A Comparative Evaluation of Seating Comfort for Future Automotive Seat Design

Ruida Chen
Student Number: 5933994

Chair : Dr. Yu (Wolf) Song
Mentor: Aernout Kruithof (MSc.)

Faculty of Industrial Design Engineering
Delft Universuty of Technology

Aug. 18th, 2025

Delft University of Technology

TUDelft

Table of Contents

1. Abstract

This report investigates the evolution of seating comfort during prolonged driving using a mixed-method evaluation of three production automotive seats. Twenty-six participants engaged in repeated 120-minute sessions within a full-scale vehicle cabin mock-up. Subjective measures, including comfort and discomfort ratings, local postural discomfort (LPD), thermal comfort, fatigue, stress, and tactile perception—were combined with objective indicators such as skeletal posture tracking, seat adjustment monitoring, anthropometric data and facial emotion analysis.

Temporal changes in perceived comfort were influenced by time, seat characteristics, user behavior, and individual anthropometry. Observable patterns emerged in both subjective responses and behavioral adaptations, revealing multifaceted interactions between thermal buildup, physical support, and postural fatigue. This paper suggests feasible design recommendations and offers insights to inform future design considerations for long-duration and autonomous driving environments.

2. Introduction

In the context of prolonged driving, both physical and psychological factors interplay to shape a driver's comfort and safety. Sustained muscle contractions and static postures inherent in vehicle seating have been shown to induce neuromuscular fatigue and elevated discomfort over time. For example, sustained low-level muscle activation typical of driving correlates with increased discomfort levels and neuromuscular fatigue, as measured by both subjective ratings and objective EMG indices (Lecocq et al., 2022). De Looze et al. (2003) further demonstrated that insufficient muscular activity—even in nominally "comfortable" postures—can lead to drowsiness, underscoring the critical balance that seat design must achieve between support and active engagement (Lecocq et al., 2022).

Lee et al. (2020) highlighted that psychological stress and cognitive demand are equally important in driving ergonomics. They found that monotonous long-distance driving can elevate mental fatigue and stress, which in turn degrade both comfort perception and driving performance. Moreover, motion-seat systems that introduce subtle, passive posture changes were shown to reduce subjective fatigue and maintain alertness in low-workload scenarios without distracting the driver from primary tasks. These findings highlight the potential of seat systems to reduce fatigue- and stress-related impairments, contributing to a more comfortable and alert driving experience.

Finally, micro-movements (small, often unconscious postural adjustments) play a dual role in both signaling discomfort onset and providing transient relief. Early research identified two categories of repositioning movements: macro-movements reflecting large postural shifts driven by significant discomfort, and micro-movements—subtle oscillations around a stable posture—used to stave off discomfort before it escalates (Lantoine et al., 2021).

Collectively, these lines of evidence establish stress, fatigue, comfort, and micro-movements as interrelated constructs essential for understanding and optimizing automotive seat design. Our study integrates subjective assessments (comfort, fatigue, stress, and emotion) with objective micro-movement metrics to answer how these factors evolve and interact across different seat designs during a long-term driving simulation.

This study aims to investigate how seating comfort changes over time and identify which variables influence these changes.

2.1 Project goal

The primary goal of this project is to apply a structured comfort assessment procedure to evaluate three production (Seat A, Seat B, Seat C) seats from an automotive company, and to provide design recommendations aimed at enhancing customer appeal.

Beyond this practical objective, the project also explores academic value by establishing a replicable methodology for long-term comfort evaluation. The data and insights generated may contribute to future research in seating ergonomics, discomfort prediction, and adaptive seat design.

2.2 Research questions

This study is guided by the following key research questions:

1. Main question:

Can changes in driver comfort and discomfort during prolonged driving be predicted by driving time, behavioral, emotional and anthropometric features, and are these features significantly correlated with comfort-related outcomes across different seat types?

2. Comparative Comfort Analysis

How do overall comfort, discomfort, fatigue, stress, and emotional valence evolve over a 120-minute driving simulation, and in what ways do these trajectories differ among seats with different seat characteristics?

3. Subjective and Objective Measures:

How do subjective perceptions (comfort/discomfort, local postural discomfort, thermal sensation, fatigue, stress) and objective indicators such as In-Chair Movement (ICM), emotional response, skeleton tracking and seat adjustment behavior evolve over time, and how do they relate to the user experience across the three seats?

This includes the following **sub questions**:

- How do subjective ratings (e.g., comfort, discomfort, fatigue, thermal sensation, stress) evolve over time and differ across seat types?
- How do objective measures (e.g., emotion analysis, In-Chair Movement (ICM), seat adjustment patterns) reflect user comfort during the 120-minute drive?
- How do interviews of participants (verbal expressions and qualitative feedback) reflect comfort/discomfort across different seats?

Predictive Factors & Design Recommendations:
Which specific subjective factors (e.g. perceived firmness, thermal sensation) and seat design attributes (e.g. cushion/backrest firmness, cover-fabric friction, thermal behavior), possibly correlate with comfort and discomfort ratings, and how can these insights inform targeted improvements for next-generation automotive seat design?

This includes the following **sub questions**:

- Which subjective or objective indicators show strong correlations with comfort/discomfort ratings?
- How do anthropometric and gender-related differences affect discomfort perception and its evolution?
- How can these predictive patterns inform targeted recommendations for next-generation automotive seat design?

2.3 Impacts

The findings of this study are expected to have a significant impact on the ergonomic design and evaluation of automotive seats by integrating human perception, human behavior, and human biometric characteristics within a replicable method. By simultaneously addressing the subjective evolution of comfort and the objective characteristics of discomfort during prolonged driving, this study aims to:

- Establish a comprehensive comfort assessment system that combines standardized tactile, thermal, and comfort/discomfort questionnaires with continuous skeletal tracking and emotional analysis to evaluate current and future seat designs. Provide evidence-based suggestions regarding seat design attributes for future design of selecting and adjusting seat cushion/backrest hardness, cover fabric characteristics, and foam structure to optimize initial tactile appeal and sustained support.
- Integrate human and material data streams: Combine anthropometry, body composition, subjective ratings, and tactile assessments to bridge the gap between driver characteristics and seat design, ensuring solutions can adapt to diverse body types and usage patterns.

Ultimately, as vehicle automation advances and occupants spend extended periods in seated positions without performing driving tasks, creating seats that actively maintain comfort and well-being will be critical for user acceptance and safety. This research lays the groundwork for the next generation of automotive seats, which will not only efficiently transport passengers but also dynamically respond to their evolving comfort needs.

3. Literature Review

This chapter outlines prior research on comfort and discomfort in seating, with a focus on thermal regulation, postural strain, behavioral movement, and anthropometric influence. Literature also informs the measurement tools and design considerations relevant to long-duration automotive seating.

3.1 Comfort and discomfort

Comfort has been conceptualized by Vink and Hallbeck (2012) as “a pleasant state or relaxed feeling of a human being in reaction to its environment,” whereas discomfort is defined as “an unpleasant state of the human body in reaction to its physical environment”. Helander and Zhang’s (1997) work further demonstrated that comfort and discomfort do not lie on a single bipolar continuum but instead represent two distinct dimensions, participants can experience low discomfort without necessarily feeling high comfort, and vice versa. Building on this, De Looze et al. (2003) argued for explicitly incorporating a physical dimension into the definition of discomfort, emphasizing that muscular strain, pressure distribution, and biomechanical loading are core drivers of the unpleasant sensations that lead users to adjust posture or seek relief.

To quantify these dual constructs, researchers typically employ separate 0–10 rating scales for comfort and discomfort (0 = “none,” 10 = “extreme”) (Anjani et al., 2020). This dual-scale approach allows us to capture both the presence of positive, pleasant feelings and the buildup of negative and active sensations independently. By administering these scales at regular intervals during prolonged seating, the temporal trajectories of comfort and discomfort can be mapped/recorded separately over time—revealing, for example, whether a seat maintains relaxed support or whether discomfort gradually emerges despite stable comfort ratings.

3.1.1 Thermal Comfort

Thermal comfort reflects the body's subjective response to temperature and is a critical component of overall seating satisfaction. The ASHRAE 7-point Thermal Sensation Vote (TSV) scale, established by the American Society of Heating, Refrigerating and Air-Conditioning Engineers, rates perceived warmth from –3 (cold) to +3 (hot), with 0 indicating a neutral sensation (ASHRAE, 2023).

This localized measurement is often complemented by a Thermal Preference Vote (TPV), where participants indicate whether they would prefer warmer, cooler, or unchanged conditions. In automotive contexts, precise control of seat heating, ventilation, and cabin climate can directly impact these votes: higher TSV readings in areas like the buttocks or thighs frequently correlate with increased local discomfort, while a stable 0–1 TSV range supports sustained comfort over long drives. Researchers use repeated TSV/TPV assessments to identify seat zones prone to thermal stress and to inform adaptive thermal management strategies (ASHRAE, 2023).

3.1.2 Local Postural Discomfort (LPD)

Grinten and Smitt (1992) originally introduced the Local Postural Discomfort method to capture fine-grained discomfort patterns during seated work. They devised a body-map divided into 22 regions where covering the head, neck, shoulders, upper and lower back, buttocks, thighs, lower legs, and arms, allowing participants to indicate discomfort in each zone on a 10-point scale (0 = no discomfort, 10 = extreme discomfort). This region-specific approach made it possible to pinpoint which anatomical areas bore the greatest strain over time, rather than relying on a single overall rating.

More recently, Anjani et al. (2021) adapted and validated a streamlined 13-region version of this tool for automotive seating studies, confirming its reliability and sensitivity to detect temporal changes in localized discomfort during long-duration drives. By administering the LPD, researchers can chart the evolving distribution of postural strain, insights that are critical for targeting ergonomic refinements in seat comfort evaluation.

3.2 In-Chair Movement (ICM)

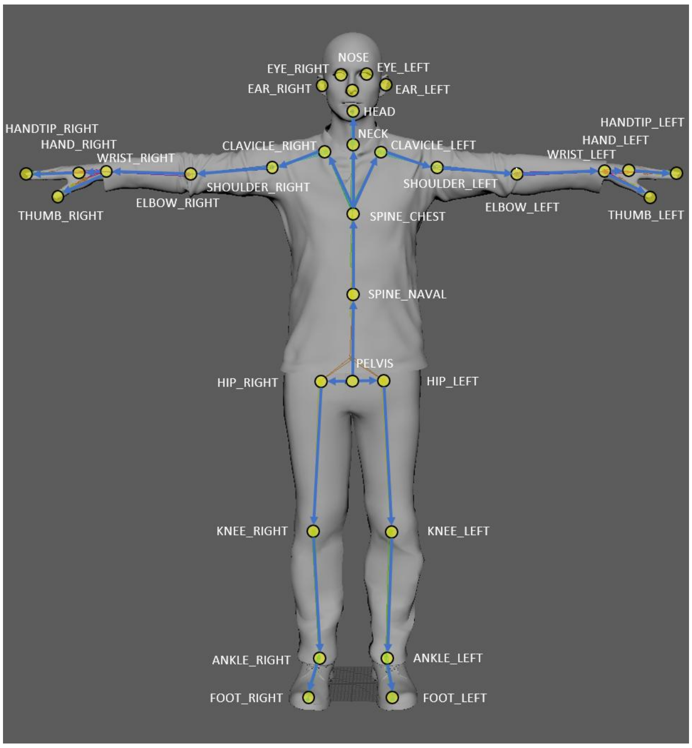
Sitting discomfort is often assessed using subjective ratings linked to static, objective measures such as posture. However, as discomfort evolves over time, it requires continuous and objective monitoring. In-chair movement (ICM) is particularly promising as an objective measure, given its established role in modern comfort–discomfort models (Vink & Hallbeck, 2012).

