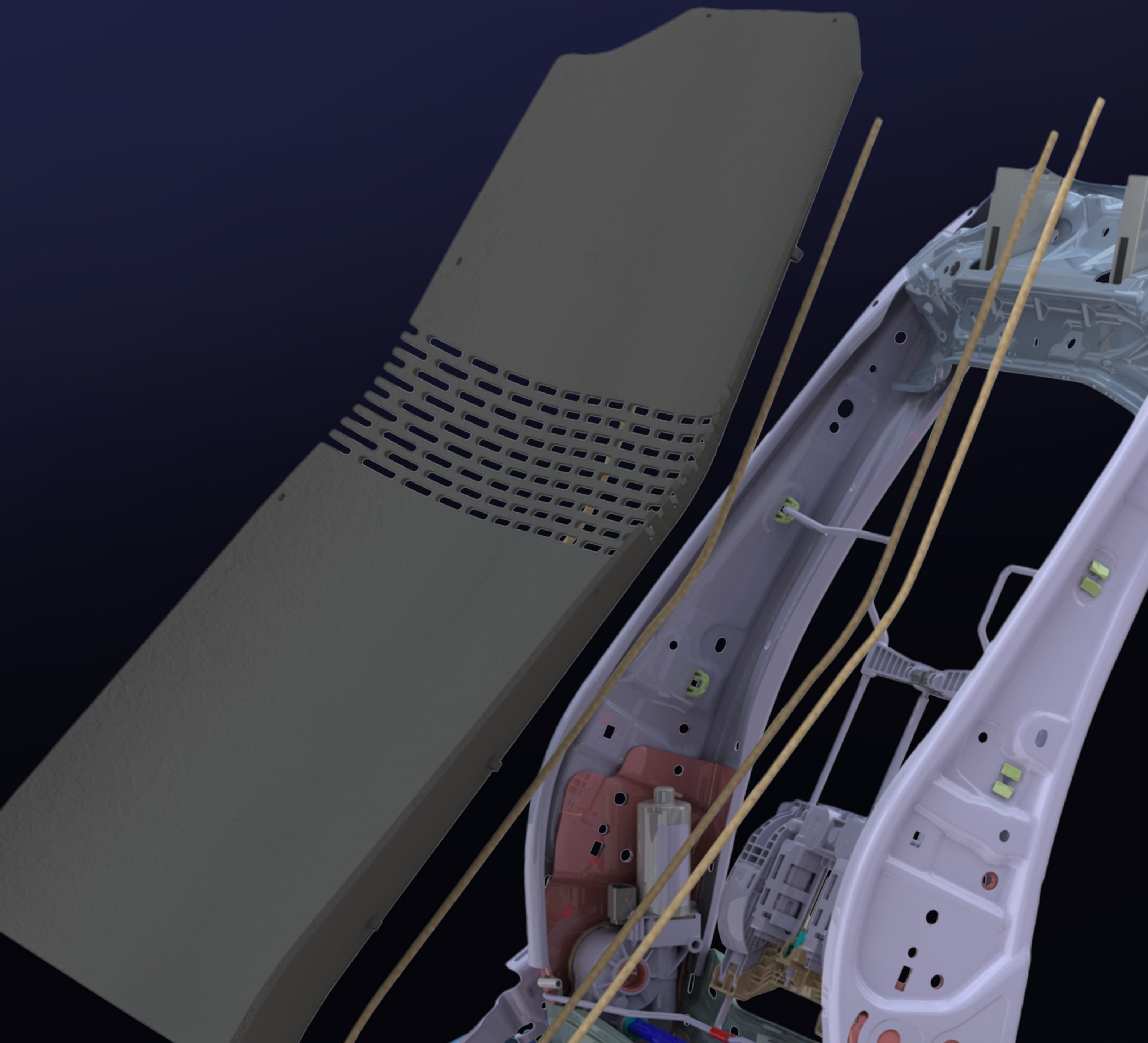
A CONCEPTUAL DESIGN FOR A RECLINING CAR SEAT BASED ON SPINAL CURVATURE

Creating a prototype to validate the working principle of a reclining car seat for p5 to p95 car seat users



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PREFACE

When I was younger, I was always amazed by inventors. I love to create things, from drawings to jeans to woodworking. In high school, hearing about the study industrial design engineering, I was sold. In my bachelor's at the University of Twente I learned the basics in product design and engineering. I was doubting to do a masters, because I wanted to create things. Then I came across the master Integrated Product Design at the TU Delft. Here, I had the option to learn more prototyping something that always piqued my interest. After 1,5 years of studying, I wanted to shift a bit more towards mechanical engineering, while still staying in the field of industrial design. Being able to do my master thesis at a company as Brose, gave me the opportunity to learn and see more about mechanical engineering in practice. Where I started with no clue what I wanted to do with my degree, I now know better what different jobs in the industry are appealing to me. I look back as this project, as something with a steep learning curve in the beginning and a more calm ending of the project were I could just create. All in all, I am happy with the results. Graduating is a journey that takes a village of people and is not done alone, I am deeply grateful to everyone who has been a part of this adventure.

