatch between occupant comfort and fixed design constraints. Investigating adjustable or adaptive anchorage systems that account for anthropometry and seat back recline angle may help bridge this gap. Such approaches are particularly relevant for autonomous driving scenarios, where seating configurations may differ significantly from traditional upright positions.

Finally, the present study was limited to static and short-duration evaluations. Future research should therefore include longer-duration studies to assess how belt fit and occupant behaviour evolve over time, as well as dynamic testing environments that capture realistic driving inputs such as braking and steering. These factors may influence both belt positioning and the effectiveness of safety systems and are essential for translating laboratory findings into real-world applications.

6

Conclusion

This study demonstrates that lap belt fit is governed by an interaction between occupant anthropometry, seating posture, and belt anchorage position, with implications for comfort, usability, and perceived safety. All reported belt displacements are expressed as mean belt displacement relative to the ASIS. In the upright position, moving the lower anchorage 10 cm forward resulted in an anterior shift of approximately 31.4 mm for the upper edge and 31.6 mm for the lower lap belt edge. In the semi-reclined position, the lap belt exhibited a more forward positioning overall, with mean anterior shifts of 41.5 mm (upper edge) and 45.8 mm (lower edge), compared to the upright condition.

BMI showed strong associations with vertical lap belt position across all conditions, indicating that overall body size plays a major role in the relative positioning of the belt with respect to the pelvis. In contrast, anterior–posterior belt displacement is strongly posture-dependent. The relationship between BMI and forward belt position weakens in the semi-reclined position, suggesting that changes in pelvic orientation and seating position play a dominant role in shaping belt routing in this condition. Local anthropometric measures such as waist circumference, hip breadth, and abdominal depth further influence belt positioning, but their associations are generally weaker or non-significant in the reclined condition, indicating that their effect is strongly modulated by posture and global body orientation.

From a comfort perspective, lap belt geometry primarily affects perceived load distributions across different anatomical regions. The forward anchorage position was associated with reduced perceived pressure in the abdominal region for many users by shifting belt forces towards the hips and thighs. However, this redistribution is not uniformly beneficial, as it may introduce new discomfort in other regions such as the thighs or upper body, depending on anthropometry and seating posture. For example moving the lap belt anchorage forward resulted in 27% of all participants reporting annoyance or obstruction of the right arm from the shoulder belt in the upright position, and similarly 23% of all participants reported shoulder belt interference in the semi-reclined position. Consequently, comfort is influenced by a multi-region trade-off rather than a single optimized contact condition, where improvements in one area can lead to increased discomfort elsewhere.

User-preferred anchorage positions show that the majority of occupants (87%) selected buckle positions outside the regulatory range, indicating a systematic shift away from predefined design limits. The selected positions also exhibited substantial variability across participants, with buckle locations ranging from 48–243 mm in the X-direction, 19–69 mm in the Y-direction, and 114–211 mm in the Z-direction in the upright condition, and from 19–193 mm, 14–61 mm, and 102–241 mm, respectively, in the semi-reclined condition. This spread indicates pronounced inter-individual differences in preferred buckle placement across all axes. These findings suggest that occupants adjust belt configuration based on a combination of comfort, usability, and perceived safety. While these adjustments reflect underlying anthropometric influences, particularly related to abdominal and pelvic geometry, they do not eliminate the overall sensitivity of the system to occupant variability. Instead, belt fit appears to be governed by a hierarchy of effects, where seatback recline angle has the strongest influence, anthropometry governs local fit characteristics, and anchorage position primarily affects contact distribution and usability.

Overall, the findings highlight that improvements in lap belt fit involve inherent trade-offs between perceived comfort, usability, and perceived safety, which vary across occupant body types and seating positions. This underlines the importance of considering restraint systems as integrated human–system interfaces, where belt geometry, seating posture, and participant perception must be addressed simultaneously in future design, particularly in the development of adaptive or adjustable anchorage positions.

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Appendix A: Pre-Test Questionnaire

This appendix presents the pre-test questionnaire administered to participants.

Please answer the following questions based on your normal driving experience.