Research has shown that drivers instinctively adjust their seating posture in response to emerging discomfort, making seat-position changes a valid proxy for shifts in comfort levels. For example, Vergara and Page (2002) distinguish “macro-movements” as large, deliberate postural adjustments—as direct responses to perceived discomfort peaks, while “micro-movements” serve to fine-tune comfort around a stable posture. Similarly, Sammonds et al. (2017) observed that the frequency of repositioning movements on the seat pan rises in tandem with self–reported discomfort during long-duration drives.

Based on the important correlation between ICM and comfort and discomfort, we can conduct a comprehensive analysis through skeletal tracking data, unobtrusively tracking in-chair movements.

3.2.1 Skeleton Tracking

Recent research has demonstrated the growing interest in using the Microsoft Azure Kinect camera for human motion tracking and biomechanical analysis. Albert et al. (2020) conducted a pilot study comparing the pose tracking performance of Azure Kinect with its predecessor, Kinect v2, using a treadmill-based gait analysis setup. Their findings showed that the Azure Kinect, equipped with improved depth-sensing hardware and a deep learning-based body tracking algorithm, achieved significantly higher accuracy in spatial gait parameters such as step length and stride width. Although temporal parameters showed no significant difference between the two devices, the spatial fidelity of the Azure Kinect supports its potential as a low-cost, marker-less alternative to laboratory-based motion capture systems like Vicon (Albert et al,.2020). This study highlights the feasibility of applying Azure Kinect in clinical and rehabilitation contexts, where real-time skeletal tracking can aid in the evaluation of movement quality (Albert et al,.2020).



3.3 Anthropometry and body composition

Prior research has demonstrated that anthropometric variables such as stature, weight, BMI, and body type significantly influence seating posture, pressure distribution, and overall comfort. Taller individuals tend to adopt postures with crossed legs and less foot contact, while shorter individuals show less backrest contact in slouched positions (Hiemstra-van Mastrigt et al., 2016). Several studies also reported strong correlations between weight and seat contact area, with body mass and hip circumference being reliable predictors (Paul et al., 2012).

Average pressure was found to increase with body weight and BMI, but differences were observed between genders—females generally showed lower average pressure due to a larger contact area (Moes, 2007). Other relevant anthropometric factors include hip breadth, buttock–popliteal length, and subcutaneous fat percentage, all of which affect seat interface pressure and comfort perception (Moes, 2007).

4. Methodology

4.1 Overview

A mixed-method approach was used to assess long-term seating comfort, combining subjective questionnaires and objective posture tracking. A custom-built 1:1 cabin mock-up equipped with three different types of production seats was constructed to simulate a driving scenario and monitoring.

Also, both objective and subjective data were collected. Objective movement data were obtained through skeleton tracking to monitor posture and in-chair movement, use RGB camera to capture participants' facial expression and analyze emotion changing, we also design a scale system (see Figure 4.6) and manually recording the seat position during the experiment (see Appendix A4).

Subjective feedback was gathered via questionnaires (see Appendix A2) focusing on overall comfort and discomfort, thermal comfort, stress, fatigue, local postural discomfort (LPD), and tactile sensations (see Appendix A3). These measures help clarify the relationship between movement behavior and perceived comfort levels during prolonged sitting.

Data was collected throughout 120-minute sitting sessions for each seat under simulated driving conditions. And figure 3.1 shows the research structure.

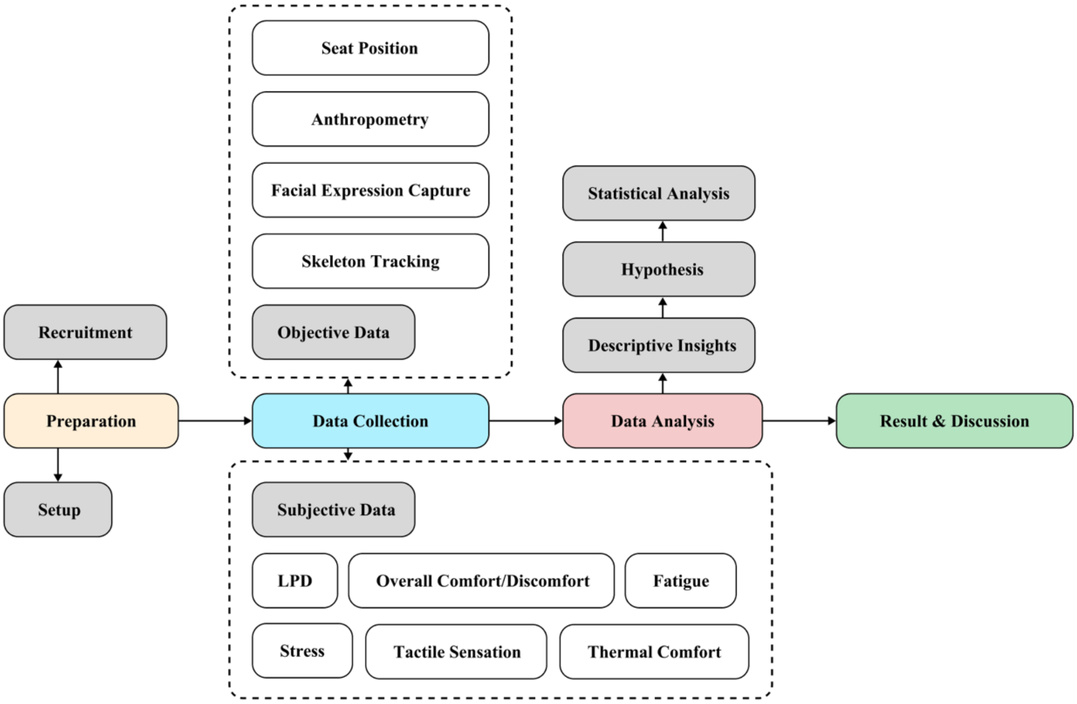


Figure 4.1 *Research structure*

4.2 Participants recruitment

The study was approved by the Human Research Ethics Committee of Delft University of Technology and finally involved 26 participants. The experiment used questionnaires to enumerate willingness as well as poster posting and distribution to recruit participants (Poster see Appendix I).

Participants were selected to represent a range of anthropometric characteristics associated with seat comfort. Written informed consent was obtained from each participant prior to the commencement of the study.

A reference ellipse was included based on Dutch population data obtained from the TU Delft DiNED anthropometric database (DiNED, n.d.) (see Figure 4.2). This helped verify that the participant sample covered the typical range of hip breadth and stature in the Dutch adult population.

Prior to the study, all participants should sign the informed consent in compliance with ethical research standards. Each participant took part in two experimental sessions, each lasting approximately 450 minutes (~7.5 hours), allowing for a comprehensive assessment of the study objectives. Upon completing both sessions, participants were compensated with a €120 voucher in recognition of their contribution.

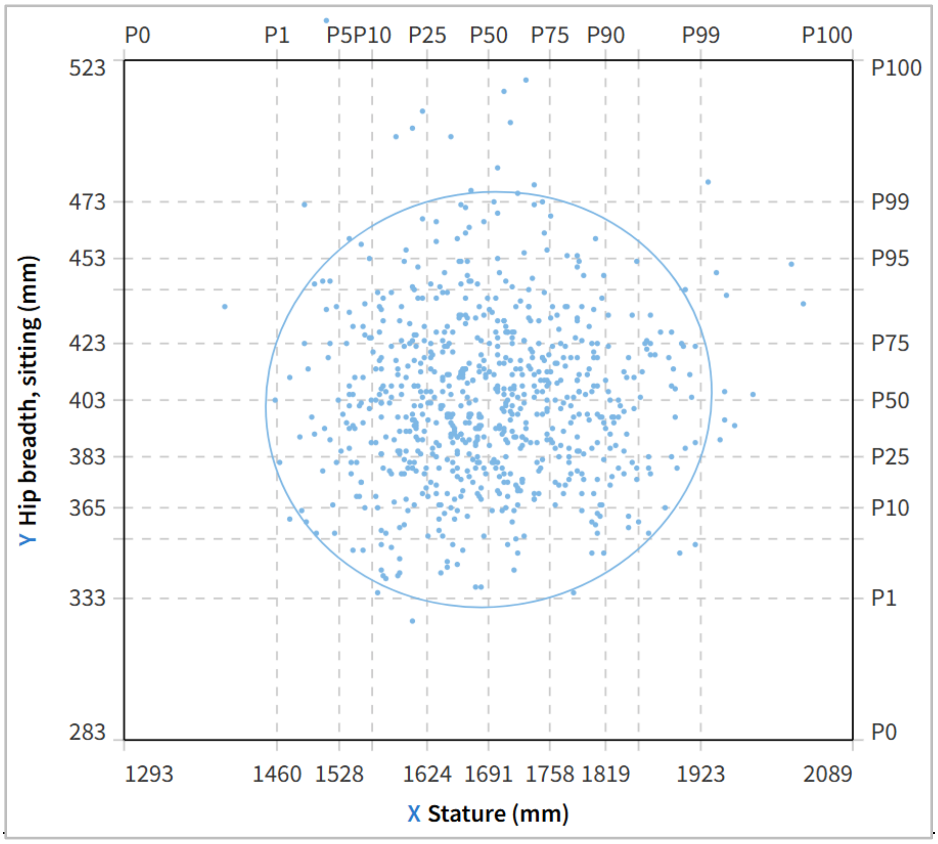


Figure 4.2 Stature vs. Hip Breadth by Gender, overlaid with Dutch reference ellipse derived from the TU Delft DiNED anthropometric database (www.dined.io.tudelft.nl).

4.2.1 Participant Background Profiling

Prior to the experimental session, participants completed a pre-questionnaire (see Appendix A1) designed to collect demographic and background information. The questionnaire included items on sex, year of birth, handedness, ethnicity (with a focus on geographic ancestry within Europe) and driving license status. This information was used to better understand the composition and background characteristics of the participant population within a European context.

4.3 Anthropometry and Body composition

Anthropometric and body composition data were collected before the sessions using custom-built lab equipment and OMRON BF511 (see Figure 4.3). This included stature, weight, shoes weight, body weight, sitting height, eye height seated, shoulder sitting height, hip breadth, shoulder breadth body fat percentage, muscle mass, and visceral fat. Additionally, we calculate the BMI value for identifying people's health status.

Figure 4.3 Measurement devices.

4.4 Comfort

In relation to comfort, this study focused primarily on overall comfort and thermal comfort. Both were quantitatively assessed through structured questionnaires administered every 20 minutes throughout the 120-minute session (7 times in total). (see Appendix A2)

4.4.1 Overall Comfort

Overall comfort was assessed using a unipolar 0–10 scale, where 0 indicated "no comfort" and 10 indicated "extreme comfort." This measure captures the participant's positive and relaxed perception of the entire driving simulation experience; ratings were collected every 20 minutes to track changes over time (see Appendix A2).

4.4.2 Thermal Comfort

Thermal comfort was assessed using the ASHRAE 7-point Thermal Sensation Vote (TSV) scale, which ranges from –3 (cold) to +3 (hot), with 0 indicating thermal neutrality. This scale captures participants' subjective thermal sensations during the simulated driving session. TSV ratings were collected every 20 minutes to monitor temporal changes in thermal comfort throughout the 120-minute experiment (see Appendix A2).