Wolf Thank you for always making time to explain how to do proper research and analysing the data. You've taught me how good research is done and how to use different software such as Rhino.

Peter Thank you for your tremendous help and being a beacon of knowledge during this and earlier projects. Your enthusiasm is contagious an always give me energy to keep going forward and trying new things.

Jochen and Christian Thank you for your guidance during this graduation project. With your knowledge in the automotive industry I learned so much in such a short time.

Stefan Thank you for helping me create the things that I had in my mind. I hope to one day find a job that is as interesting as yours.

Bertus Thank you for helping me with the research study set-up and adjusting the kyphosis meter.

My parents Thank you for always believing in me, even if I am not sure of it myself yet. Thank you for always supporting and encouraging me to do things I couldn't foresee was possible.

Babet, Sasja and Karin Thank you for listening, giving your opinion and just being there. I could always rely on you. Not only for this project, but also getting adjusted in Germany.

ABSTRACT

The automotive industry is looking at improving their new cars in different ways. Comfortability is a hot topic since it is dependent on so many aspects. The entire interior of the car influences how comfortable the end user is. Furthermore, autonomous vehicles are rising. That means that people have a lot of time to do other things while commuting, an activity that sticks out is relaxing and sleeping. The reclining of a car seat usually is arranged in one joint between the seat pan and the backrest. That means that the entire backrest is straight. However, the spine moves differently. This research shows that especially in a laying position the spine is quite rounded. To be able to support the body and optimize comfort, it would be ideal to have the seat follow this movement of the human body. After the research, ideation and conceptualization were performed. From this, a final concept direction was chosen and improved on the hand of anthropometric design. In the end, a simplified working prototype was constructed. The evaluation test was perceived as relatively good but also showed improvement points, as stated in the final recommendations. To conclude, the principle of creating a more rounded backrest works, and the prototype scored slightly lower on comfortability than the original seat. The concept has the potential to improve the comfortability of car seating.

CONTENT

INTRODUCTION

01

1.1 Project introduction

The reclining of a car seat usually is arranged in one joint between the seat pan and the back rest. That means that the entire backrest is straight. However, when reclining, the spine has a lordose sitting upright, which changes into a kyphose while reclining, see figure 1 for the differences. To optimize comfort, it would be ideal to have the seat follow this movement of the human body. The focus of this graduation project will be to optimize a reclining car seat. The project will be conducted at Brose, an automotive supplier, and TU Delft. The project starts at TU Delft with an ergonomic research in which the back rest curve is recorded in different back rest angles. It will continue at Brose with the actual conceptualizing of a seat based on the recorded data. Since Brose is already a leading company in the industry, this project will be one of many. With the idea of making a new reclining mechanism, I could help with a starting point for future innovation. A big opportunity for me is that Brose is already a leading company and has the resources to do these projects. Limitations I foresee are that I might not have enough technical skills. Other limitations can be the language; I don´t speak very well German, so I hope most contact will go in English. Lastly, I want a lot of things in short amount of time. This requires a high work pace, but also a good planning.

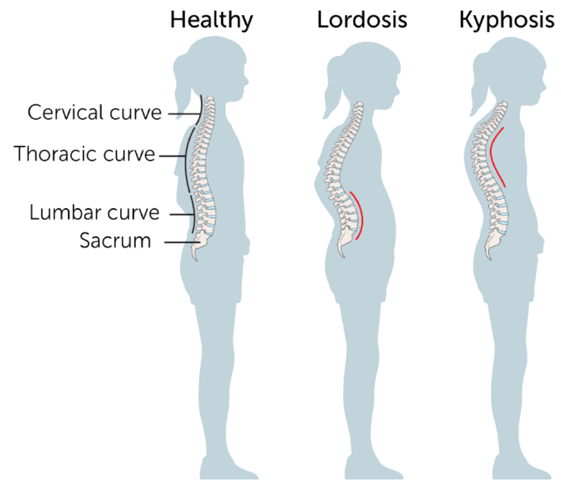


Figure 1: Kyphosis and lordosis (Smulders et al., 2020)

1.2 Problem definition

I want to create a working principle for a reclining car seat that follows the curvature of the spine in different back rest angles. Therefore I first need to understand how the curvature of the spine actually moves. The working principle should be created with a minimum of material to reduce weight and with a minimum of mechanisms to maintain durability, while also taking into account car safety regulations. This means that the problem is challenging and this project would probably deliver a first version or part of a first version of a mechanism. For the full graduation brief, see appendix 1.

1.3 The client

The project is conducted at Brose, one of the five largest family-owned automotive suppliers. Worldwide, each third new car is equipped with at least one Brose product. Brose has 69 locations in 24 countries with around 32,000 employees. (Brose Fahrzeugteile SE & Co. KG, n.d.) Brose sells their ideas and concepts to car companies. They focus on interior, such as doors, frames of seats and electric motors and drives. I have been working in the office in Bamberg (figure 2) in the Innovationslab. The seat development department is in Coburg.