Participant ID: ____________

Age: ____________

Biological sex:
☐ Female ☐ Male ☐ Other / Prefer not to say

Travel Habits

1. How many days per week do you usually travel by car?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

2. What is the average duration of your car trips?

☐ 0–15 min ☐ 15–30 min ☐ 30–45 min

☐ 45–60 min ☐ 1–2 h ☐ >2 h

3. What is your usual seating position in the car?

☐ Driver ☐ Front passenger ☐ Rear passenger

Sitting comfort in the car

4. When you sit in a car, how comfortable do you generally feel throughout the trip?

Mark your perceived discomfort (1 = no discomfort at all, 5 = extreme discomfort). Circle the number that best represents your feeling:

1 2 3 4 5

5. Please describe factors that affect your seating comfort in the car.

____

Perceived safety when using a seat belt

6. How safe do you generally feel when wearing a seatbelt while driving?

Mark your perceived safety (1 = not safe at all, 5 = completely safe). Circle the number that best represents your feeling:

1 2 3 4 5

7. How safe do you generally feel when wearing a seatbelt while riding as a passenger?

Mark your perceived safety (1 = not safe at all, 5 = completely safe). Circle the number that best represents your feeling:

1 2 3 4 5

8. Please describe factors that affect how safe you feel when using a seat belt.

____

Discomfort from the seat belt

9. Do you experience discomfort or irritation from the seatbelt while driving?

☐ No

☐ Yes, please specify: ____________________________

10. Do you experience discomfort or irritation from the seatbelt while riding as a passenger?

☐ No

☐ Yes, please specify: ____________________________

Use of accessories

11. Do you use any accessories to increase comfort while driving (e.g., seat belt pads, back cushions, neck support, thigh support, belt extender)

☐ No

☐ Yes, please specify: ____________________________

12. Do you use any accessories to increase comfort while riding as a passenger (e.g., seat belt pads, back cushions, neck support, thigh support, belt extender)

☐ No

☐ Yes, please specify: ____________________________

Physical activity

13. How many times per week do you exercise or work out? (e.g., running, cycling, gym, swimming)

☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5+

Appendix B: Structured Interview Questions

This appendix lists the structured interview questions used in the study. Participants first evaluated two predefined lap belt positions for each seatback configuration (upright and reclined). They then selected their preferred position in each scenario, performed a secondary task, and were allowed to adjust the position before completing the full set of questions on discomfort, safety and usability.

Physical sensation

1. Do you feel pressure from the lap belt in this seating configuration?

Indicate the level of pressure from the lap belt:

1 No pressure: no noticeable pressure from the lap belt
2 Slight pressure: light pressure, barely noticeable
3 Moderate pressure: clearly noticeable pressure, but tolerable
4 High pressure: strong pressure, uncomfortable and distracting
5 Very high pressure: extremely strong pressure, difficult to tolerate

Discomfort

2. How much discomfort do you experience from the lap belt in this seating configuration?

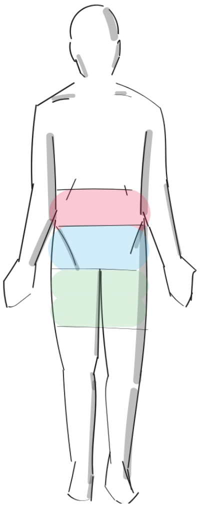
Mark your perceived lap belt discomfort.

1 No discomfort: sits completely comfortably, barely noticeable
2 Mild discomfort: slight pressure, does not bother you much
3 Moderate discomfort: noticeable pressure, could be annoying on long trips
4 Significant discomfort: strong pressure, annoying, would like adjustment
5 Maximum discomfort: very uncomfortable, could not sit like this for long

3. Indicate where on your body you experience the lap belt as disturbing or causing discomfort.

If you experience discomfort, mark the area(s) on the image where you feel it by placing a cross (x). If you do not experience any discomfort, tick the box below and leave the image blank.

☐ I do not experience any discomfort from the lap belt



Observations

4. Please describe any specific sensations, observations, or issues you noticed with the lap belt, and also note if you experience anything related to the shoulder belt (e.g., pressure points, sliding, restricted movement).

____

____

____

Perceived safety

5. How safe do you perceive the seatbelt in this configuration?

Mark your perceived safety. Circle the number that best represents your feeling:

1 Not safe at all: I would feel very unsafe using this seatbelt.
2 Slightly unsafe: I notice some risk, but it is somewhat tolerable.
3 Moderately safe: I feel reasonably safe, but not fully confident.
4 Safe: I feel the seatbelt would protect me well.
5 Completely safe: I feel fully secure and confident using this seatbelt.

6. Describe why you feel safe or unsafe when using the seat belt in this configuration.

____

____

____

Seat belt usability

For the following questions, the participant may unbuckle and fasten the seat belt in order to answer the questions.