4.4.3 Tactile Questionnaire

The tactile questionnaire used in this study was adapted from the framework proposed by Wegner (2020), which provides a structured approach to quantifying seat comfort through sensory attributes. Participants rated the seat cushion and backrest of each seat across 8 bipolar adjective pairs (e.g., "Soft–Hard," "Stiff–Elastic," "Loose–Firm", full tactile questionnaire see Appendix A3) on a 7-point Likert scale ranging from –3 to +3. A score of 0 indicated a neutral perception between the two descriptors, while –3 and +3 represented strong agreement with the respective adjective. This method enabled a nuanced evaluation of seat surface characteristics before prolonged sitting.

4.5 Discomfort

In relation to discomfort, this study focused primarily on overall discomfort, LPD, fatigue, and stress. Both were quantitatively assessed through structured questionnaires administered every 20 minutes throughout the 120-minute session (7 times in total) (see Appendix A2).

4.5.1 Local Postural Discomfort (LPD)

Local Postural Discomfort (LPD) was measured using a 13-region body map covering key areas such as the neck, back, buttocks, and legs. Participants rated discomfort in each region on a 0–10 scale (0 = no discomfort, 10 = extreme discomfort). This method, adapted from Grinten and Smitt (1992) and validated for automotive use by Anjani et al. (2021), allowed us to track localized discomfort changes over time. Ratings were collected every 20 minutes to track changes over time (see Appendix A2).

4.5.2 Fatigue and Stress

Fatigue and psychological stress were assessed using separate 0–10 numerical rating scales, where 0 indicated no fatigue or stress and 10 indicated extreme fatigue or stress. Participants provided these ratings every 20 minutes during the 120-minute session to capture the progression of mental and physical strain over time (see Appendix A2).

4.6 In-Chair Movement

In-chair movement (ICM) was continuously monitored using the Microsoft Azure Kinect camera. This RGB-D sensor combines a high-resolution RGB camera with a Time-of-Flight (ToF) depth sensor that estimates distance by measuring the phase shift of reflected infrared light. The system enables marker less skeletal tracking through the Azure Kinect Body Tracking SDK, which uses a neural network-based solution for 2D pose estimation and 3D model fitting. Specifically, the SDK processes the IR image from the depth sensor to detect and track up to 32 anatomical joints in real time (Microsoft, 2019). This setup allowed us to capture full-body posture changes and micro-movements throughout each 120-minute seated session. The resulting movement data provide a non-intrusive, temporally rich record of in-chair adjustments, which can be correlated with emerging discomfort or fatigue over time (Vink & Hallbeck, 2012; Zhang et al., 2020).

4.7 Seat Position Adjustment

In this study, seat positions—including backrest angle, seat pan fore-aft, height, and headrest height—were recorded every 10 minutes. It is important to note that this setup captures static seat configurations, rather than direct adjustment behaviors. Consequently, we do not observe real-time interactions but rather periodic outcomes of participant-seat interaction.

To accurately identify adjustment events (i.e., when and how users interact with seat controls), further analysis is required by aligning position changes with skeleton tracking data to detect transition patterns or postural shifts.

While this behavioral-level interpretation is beyond the scope of the current report, it is planned as a future research extension to more precisely understand user-initiated adjustments and their temporal relationship with comfort dynamics.

4.8 Experimental Setup

Three production-grade automotive seats were mounted on individual customized fixtures to simulate realistic cockpit postures and layouts. Each fixture was equipped with a fixed steering wheel, a seat belt, and a monitor that continuously showed a first-person German Autobahn driving video. A calibrated skeleton tracking system and a RGB camera were mounted on the sides and front to capture full-body posture data and facial expression at a high frequency.

The experimental environment was controlled for lighting, noise, and fresh air. Monitors and room dividers were used to isolate each buck and prevent distraction (see figure 4.4 and figure 4.5).

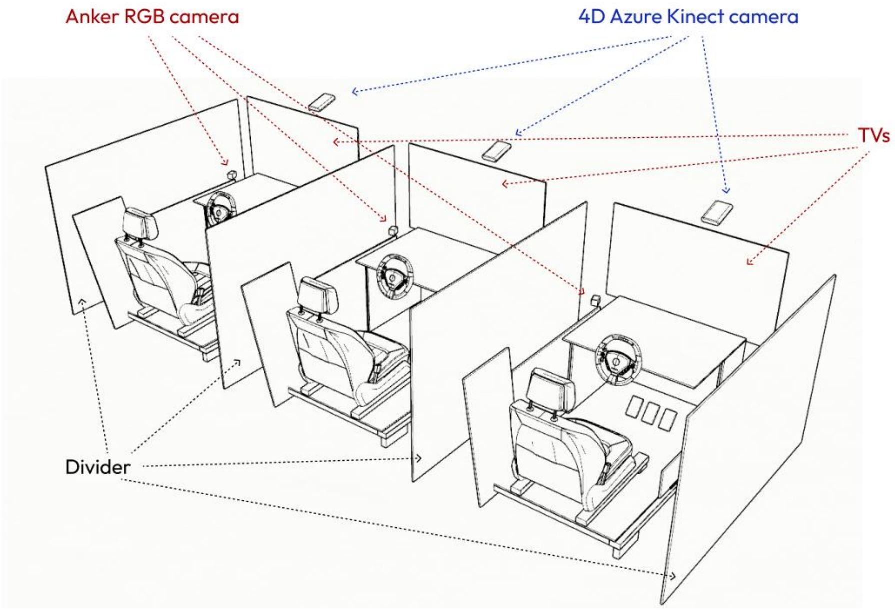


***Figure 4.4** Overview of setup in Rhino 7.*

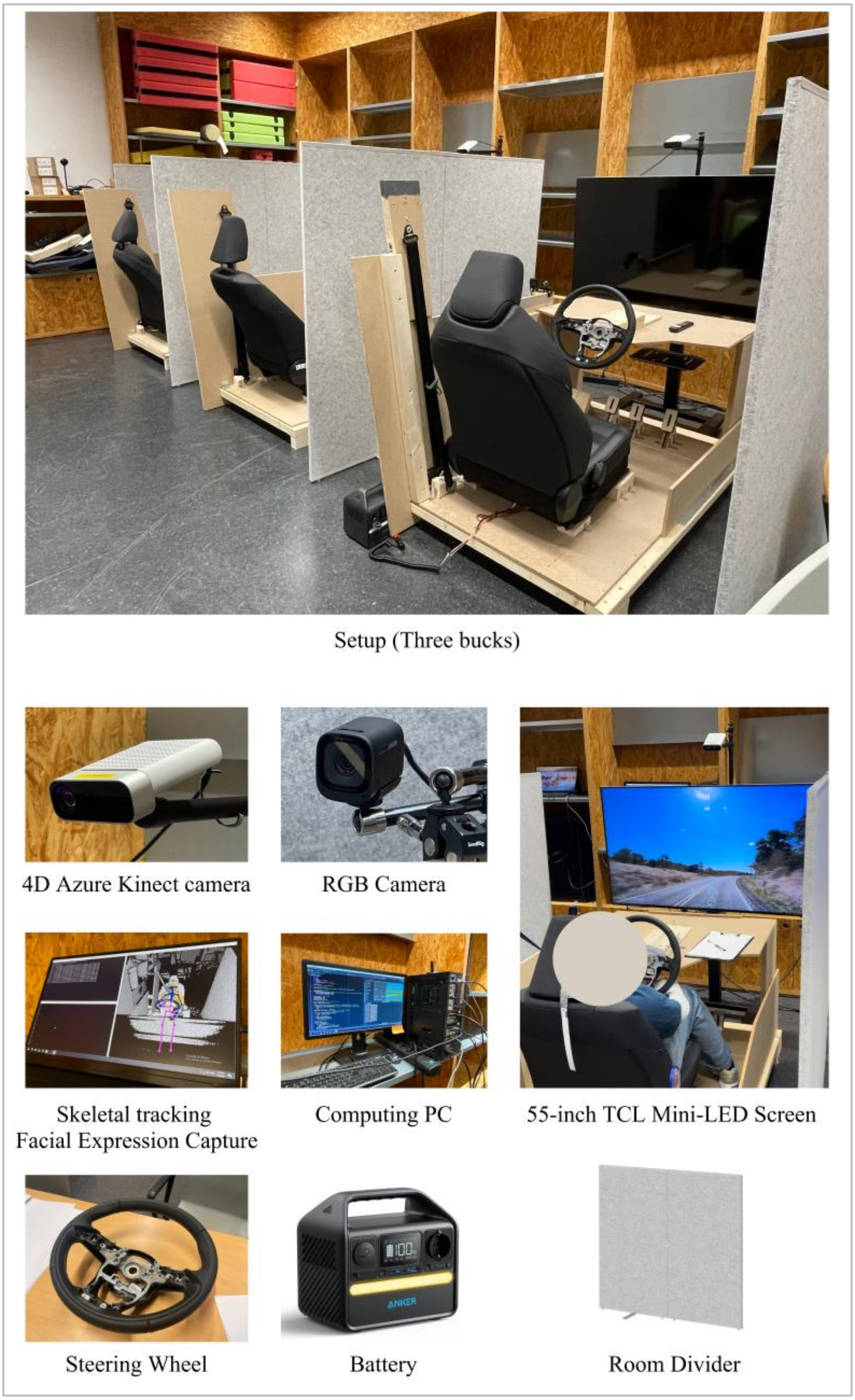


Figure 4.5 *Overview of setup*

4.8.1 Seats and Buck Mock-up

Three identical buck setups were constructed, each designed to accommodate one of the three production seats (Seat A, Seat B and Seat C) under evaluation. All bucks were built to the same dimensions based on the interior geometry of a real vehicle, to ensure consistency across conditions and to simulate a realistic vehicle cabin environment.

4.8.2 Seat Adjustment Scale System

A custom-built scale system was implemented to record seat adjustments throughout the experiment. This system monitored four seat position parameters:

- Headrest height.
- Seat height.
- Seatback angle.
- Fore–aft seat position.

The system allowed detection of seat position every 10 minutes, offering insight into seat position changing over time (see Figure 4.6).

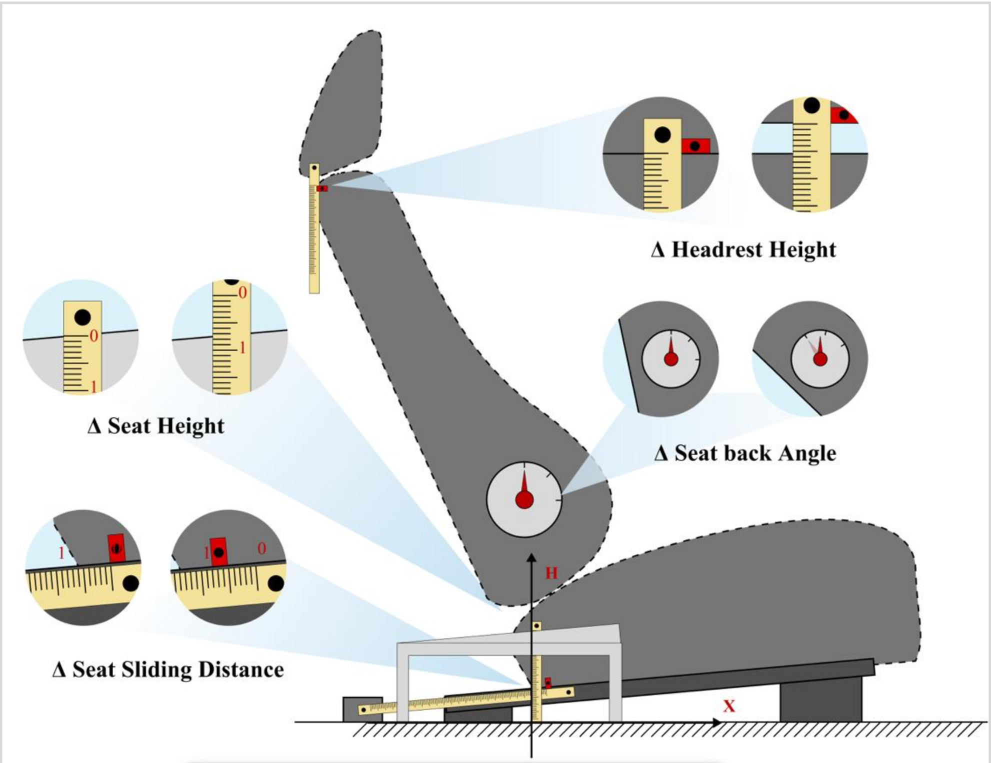


Figure 4.6 Multi-scale system

*Figure 4.6 **(a)** Headrest measurement. **(b)** Fore–aft seat position **(c)** Seat angle gauge.*

4.8.3 Seating-buck

To simulate a realistic driving environment and capture participants' physical and emotional responses, the setup included the following equipment:

Cameras

Azure Kinect was used to track full-body skeletal movement in real time.

RGB camera was mounted to capture participants' facial expressions for potential emotion analysis.

Cabin Dividers

IKEA Scheidings Wand room dividers were installed between the three seat setups to simulate a private car cabin environment and minimize distraction.

Steering Wheels

Realistic steering wheels were provided for each buck to enhance the driving simulation experience.

Measurement Instruments

Anthropometric and body composition data were collected using lab-made instruments, including devices for measuring body dimensions (e.g., hip breadth, sitting height) and composition (e.g., muscle mass, body fat percentage, visceral fat).

4.9 Experimental Protocol

We plan to recruit 24 participants for this study. The experiment was conducted in 12 sessions, with 3 participants per session, each assigned to one of three seats mounted on identical testing jigs. This setup allowed all three seat types to be evaluated simultaneously under consistent environmental and procedural conditions.

To counterbalance potential order and position effects, seat assignments followed a Balanced Latin Square Design (Bradley, 1958). This method ensured that each participant experienced all three seats in different sequences and physical positions across sessions, allowing for fair comparison across seat conditions while minimizing confounding effects related to seating order or jig position. Each participant completed three 120-minute sitting trials, one per seat, with the order systematically rotated across the sample (see Table 3.1).

Table 4.1 *Example of Balanced Latin Square Assignment for 3 Participants and 3 Seats*

Session	Seat 1	Seat 2	Seat 3	Note
Session 1	P1	P2	P3	Round 1: P1–P3 each on a seat
	P3	P1	P2	Rotation: counterbalanced order
Session 2	P2	P3	P1	Ensures each seat seen in each jig
	…	…	…	

To avoid participant fatigue and ensure high-quality feedback, the evaluation of the three seats was divided into two sessions (Figure 3.7 uses an example of long session which evaluates two seats shows the experiment procedure).

- **Short Session (120 minutes)**:

  Conducted in the morning from **9:30 to 11:30**, this session involved the evaluation of **one seat**. It allowed participants to familiarize themselves with the process and reduced the cognitive and physical load of assessing multiple seats consecutively.

- **Long Session (330 minutes)**:

  Scheduled in the afternoon from **12:30 to 18:00**, this session included the evaluation of the remaining **two seats**. A longer time frame was allocated to accommodate sufficient breaks and maintain data reliability across multiple assessments.

This two-part structure was designed to balance time efficiency and participant comfort, ensuring consistent data quality throughout the experiment. Each participant was arranged to take one long and one short session as close to three days apart as possible, and as far as possible not to complete all sessions in one day to prevent excessive differences in physical condition or fatigue.

Each participant completed the following procedures (one long session and one short session):

4.9.1 Long session

a. **Arrival and preparation** (0-15 minutes): welcome, orientation, consent form, and completion of pre-questionnaire.
b. **Tactile comfort assessment** (15-30 minutes): Participants assessed all three seats using tactile questionnaire.
c. **Sitting Session 1** (30-150 minutes): Participants sit in Seat 1 for 2 hours. An in-experiment questionnaire was administered every 20 minutes to collect subjective data on comfort, discomfort, heat, fatigue and stress. Participants completed the questionnaire independently and returned it to the tray.
d. **Rest and Anthropometry measurement** (150-180 minutes): Light walking and recovery, followed by anthropometric measurements (height, hip circumference, weight, and body fat percentage).
e. **Sitting Session 2** (180-300 minutes): The same 2-hour program is repeated in Seat 2.
f. **Post-session interview** (305-320 minutes): Participants provide qualitative feedback on comfort and postural behavior.

4.9.2 Short session

a. Sitting Session 3 (0-120 minutes): The same 2-hour program is repeated in Seat 3.
b. Post-session interview (120-135 minutes): Participants provide qualitative feedback on comfort and postural behavior.

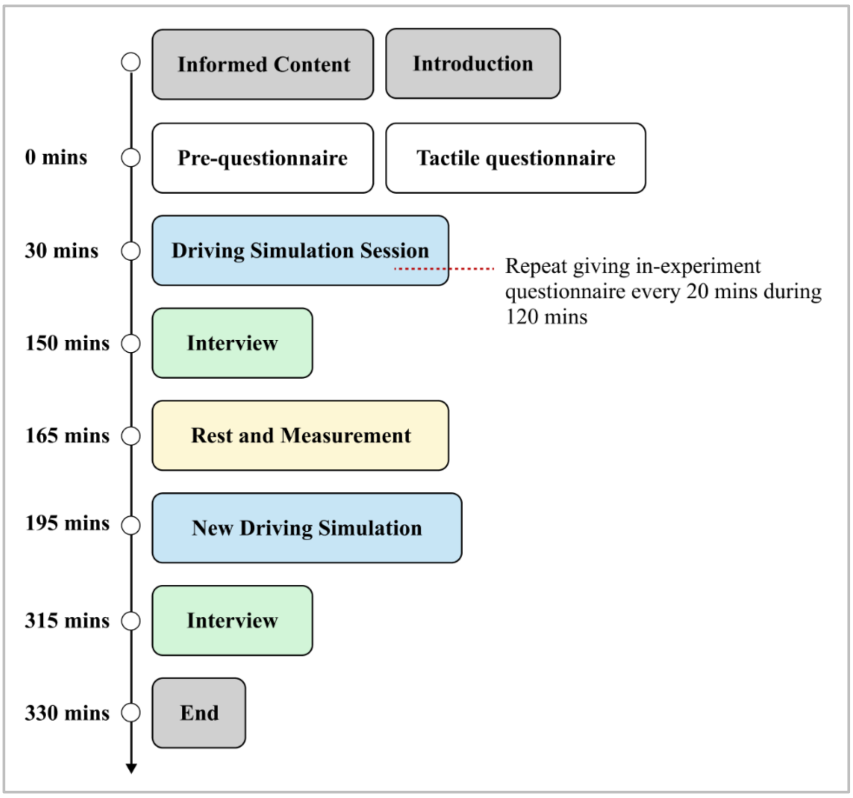


Figure 4.7 *Experiment procedure (An example of long session: evaluate two seats)*

4.9.3 Interview on overall experience

After each seat trial, participants were asked to complete a semi-structured interview consisting of five open-ended questions (see Table 4.2). These questions were designed to elicit in-depth reflections on comfort, discomfort, posture adjustments, and seat-related factors influencing the overall experience. Participants responded in writing, enabling detailed qualitative analysis.

The questions covered:

1. Overall comfort rating and reasoning (1–10 scale)
2. Discomfort location and onset time
3. Postural changes and their causes
4. Seat features that supported or interfered with comfort
5. Any additional feedback or subjective impressions

These responses were later coded thematically to complement quantitative measurements such as pressure ratings, fatigue, and in-chair movement.

Table 4.2 *Interview questions.*

Interview Questions
Overall, how comfortable did you feel in this seat (1–10)? Why?
Did you feel any discomfort during the session? Where and when did it start?
Did you adjust your posture at any point? What made you do that?
Was there anything about the seat that helped or worsened your comfort?
Any other thoughts about your experience with this seat?

Interview analysis

The interview analysis directly addresses Research Question 1 – Subjective and Objective Measures, specifically sub-question 3, which explores how participants' verbal expressions and qualitative feedback reflect comfort and discomfort across different seat types. While the primary evaluation relied on structured quantitative questionnaires and objective indicators such as in-chair movement patterns and emotional responses, interviews were conducted to capture participants' subjective narratives and nuanced impressions that are often difficult to quantify.

These qualitative insights provide contextual understanding of how comfort and discomfort are experienced during prolonged seating, supplementing the numerical trends identified through questionnaires. For instance, verbal expressions regarding perceived firmness, tactile sensations, or localized discomfort offer perceptual patterns that enhance the interpretation of comfort-related outcomes.

Given the exploratory nature of this study and the large volume of qualitative data, a word frequency approach was employed to identify recurring descriptors related to seating comfort. Descriptive adjectives referring to tactile impressions, supportiveness, softness, or discomfort were extracted and categorized by seat type, allowing for structured comparisons across seats.

In addition to frequency analysis, sentiment polarity classification was performed to categorize adjectives into positive and negative groups. This supplementary analysis provided an overview of participants' emotional valence towards each seat, enabling a higher-level understanding of the tone and directionality of qualitative feedback. The polarity classification method complements the frequency-based approach by highlighting not only descriptor prevalence but also their underlying sentiment orientation.

This light-weight linguistic analysis method allowed for rapid identification of prevailing comfort themes and supported the interpretation of questionnaire trends. The approach draws on word frequency visualization methods as discussed by McNaught & Lam (2010), who demonstrated the utility of word clouds in surfacing prominent textual patterns within large qualitative datasets.

4.9.4 Exploratory Analysis

Prior to formal hypothesis testing, we visualized all normalized subjective ratings across seats and time points to gain an intuitive overview of temporal comfort evolution. These descriptive visualizations served to support our general understanding but were not used as the basis for hypothesis formulation or statistical test selection.

4.10 Overview of Analysis Strategy

For the seat A/B/C's comparative analysis, which contains:

Development of overall comfort/discomfort, local postural discomfort (LPD) thermal comfort, fatigue, stress.

All statistical analyses, visualization and reported findings of comparative analysis are based on raw, non-normalized questionnaire data. This decision was made to preserve the original scale interpretation and maintain transparency in participant response variance.

However, to address inter-individual variability in subjective perception, normalized data were also computed using min-max scaling within each participant. This additional step was intended to reduce individual response bias—where some participants might consistently give higher or lower scores due to their personal interpretation of comfort-related scales, rather than actual experiential differences.

By normalizing participant ratings across repeated time points, we aim to capture intra-individual changes (e.g., the relative increase in discomfort over time), enabling fairer comparisons across individuals. This approach is particularly valuable for subjective variables such as overall comfort, discomfort, thermal sensation, and fatigue.

Normalized data has been used not only for trend visualization purposes, but also as the basis for quantitative modeling and statistical inference. Specifically, normalized discomfort scores were analyzed through Ordinary Least Squares (OLS) regression to identify potential anthropometric predictors of mean discomfort. Additionally, Linear Mixed Models (LMM) were applied to account for within-subject variability and model discomfort progression over time. Pearson correlation analysis was also performed to examine the relationships between discomfort and individual measurement variables across different body regions. These results informed variable importance rankings and guided interpretation of temporal trends. A more systematic analysis focusing on pattern recognition and cross-variable comparisons across seats and measurement dimensions will be conducted in the next stage of this study.