7. How easy or difficult was it to locate the buckle position in this configuration?

(1 = very easy, 5 = very difficult)

1 2 3 4 5

8. How easy or difficult was it to buckle the seat belt?

(1 = very easy, 5 = very difficult)

1 2 3 4 5

9. How easy or difficult was it to unbuckle the seat belt?

(1 = very easy, 5 = very difficult)

1 2 3 4 5

10. Please provide any additional comments or observations regarding the usability of locating, buckling, or unbuckling the seat belt in this configuration.

____

____

____

Appendix C: Participant anthropometric overview

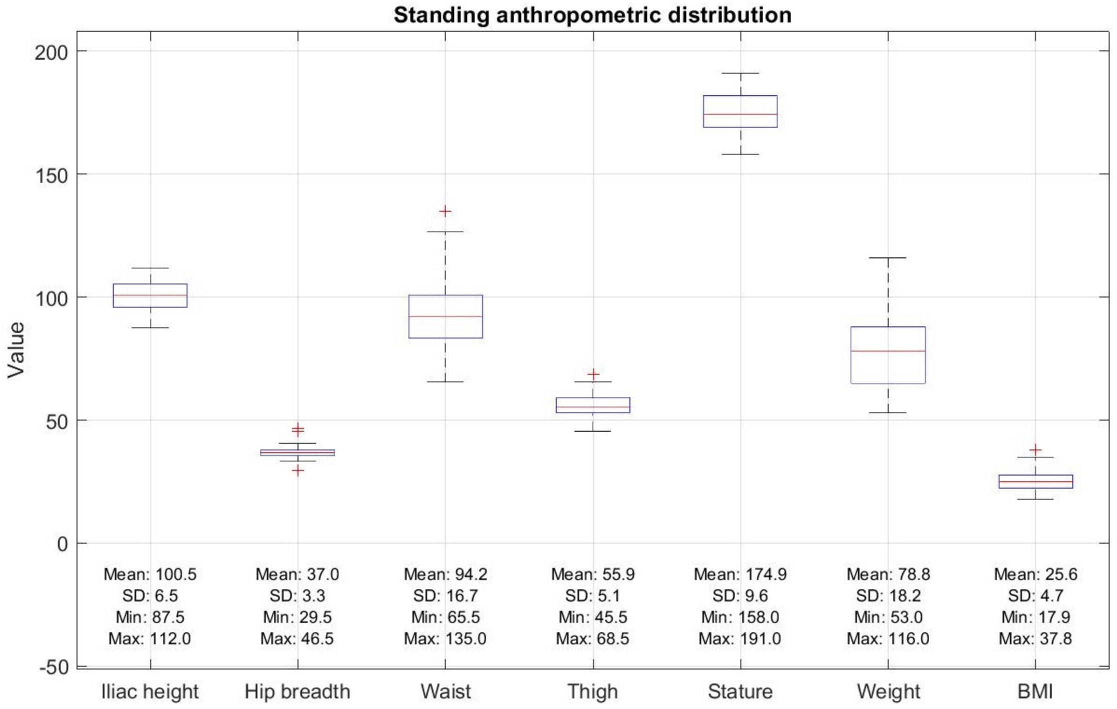
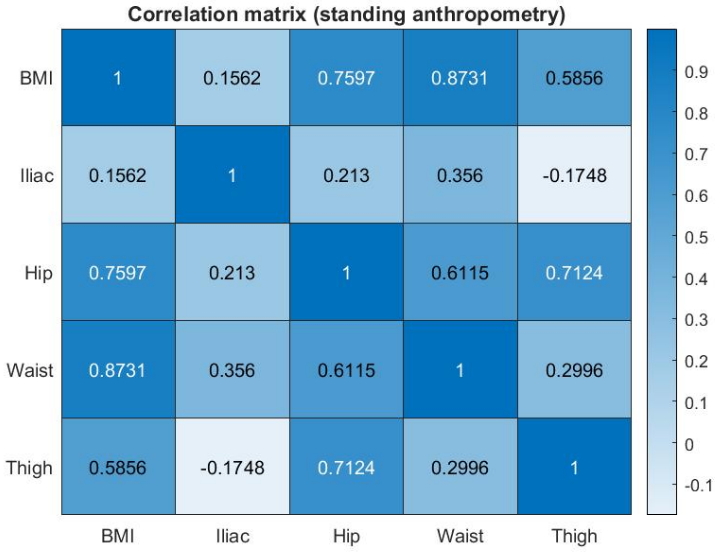


Figure C.1: Distribution of standing anthropometric measurements across participants. Boxplots represent median, standard deviation and data range for each variable. All measurements are expressed in centimetres (cm), body weight in kilograms (kg), and BMI in kg/m^2.