4.11 Statistical Data Analysis Methods

The following statistical and computational methods were applied to analyze the multi-modal data collected during the long-duration seating experiment. All analyses were conducted using Python (Pandas, NumPy, SciPy, Matplotlib, Seaborn) and supporting natural language processing tools.

4.11.1 Preprocessing

- Time Extraction & Alignment: Timestamps (0, 20, 40, 60, 80, 100 and 120 minutes) were extracted and aligned across datasets.

- Min–Max Normalization: To enable participant-independent comparisons, min–max normalization was applied to subjective ratings (comfort, discomfort, fatigue, thermal sensation, stress).

- Data Cleaning: Missing or invalid entries were removed or converted to NaN; all variables were type-cast for numeric computation.

4.11.2 Statistical Testing

1. Normality Check:

- Shapiro–Wilk Test was used to assess normality of subjective score distributions at each time point.

2. Significance Testing (Time Series vs. Baseline):

- Wilcoxon Signed-Rank Test (non-parametric): Used to compare each time point (20, 40, 60, 80, 100 and 120 minutes) against the 0-minute baseline for each seat and variable.
- Paired t-tests were considered but not used when normality was violated.

3. Between-Seat Comparison:

- Friedman Test (non-parametric equivalent of repeated-measures ANOVA): Used to assess differences in variables across Seat A, B, and C.
- Post-hoc pairwise comparisons with Bonferroni correction were applied when needed.

4.11.3 Correlation Analysis

Spearman's Rank Correlation Coefficient: Used to assess monotonic relationships between:

- Thermal sensation scores and regional discomfort (upper body, thighs, legs).
- Local Pressure Discomfort (LPD) and overall discomfort.
- Seat position changes and perceived comfort.

4.11.4 Statistical Modeling of Discomfort

To investigate the influence of individual physical characteristics on seating discomfort over time, two complementary statistical methods were applied: Ordinary Least Squares (OLS) regression and Linear Mixed Models (LMM). These analyses aimed to identify which anthropometric indicators significantly correlate with discomfort and how these effects evolve with time and gender.

1. Ordinary Least Squares (OLS) Regression

Initial analysis was conducted using OLS regression to explore the linear relationship between average normalized discomfort ratings and a range of anthropometric and body composition variables. For each participant, the mean discomfort across all time points and seat conditions were calculated. This mean score served as the dependent variable, regressed against independent variables such as sitting height, shoulder breadth, hip breadth, body fat percentage, and other anthropometric indicators. This approach enabled a preliminary ranking of the predictors in terms of their potential association with overall discomfort, although time-related dynamics were not included.

2. Linear Mixed-Effects Model (LMM)

To account for the repeated-measures structure of the data and temporal variation in discomfort, a series of Linear Mixed Models were implemented. These models included Time and individual anthropometric variables as fixed effects, with Participant ID modeled as a random intercept to capture between-subject variability. The general form of the model was:

$$Discomfort_{i,t} = \beta_0 + \beta_1 \cdot Time_t + \beta_2 \cdot X_i + \beta_3 \cdot (Time_t \times X_i) + \boldsymbol{u_i} + \boldsymbol{\epsilon_{i,t}}$$

Where:

- $Discomfort_{i,t}$ is the normalized discomfort score of participant $\boldsymbol{i}$ at time $\boldsymbol{t}$,
- $X_{\boldsymbol{i}}$ represents an anthropometric variable,
- $\boldsymbol{u}_i$ is the random effect for participant $\boldsymbol{i}$,
- $\boldsymbol{\epsilon_{i,t}}$ is the residual error.

This modeling strategy enabled us to identify not only which physical traits influenced discomfort, but also how these effects interacted with time. The significance of fixed effects (main and interaction terms) was used to classify variables as temporally dominant, baseline-dominant, or statistically insignificant.

4.11.5 Seat Position Analysis

- **Seat Position Delta Calculation:**

  Time-series data of seat position adjustments were processed to compute deltas relative to the 0-minute baseline.

- **Trend Visualization:**

  Averaged trajectories were plotted per seat type, with shaded confidence intervals (min–max or standard deviation).

4.11.6 Skeleton Tracking Analysis

To capture objective postural data throughout the prolonged sitting experiment, skeletal tracking was performed using the **Microsoft Azure Kinect** depth-sensing camera system. This system provides 3D motion tracking based on an infrared time-of-flight sensor and a machine learning-based body tracking SDK. The Azure Kinect was positioned in front of the seated participant to continuously record joint positions in real-time.

A predefined set of key joints was selected for analysis based on their relevance to seated posture and upper-body alignment:

- **Pelvis**
- **Spine (Navel and Chest)**
- **Neck**
- **Nose**
- **Clavicles (Left and Right)**
- **Shoulders (Left and Right)**

These joints represent critical anatomical landmarks involved in upper-torso balance, lean behavior, and compensatory postural adjustments.

The tracked skeletal model followed the default Azure Kinect Body Tracking SDK structure, enabling robust frame-by-frame analysis of joint displacement and alignment. Postural trends were extracted to identify micro-movements and behavioral markers of discomfort. The bilateral joints (clavicles and shoulders) were particularly useful in assessing asymmetry, which can be indicative of uneven support or discomfort-driven shifting.

This skeleton-based motion data was used as an objective input for subsequent correlational and temporal analysis, helping to map physical movement patterns to subjective comfort transitions over time.

4.11.7 Sentiment and Language Analysis

- **Adjective Extraction:**

  Tokenization were used to extract adjectives from open-ended participant feedback.
- **Sentiment Polarity Analysis:**

  TextBlob was used to compute sentiment polarity scores (positive/negative) for each seat group.
- **Word Frequency and Visualization:**

  Frequency counts and word clouds were generated to identify dominant comfort-related descriptors.

4.11.8 Data Visualization

- **Box Plots:** Used to show variation and medians in subjective scores at each time point.
- **Line Charts:** Plotted normalized scores over time with significance markers.
- **Bar Charts:** Used to show adjective counts and sentiment polarity.
- **Heatmaps:** Used for visualizing tactile questionnaire.

5. Results

5.1 Participant demographic characteristics

Table 5.1 presents the demographic characteristics of the 26 participants involved in this study. The average age was 23.2 years (±2.88), with a relatively balanced gender distribution—54% male and 46% female. In terms of ethnicity, the majority of participants were from Western Europe (46%) and Eastern Europe (42%), with a smaller portion from East and Central Asia (12%). No participants were from other listed regions. Most participants were right-handed (96%), while only 4% were left-handed. Additionally, 77% of participants held a valid driving license, indicating prior driving experience, whereas 23% did not.

***Table 5.1** Participants Demographics of 26 paricipants*

Participant	n=26	Percentage
Age	23.2 ¬± 2.88	
Gender	Male	54%
	Female	46%
Ethnicity	Western Europe (e.g., Greece, Sweden, United Kingdom)	46%
	Eastern Europe (e.g., Hungary, Poland, Russia)	42%
	North Africa (e.g., Egypt, Morocco, Sudan)	0%
	Sub-Saharan Africa (e.g., Kenya, Nigeria, South Africa)	0%
	West Asia/Middle East (e.g., Iran, Israel, Saudi Arabia)	0%
	South and Southeast Asia (e.g., India, Indonesia, Singapore)	0%

	East and Central Asia (e.g., China, Japan, Uzbekistan)	12%
	Pacific/Oceania (e.g., Australia, Fiji, Papua New Guinea)	0%
	North America (Canada, United States)	0%
	Central America and Caribbean (e.g., Jamaica, Mexico, Panama)	0%
	South America (e.g., Brazil, Chile, Colombia)	0%
Dominant Hand	Left	4%
	Right	96%
Driving License	Yes	77%
	No	23%

Table 5.2 *Participants Anthropometry*

Anthropometry	Overall		Male		Female	
	Mean	SD	Mean	SD	Mean	SD
Statue with shoes (mm)	1772.2	90.6	1829.1	72.1	1705.8	59.8
Stature(mm)	1746.4	91	1801.9	73.5	1681.7	62.7
Shoes Weight(kg)	0.7	0.3	0.8	0.4	0.5	0.2
Weight with shoes(kg)	72.4	11.5	77.6	9.1	66.4	11.4
Body weight(kg)	71.8	11.4	76.8	8.9	65.9	11.5
Sitting height(mm)	905	39.6	925.9	38.1	880.8	25.4
Eye height seated(mm)	786.2	39.5	806.3	40.2	762.7	22.8
Shoulder sitting height(mm)	593.7	33.5	608.3	32.3	576.7	26.9
Hip breadth(mm)	393.2	29.8	388.9	24.2	398.2	35.7
Shoulder breadth(mm)	423.7	35.1	449.1	24.7	394	17.3
Elbow to elbow(mm)	390.4	49.4	416.1	41.5	360.3	41.1
Popliteal height with shoes(mm)	500.8	38	520.6	35.1	477.7	27.1
Popliteal to knee(mm)	115.5	9.2	119.3	10.1	111.1	5.6

Buttock to popliteal(mm)	501.7	36	513.6	30.4	487.7	38.2
Buttock to knee(mm)	617.2	41.3	632.9	36.3	598.8	40.5

***Table 5.3** Participants Body Composition*

Body Composition	Overall		Male		Female	
	Mean	SD	Mean	SD	Mean	SD
Visceral fat	4.8	2.3	5.6	2.6	3.9	1.2
Body fat percentage	0.3	0.1	0.2	0.1	0.3	0.1
Muscle percentage	0.3	0.1	0.4	0	0.3	0.1
Metabolism (kcal)	1575.2	213.4	1706.1	146.4	1422.5	175.9

During the initial stage of the experiment, anthropometric and body composition data were collected from all participants. These results are summarized in Table 5.2 and Table 5.3, divided into overall, male, and female groups.

The body mass index (BMI) is the standard metric currently used to define anthropometric height/weight characteristics in adults and to classify them into health-related categories. It is widely accepted as a proxy for body fatness and a risk factor for various health conditions. Furthermore, BMI is frequently used in public health research to assess population-level health trends and guide policy (Nuttall, 2015).

In this study, BMI was used to ensure that the participant group represented a broader population rather than only healthy individuals. According to the World Health Organization (n.d.), a BMI between 18.5–24.9 is classified as normal, 25.0–29.9 as pre-obese, and ≥30 as obese.

By including participants with BMI values in the "overweight" range (25.0–29.9) even obesity people (BMI ≥ 30), we aimed to improve the generalizability of our findings across varied body compositions.

Figure 5.1 shows the participants' BMI values ranged primarily (n=20, 76.9%) within the normal weight (18.5–24.9) (n=4, 15.4%) and pre-obesity (25.0–29.9) categories, with two obesity participants (n=2, 7.7%) exceeding a BMI of 30. Figure 5.1 shows the BMI Category distribution. Figure 5.2 shows the BMI distribution by sex; and Figure 5.3 visualizes the relationship between stature and weight across all participants (World Health Organization, n.d.).

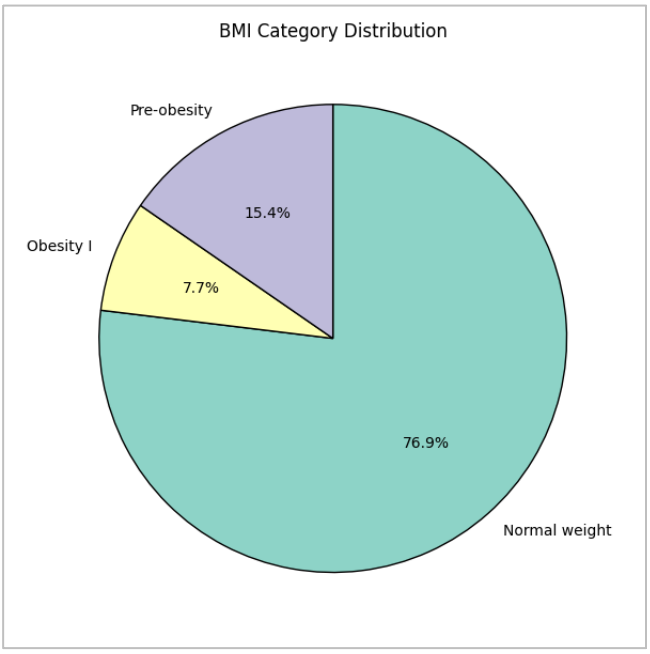


Figure 5.1 *BMI Category Distribution*

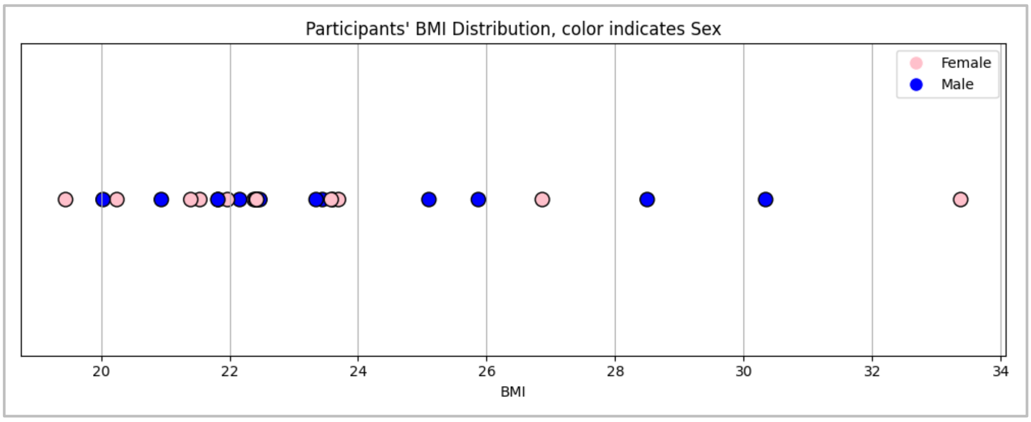


Figure 5.2 *BMI Distribution, color indicates sex*

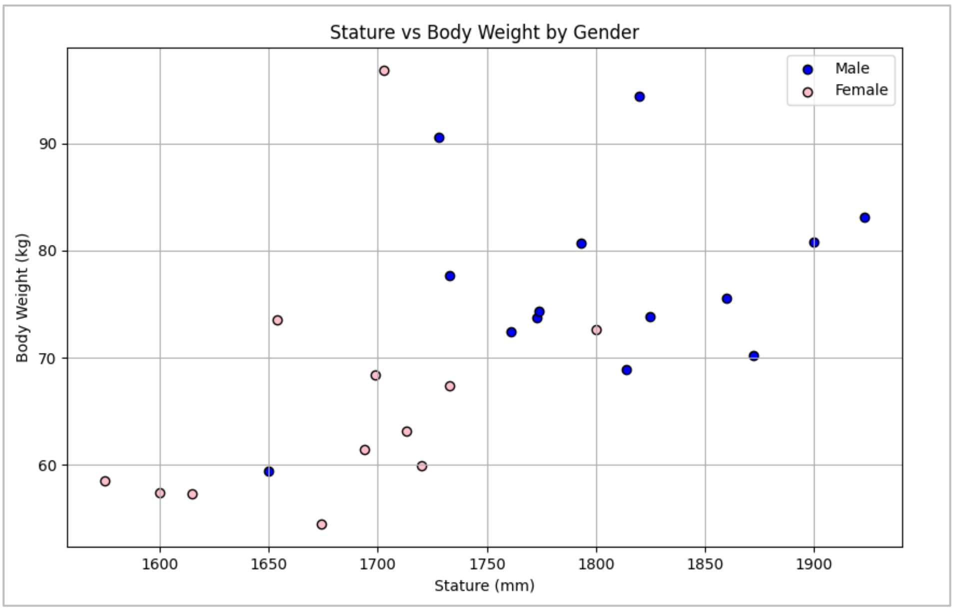


Figure 5.3 Participants' Weight and Stature Distribution

5.2 Comparative Comfort and discomfort Analysis

Please refer to Appendix F for the results.

5.3 Insights from Subjective Measures

Please refer to Appendix F for the results.

5.4 Insights from Objective Measures

Please refer to Appendix F for the results.

5.5 Interview data analysis

Please refer to Appendix F for the results.

5.6 Correlation Analysis

Please refer to Appendix F for the results.

5.7 Modelling Temporal and Gender Effects on Discomfort

Please refer to Appendix F for the results.

5.8 Anthropometry and Discomfort

Please refer to Appendix F for the results.

6. Summary of Key Findings

Please refer to Appendix G for the results.

7. Discussion

7.1 Interpreting Comfort and Discomfort Dynamics

The progressive rise of discomfort across all seats highlights the inevitability of physical strain during prolonged sitting. Seat C's sustained comfort suggests that firmness combined with stable support may better mitigate fatigue and micro-pressure accumulation, while Seat A's softness, despite initial appeal, lacked structural stability over time.

7.2 Thermal and Postural Interactions

Thermal discomfort was one of the dominant factors influencing local discomfort, particularly in the thighs and upper body. Seat A's strong thermal–discomfort correlation confirms that inadequate ventilation (Areas of close compaction with the body for long periods of time) can amplify postural discomfort. The combination of thermal and LPD analysis supports the conclusion that localized heat buildup directly triggers positional micro-adjustments and discomfort perception.

7.3 Seat Adjustment Behavior

Observed adjustment behaviors aligned closely with subjective reports.

- Participants using Seat A showed a "set and forget" pattern, adjusting early but failing to respond effectively to growing discomfort.
- Seat B participants adopted compensatory adjustments later in the session, reflecting reactive discomfort management.
- Seat C promoted greater flexibility, with proactive posture management and early adjustments that prevented discomfort peaks.

This suggests that seat design can influence behavioral strategies, not just comfort ratings.

7.4 Gender and Anthropometric Influences

Modeling revealed that female participants experienced faster discomfort growth, possibly due to seat contour mismatches or reduced load distribution for smaller body frames. Similarly, hip breadth and seated eye height emerged as predictive variables, highlighting the need for adjustable and inclusive seat ergonomics.

An interesting pattern was observed in the significance results: all predictors that showed a significant main effect (i.e., baseline discomfort impact) also exhibited a significant interaction with time. In other words, main effect significance was always accompanied by time interaction significance, but not vice versa. This suggests that variables influencing initial discomfort levels may also play a continuous role in modulating discomfort progression throughout prolonged sitting. This pattern reflects a potentially stable influence mechanism and warrants further exploration in future studies.

7.5 Emotional and Cognitive Responses

While stress levels remained low, emotional expression analysis revealed subtle affective differences. Seat C's reduced negative emotional expressions indicate a closer alignment with psychological comfort, suggesting that emotional metrics can serve as a secondary validation of physical comfort.

7.5.1 Unexpected Emotional Performance of Seat A

Although Seat A and Seat C are from the same vehicle platform and share similar structural characteristics, participants in Seat A exhibited significantly more negative emotional expressions than those in Seat C ($p < 0.05$).

This result is somewhat unexpected, and no specific design or behavioral cause has been identified. One possibility is that Seat A was located closer to the laboratory wall, which might have induced a subconscious sense of spatial confinement. However, room dividers were used to visually and spatially balance the setup, ensuring equal separation between stations.

This suggests that emotional comfort may be influenced by subtle environmental cues, beyond the seat design itself, and highlights the need for further investigation using multimodal emotional assessments.

7.6 Limitations and Future Research

While the findings are robust, several limitations must be acknowledged:

- The study was conducted in a lab-based simulated environment without real driving dynamics.
- Emotional expression analysis was limited to facial features without multimodal affect detection.
- Sample size, though diverse, was limited to 26 participants,
- A wider variety of body types of participants are needed to fit the overall European body type as much as possible, and the experiment lacks low height and large weight participants and also high height and extra-large weight participants.

7.6.1 Future research

- Real-world vehicle testing with embedded sensors
- Adaptive seating systems that respond in real-time to fatigue or posture drift
- Analysis of In-chair movement based on detailed skeletal motion tracking data, to see the features like movement direction, angle, distance and acceleration, which can validate the connection between comfort/discomfort and human behavior.
- Cross-cultural differences in comfort perception and semantic material feedback

8. Conclusion

This study comprehensively evaluated long-duration seating comfort across three production automotive seats (Seat A, Seat B, Seat C) in a simulated 120-minute driving scenario. A multi-modal approach was applied, integrating subjective comfort ratings, local postural discomfort mapping, behavioral tracking via skeleton data, and predictive modeling. The findings provide valuable insights into how seat design influences comfort trajectories over time.

Seat C consistently achieved the highest comfort ratings and slowest discomfort progression, demonstrating superior long-term support. Seat A exhibited a marked discomfort increase after approximately 60 minutes, while Seat B showed the earliest and most pronounced discomfort onset at around 20 minutes. Local postural discomfort analysis highlighted the upper and lower back and buttocks as key discomfort regions. Modelling revealed that anthropometric characteristics, such as hip breadth, had notable but not always statistically significant effects on discomfort development.

The study acknowledges limitations, including a relatively homogeneous participant sample, a static driving scenario, reliance on manual visual measurement and recording for seat position and some anthropometric parameters. Nevertheless, the integrated methodology and findings offer an evidence-based foundation for future seat design improvements, with potential applications in enhancing user satisfaction, reducing fatigue, and informing adaptive comfort systems in both conventional and automated driving contexts.

Acknowledgements

My two-year Master's journey at TU Delft is now coming to an end. This period has been filled with challenges and growth, enabling me to develop both academically and personally. First and foremost, I would like to express my deepest gratitude to my supervisor and Chair, Dr. Wolf Song, for his invaluable guidance and generous support throughout this research. He introduced me to the fields of computational comfort and ergonomics, inspiring me with his rigorous academic attitude, logical thinking, and unique insights into interdisciplinary research methods. I am especially grateful for his trust in allowing me to take full responsibility for conducting the entire experiment. This trust not only provided me with the opportunity to gain hands-on experience in conducting cutting-edge scientific experiments but also honed my data analysis skills and my ability to work with scientific rigor.

I would also like to sincerely thank my mentor Aernout Kruithof for his patient guidance and insightful feedback throughout the process. His advice on data analysis and writing has been instrumental in enhancing the quality and clarity of my thesis.

My heartfelt thanks go to my friends at TU Delft for their constant encouragement, support, and shared moments that made my journey memorable. I am especially indebted to my good friend and research assistant, Sabhareesh, whose contributions to experimental setup, execution, and data collection were critical to the successful completion of the study.

I am particularly grateful to Sophie, whose care, understanding, and encouragement gave me the strength to overcome the most challenging phases of this work.

Lastly, I wish to thank the collaborating company for their support in providing experimental conditions, equipment, and data resources, which ensured the rigorous and high-quality execution of this study.