	BMI	Iliac	Hip	Waist	Thigh
BMI	1	0.1562	0.7597	0.8731	0.5856
Iliac	0.1562	1	0.213	0.356	-0.1748
Hip	0.7597	0.213	1	0.6115	0.7124
Waist	0.8731	0.356	0.6115	1	0.2996
Thigh	0.5856	-0.1748	0.7124	0.2996	1

Figure C.2: Correlation for standing anthropometric variables and BMI. Correlation coefficients (r-values) illustrate relationships between variables.

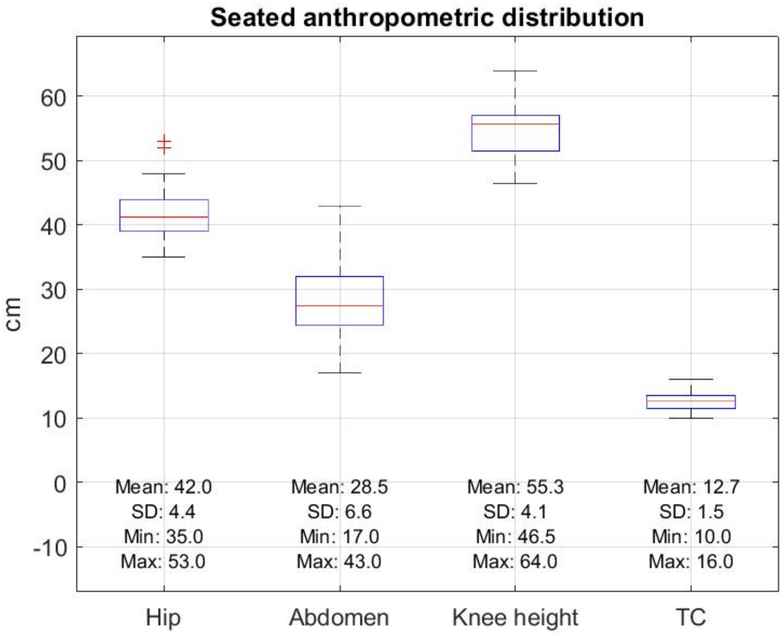
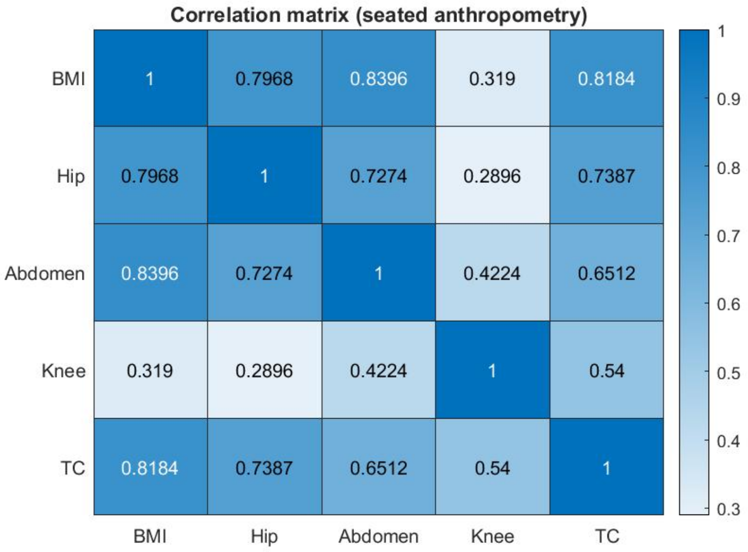


Figure C.3: Distribution of seated anthropometric measurements across participants. Boxplots represent median, standard deviation and data range for each variable. All measurements are expressed in centimeters (cm).



	BMI	Hip	Abdomen	Knee	TC
BMI	1	0.7968	0.8396	0.319	0.8184
Hip	0.7968	1	0.7274	0.2896	0.7387
Abdomen	0.8396	0.7274	1	0.4224	0.6512
Knee	0.319	0.2896	0.4224	1	0.54
TC	0.8184	0.7387	0.6512	0.54	1

Figure C.4: Correlation matrix for seated anthropometric variables and BMI. Correlation coefficients (r-values) illustrate relationships between variables.

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