Above all, I am deeply thankful to my parents for their unconditional love, support, and faith in me throughout my life. Their encouragement and sacrifices have been the foundation of my achievements, and this work would not have been possible without them.

9. References

Albert, J. A., Owolabi, V., Gebel, A., Brahms, C. M., Granacher, U., & Arnrich, B. (2020). Evaluation of the pose tracking performance of the Azure Kinect and Kinect v2 for gait analysis in comparison with a gold standard: A pilot study. Sensors, 20(18), 5104. https://doi.org/10.3390/s20185104

Anjani, S., Kühne, M., Naddeo, A., Frohriep, S., Mansfield, N., Song, Y., & Vink, P. (2020). PCQ: Preferred Comfort Questionnaires for product design. WORK, 68(s1), S19–S28. https://doi.org/10.3233/WOR-208002 (Original work published 2021)

Arbogast, K. B., Loeb, H., Cross, S., Davydov, J., Mascarenhas, K., Koppel, S., & Charlton, J. (2013). Use of Kinect™ for naturalistic observation of occupants in vehicles. Annals of Advances in Automotive Medicine. Association for the Advancement of Automotive Medicine. Annual Scientific Conference, 57, 343–344.

ASHRAE. (2023). Standard 55 – Thermal environmental conditions for human occupancy. https://www.ashrae.org/technical-resources/bookstore/standard-55-thermal-environmental-conditions-for-human-occupancy

Bradley, J. V. (1958). Complete counterbalancing of immediate sequential effects in a Latin square design. Journal of the American Statistical Association, 53(282), 525–528. https://doi.org/10.1080/01621459.1958.10501456

DE LOOZE, M. P., KUIJT-EVERS, L. F. M., & VAN DIEËN, J. (2003). Sitting comfort and discomfort and the relationships with objective measures. Ergonomics, 46(10), 985–997. https://doi.org/10.1080/0014013031000121977

DINED. (n.d.). Anthropometric database. Delft University of Technology. https://www.dined.io.tudelft.nl

Fenety, P. A., Putnam, C., & Walker, J. M. (2000). In-chair movement: Validity, reliability and implications for measuring sitting discomfort. Applied Ergonomics, 31(4), 383–393. https://doi.org/10.1016/S0003-6870(00)00003-X

Grinten, M. P. van der, & Smitt, P. (1992). Development of a practical method for measuring body part discomfort. In S. Kumar (Ed.), Advances in Industrial Ergonomics and Safety IV (pp. 311–318). Taylor & Francis.

Helander, M. G., & Zhang, L. (1997). Field studies of comfort and discomfort in sitting. Ergonomics, 40(9), 895–915. https://doi.org/10.1080/001401397187739

Hiemstra-van Mastrigt, S., Groenesteijn, L., Vink, P., & Kuijt-Evers, L. F. M. (2016). Predicting passenger seat comfort and discomfort on the basis of human, context and seat characteristics: a literature review. Ergonomics, 60(7), 889–911. https://doi.org/10.1080/00140139.2016.1233356

Lantoine, P., Lecocq, M., Bougard, C., Dousset, E., Marqueste, T., Bourdin, C., ... & Mesure, S. (2021). Car seat impact on driver's sitting behavior and perceived discomfort during prolonged real driving on varied road types. PLOS ONE, 16(11), e0259934.

Lecocq, M., Lantoine, P., Bougard, C., Allègre, J. M., Bauvineau, L., González, D., Bourdin, C., Marqueste, T., & Dousset, E. (2022). Perceived discomfort and neuromuscular fatigue during long-duration real driving with different car seats. PLOS ONE, 17(12), e0278131. https://doi.org/10.1371/journal.pone.0278131

Lee, S., Kim, M., Jung, H., Kwon, D., Choi, S., & You, H. (2020). Effects of a motion seat system on driver's passive task-related fatigue: An on-road driving study. Sensors, 20(9), 2688. https://doi.org/10.3390/s20092688

McNaught, C., & Lam, P. (2010). Using Wordle as a supplementary research tool. The Qualitative Report, 15(3), 630–643.

Microsoft. (2019). Skeletal tracking on Azure Kinect. https://www.microsoft.com/en-us/research/project/skeletal-tracking-on-azure-kinect/

Moes, N. C. (2007). Variation in sitting pressure distribution and location of the points of maximum pressure with rotation of the pelvis, gender and body characteristics. Ergonomics, 50(4), 536–561.

Nuttall, F. Q. (2015). Body mass index: Obesity, BMI, and health: A critical review. Nutrition Today, 50(3), 117–128. https://doi.org/10.1097/NT.0000000000000092

Paul, G., Daniell, N., & Fraysse, F. (2012). Patterns of correlation between vehicle occupant seat pressure and anthropometry. Work, 41(S1), 2226–2231.

Sammonds, G. M., Fray, M., & Mansfield, N. J. (2017). Effect of long-term driving on driver discomfort and its relationship with seat fidgets and movements (SFMs). Applied Ergonomics, 58, 119–127. https://doi.org/10.1016/j.apergo.2016.05.009

Vergara, M., & Page, Á. (2002). Relationship between comfort and back posture and mobility in sitting-posture. Applied Ergonomics, 33(1), 1–8. https://doi.org/10.1016/S0003-6870(01)00056-4

Vink, P., & Hallbeck, S. (2012). Editorial: comfort and discomfort studies demonstrate the need for a new model. *Applied ergonomics*, *43*(2), 271–276. https://doi.org/10.1016/j.apergo.2011.06.001

Wegner, M. B. (2020). Seat comfort objectification: A new approach to objectify the seat comfort [Doctoral dissertation, Delft University of Technology]. https://doi.org/10.4233/uuid:b772802d-b738-4312-8903-9eedfab62e6e

World Health Organization. (n.d.). Body mass index (BMI). https://www.who.int/data/gho/data/themes/topics/topic-details/GHO/body-mass-index

Appendix A: Questionnaires

Appendix A1: Pre-Questionnaire

Pre-Questionnaire

1. Participant No. :_________________________

2. Sex
   - O Male
   - O Female
   - O Prefer not to say

3. Your year of birth (YYYY) :_________________________

4. Dominant hand:
   - O Left
   - O Right

4. Ethnicity

Select all geographic areas from which your ancestors first originated.

   - O Western Europe (e.g., Greece, Sweden, United Kingdom)
   - O Eastern Europe (e.g., Hungary, Poland, Russia)
   - O North Africa (e.g., Egypt, Morocco, Sudan)
   - O Sub-Saharan Africa (e.g., Kenya, Nigeria, South Africa)
   - O West Asia/Middle East (e.g., Iran, Israel, Saudi Arabia)
   - O South and Southeast Asia (e.g., India, Indonesia, Singapore)
   - O East and Central Asia (e.g., China, Japan, Uzbekistan)
   - O Pacific/Oceania (e.g., Australia, Fiji, Papua New Guinea)
   - O North America (Canada, United States)
   - O Central America and Caribbean (e.g., Jamaica, Mexico, Panama)
   - O South America (e.g., Brazil, Chile, Colombia)
   - O Others: _________________________

5. Do you have a driving license?
   - O Yes
   - O No

Appendix A2: In-experiment Questionnaire

In experiment Questionnaire

Please mark your selected choice

To be filled in by facilitator
Participant No. :_______________
Date :_______________
Time :_______________

Time period 0 20 40 60 80 100 120

Comfort Rating

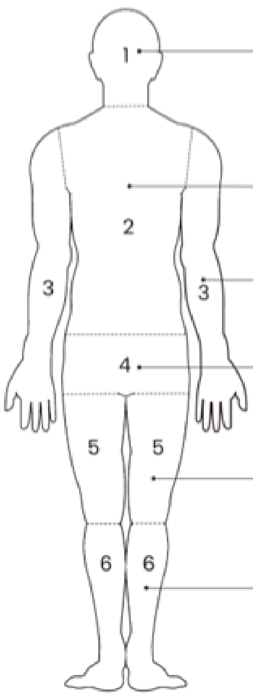
Comfort is a pleasant state or a relaxed feeling of a human being in reaction to its environment.

1. What is the **comfort** rating of this setup?

(0)—(1)—(2)—(3)—(4)—(5)—(6)—(7)—(8)—(9)—(10)

No comfort … Extreme comfort

2. How do you feel about the **thermal** environment?



	Hot	Warm	Slightly warm	Neutral	Slightly cool	Cool	Cold
Overall feeling	○	○	○	○	○	○	○
Head	○	○	○	○	○	○	○
Upper body	○	○	○	○	○	○	○
Arms	○	○	○	○	○	○	○
Buttocks	○	○	○	○	○	○	○
Thighs	○	○	○	○	○	○	○
Legs	○	○	○	○	○	○	○

Feeling

3. Fatigue (0)—(1)—(2)—(3)—(4)—(5)—(6)—(7)—(8)—(9)—(10)

Not at all ... Extremely

4. Stress (0)—(1)—(2)—(3)—(4)—(5)—(6)—(7)—(8)—(9)—(10)

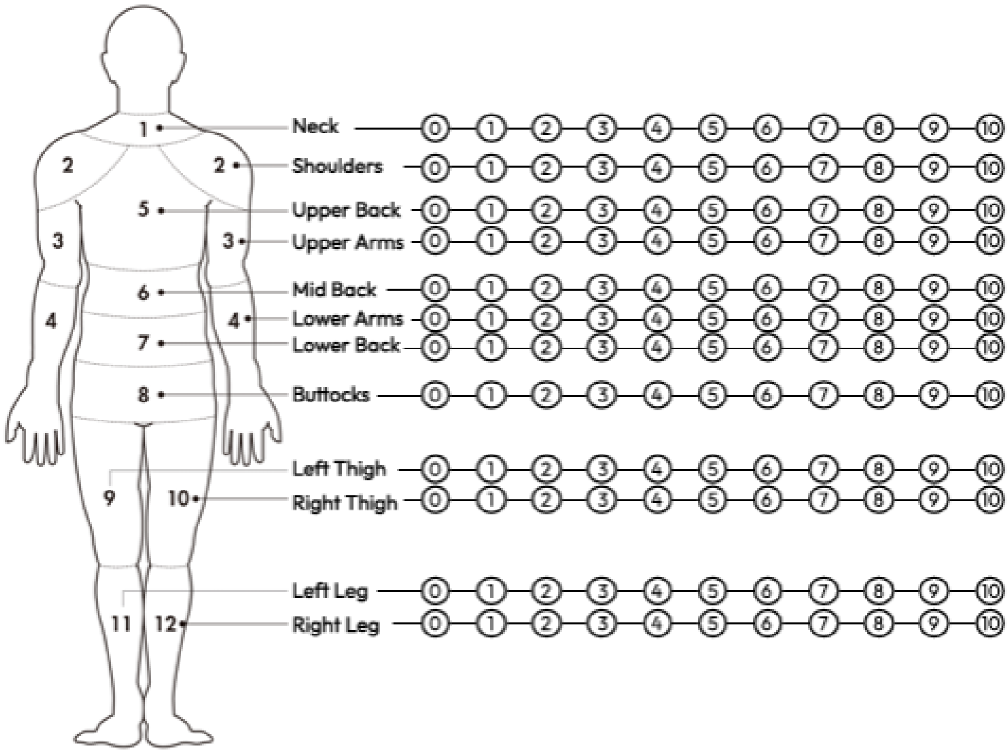
Not at all ... Extremely

Discomfort

Discomfort is an unpleasant state of the human body in reaction to its physical environment.

5. Local postural discomfort

Please rate the **discomfort** in these body parts!



6. Please rate your overall discomfort sitting in this seat?

(0)—(1)—(2)—(3)—(4)—(5)—(6)—(7)—(8)—(9)—(10)

No discomfort ... Extreme discomfort

Appendix A3: Tactile Questionnaire

Tactile Questionnaire

Participant No. :________________
Date :________________

The objective of this evaluation is to compare the tactile attributes of three car seats. By filling this questionnaire, you will provide valuable insights that can evaluate these 3 seats and also guide the development of ergonomic and comfortable car seats. **(Duration: 15 minutes)**

Position 1: Seat cushion

PART ONE

1. Soft & Hard: Describes how soft or rigid the seat cushion feels when sitting down.

		-3	-2	-1	0	1	2	3	
Seat 1	Soft The cushion feels plush, with a sinking-in sensation.	○	○	○	○	○	○	○	Hard Hard: The cushion feels solid, with little give or deformation.
Seat 2		○	○	○	○	○	○	○	
Seat 3		○	○	○	○	○	○	○	

2. Stiff & Elastic: Refers to how the cushion responds to pressure and movement.

		-3	-2	-1	0	1	2	3	
Seat 1	Stiff The material feels rigid and resists compression.	○	○	○	○	○	○	○	Elastic The cushion bounces back and feels springy or responsive.
Seat 2		○	○	○	○	○	○	○	
Seat 3		○	○	○	○	○	○	○	

3. Loose & Firm: Describes how secure or tight the seat cushion feels.

		-3	-2	-1	0	1	2	3	
Seat 1	Loose The cushion may feel saggy, unstable, or lacking structure.	○	○	○	○	○	○	○	Firm The cushion feels compact, with stable and even support.
Seat 2		○	○	○	○	○	○	○	
Seat 3		○	○	○	○	○	○	○	

4. Supporting & Unstable: Reflects whether the seat provides adequate support during sitting.

		-3	-2	-1	0	1	2	3	
Seat 1	Supporting The seat feels stable and holds the body in place.	○	○	○	○	○	○	○	Unstable The seat may feel wobbly or shift under your weight.
Seat 2		○	○	○	○	○	○	○	
Seat 3		○	○	○	○	○	○	○	

PART ONE

5. Sportive & Lame: Related to the seat's feedback and suitability for active or precise control.

	-3	-2	-1	0	1	2	3	
Seat 1	○	○	○	○	○	○	○	
Seat 2	○	○	○	○	○	○	○	
Seat 3	○	○	○	○	○	○	○	

Sportive — The cushion feels dynamic, tight, and responsive—like a sport seat.

Lame — The cushion feels weak, unresponsive, or overly soft.

6. Close & Wide: Describes the degree of contact and fit between the seat and the body.

	-3	-2	-1	0	1	2	3
Seat 1	○	○	○	○	○	○	○
Seat 2	○	○	○	○	○	○	○
Seat 3	○	○	○	○	○	○	○

Close — The seat feels snug and wraps around the body.

Wide — The seat feels spacious, with less contact or containment.

7. Formative & Loose: Reflects whether the cushion maintains shape and supports body contours.

	-3	-2	-1	0	1	2	3
Seat 1	○	○	○	○	○	○	○
Seat 2	○	○	○	○	○	○	○
Seat 3	○	○	○	○	○	○	○

Formative — The seat has a defined structure and supports posture well.

Loose — The seat feels shapeless or collapsible.

8. Slippery & Coarse: Describes the surface texture of the cushion.

	-3	-2	-1	0	1	2	3
Seat 1	○	○	○	○	○	○	○
Seat 2	○	○	○	○	○	○	○
Seat 3	○	○	○	○	○	○	○

Slippery — The material feels smooth, slick, and low-friction.

Coarse — The texture is rougher, with more grip or friction.

Position 2: Back rest

PART TWO

1. Soft & Hard: Describes how soft or rigid the seat cushion feels when sitting down.

	Soft The cushion feels plush, with a sinking-in sensation.	-3	-2	-1	0	1	2	3	Hard Hard: The cushion feels solid, with little give or deformation.
Seat 1		○	○	○	○	○	○	○	
Seat 2		○	○	○	○	○	○	○	
Seat 3		○	○	○	○	○	○	○	

2. Stiff & Elastic: Refers to how the cushion responds to pressure and movement.

	Stiff The material feels rigid and resists compression.	-3	-2	-1	0	1	2	3	Elastic The cushion bounces back and feels springy or responsive.
Seat 1		○	○	○	○	○	○	○	
Seat 2		○	○	○	○	○	○	○	
Seat 3		○	○	○	○	○	○	○	

3. Loose & Firm: Describes how secure or tight the seat cushion feels.

	Loose The cushion may feel saggy, unstable, or lacking structure.	-3	-2	-1	0	1	2	3	Firm The cushion feels compact, with stable and even support.
Seat 1		○	○	○	○	○	○	○	
Seat 2		○	○	○	○	○	○	○	
Seat 3		○	○	○	○	○	○	○	

4. Supporting & Unstable: Reflects whether the seat provides adequate support during sitting.

	Supporting The seat feels stable and holds the body in place.	-3	-2	-1	0	1	2	3	Unstable The seat may feel wobbly or shift under your weight.
Seat 1		○	○	○	○	○	○	○	
Seat 2		○	○	○	○	○	○	○	
Seat 3		○	○	○	○	○	○	○	

PART TWO

5. Sportive & Lame: Related to the seat's feedback and suitability for active or precise control.

		-3	-2	-1	0	1	2	3	
Seat 1	**Sportive** The cushion feels dynamic, tight, and responsive—like a sport seat.	○	○	○	○	○	○	○	**Lame** The cushion feels weak, unresponsive, or overly soft.
Seat 2		○	○	○	○	○	○	○	
Seat 3		○	○	○	○	○	○	○	

6. Close & Wide: Describes the degree of contact and fit between the seat and the body.

		-3	-2	-1	0	1	2	3	
Seat 1	**Close** The seat feels snug and wraps around the body.	○	○	○	○	○	○	○	**Wide** The seat feels spacious, with less contact or containment.
Seat 2		○	○	○	○	○	○	○	
Seat 3		○	○	○	○	○	○	○	

7. Formative & Loose: Reflects whether the cushion maintains shape and supports body contours.

		-3	-2	-1	0	1	2	3	
Seat 1	**Formative** The seat has a defined structure and supports posture well.	○	○	○	○	○	○	○	**Loose** The seat feels shapeless or collapsible.
Seat 2		○	○	○	○	○	○	○	
Seat 3		○	○	○	○	○	○	○	

8. Slippery & Coarse: Describes the surface texture of the cushion.

		-3	-2	-1	0	1	2	3	
Seat 1	**Slippery** The material feels smooth, slick, and low-friction.	○	○	○	○	○	○	○	**Coarse** The texture is rougher, with more grip or friction.
Seat 2		○	○	○	○	○	○	○	
Seat 3		○	○	○	○	○	○	○	

Appendix A4: Seat Position Recording

Seat Position Recording

Participant No.:__________________________

A	0	10	20	30	40	50	60	70	80	90	100	110	120
X(mm)													
Y(mm)													
H(mm)													
Angle													

B	0	10	20	30	40	50	60	70	80	90	100	110	120
X(mm)													
Y(mm)													
H(mm)													
Angle													

C	0	10	20	30	40	50	60	70	80	90	100	110	120
X(mm)													
Y(mm)													
H(mm)													
Angle													

Appendix H: Project Brief

DESIGN FOR our future

TU Delft

Personal Project Brief – IDE Master Graduation Project

Name student | **Student number**

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT
Complete all fields, keep information clear, specific and concise

Project title A Comparative Evaluation of Seating Comfort for Future Automotive Seat Design

Please state the title of your graduation project (above). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

Introduction

Describe the context of your project here; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

Seating comfort plays a critical role in driver and passenger satisfaction, influencing physical well-being, fatigue levels, and o verall user experience. In automotive seat design, comfort of driver is essential, especially as vehicles transition towards high er levels of automation, where users may adopt more relaxed and variable postures over extended periods. While traditiona l assessments primarily rely on subjective feedback, recent advancements in motion tracking, physiological monitoring, and biomechanical modeling provide new opportunities for objective and data-driven evaluations of seating comfort.

➔ space available for images / figures on next page

58

introduction (continued): space for images

image / figure 1

image / figure 2

DESIGN FOR our future

TU Delft

Personal Project Brief – IDE Master Graduation Project

Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice.
(max 200 words)

This project addresses the need for a systematic, evidence-based approach to evaluating automotive seating comfort by integrating subjective perceptions with objective ergonomic metrics. Through a comparative analysis of multiple seat configurations, this research seeks to uncover relationships between comfort perception and postural adjustments over time. The findings will contribute to data-driven design recommendations, helping to enhance seating ergonomics, reduce discomfort, and support long-term usability in future automotive seats. Key Focus Areas of the Project are 1) Developing a repeatable framework for evaluating seating comfort that combines self-reported comfort ratings, biomechanical data, and motion tracking to create a holistic assessment method tailored for automotive seating. 2) Leveraging skeleton tracking and movement analysis to examine the relationship between fidgeting, postural shifts, and perceived comfort over extended durations. This approach will help identify discomfort-driven movements and their correlation with specific seat design features. and 3) Providing actionable insights for automotive seat designers, translating empirical findings into ergonomic recommendations that improve seating comfort, support, and adaptability for drivers and passengers.

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project. (1 sentence)
As you graduate as an industrial design engineer, your assignment will start with a verb (Design/Investigate/Validate/Create), and you may use the green text format:

Develop a repeatable, reliable evaluation procedure for automotive seating comfort, combining subjective feedback with objective ergonomic data to enhance customer experience and guide product improvements.

Then explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words)

This project follows a structured, research-driven methodology to develop and validate a systematic automotive seating comfort evaluation framework:

1. Review existing methods in comfort assessment, ergonomics, and industry standards.
2. Design experimental setups for structured, repeatable evaluations.
3. Collect and analyze data to identify patterns in comfort perception and postural behavior.
4. Validate the framework in a controlled research environment for reliability and applicability.
5. Deliver a transferable methodology for future automotive seat design improvements.

Project planning and key moments

To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include a ***kick-off meeting, mid-term evaluation meeting, green light meeting*** *and* ***graduation ceremony****. Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities).*

Make sure to attach the full plan to this project brief.
The four key moment dates must be filled in below

Kick off meeting	18/02/2025
Mid-term evaluation	15/04/2025
Green light meeting	10/06/2025
Graduation ceremony	07/07/2025

In exceptional cases (part of) the Graduation Project may need to be scheduled part-time. Indicate here if such applies to your project

Part of project scheduled part-time	
For how many project weeks	
Number of project days per week	

Comments:

Motivation and personal ambitions

Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

Optionally, describe whether you have some personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology. Personal learning ambitions are limited to a maximum number of five.
(200 words max)

This project aligns with my academic and professional aspirations to contribute to user-centered design practices through re search-driven insights. My primary motivation is to advance knowledge in ergonomic evaluation methodologies, a critical are a within industrial design engineering.

Through this project, I aim to:
1. Strengthen my expertise in user research and ergonomic analysis.
2. Gain practical experience in designing and implementing comfort assessment protocols.
3. Develop skills in statistical analysis and qualitative research.
4. Explore innovative approaches to seating design and user experience.
5. Contribute to the development of tools and frameworks that enhance design processes.

By engaging with this project, I aim to bridge the gap between academic research and practical application, ensuring that the outcomes are both scientifically rigorous and industry-relevant.

Appendix I: Poster for Recruitment