Figure 2: Brose office in Bamberg

1.4 Planning

The planning consists in total of 25 weeks. In which the first 3 weeks I start parttime with a research study at the TU Delft. The period between January and June has a lot of holidays and also incorporating that I had to move from Delft to Bamberg, I included 2 more weeks to my planning, see figure 3.

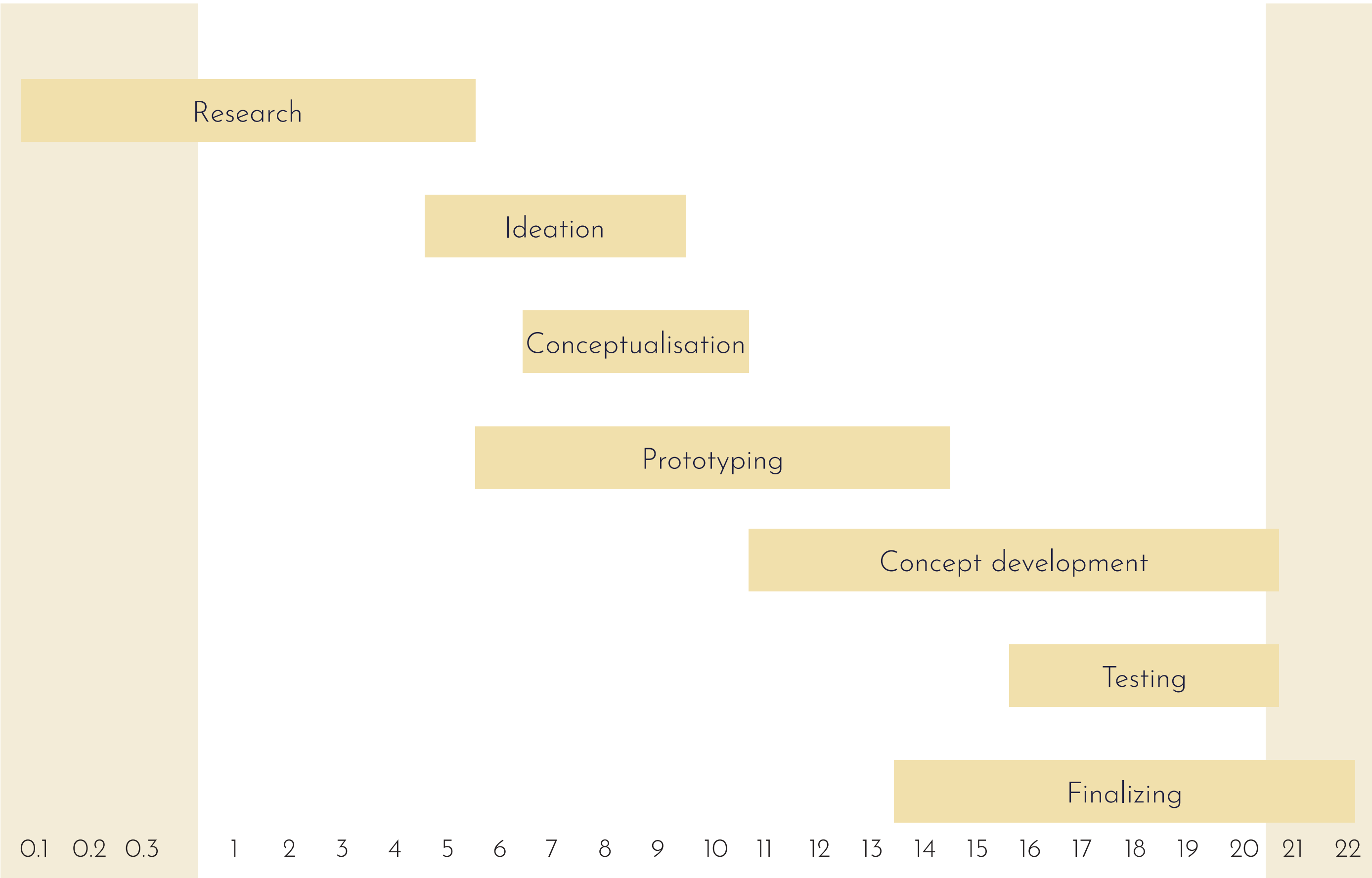


Figure 3: Planning

LITERATURE ANALYSIS 02

2.1 Literature research

Comfort vs discomfort

Comfort and discomfort are two different entities. Zhang et al. (1996) and Helander et al. (1997) showed with the use of questionnaires that discomfort was found related to physical characteristics of the environment. In the absence of discomfort, it not automatically was experienced as comfort.
Comfort is subjective; there is not one thing that fits all. However, there are certain options to find out what can be seen as comfort and discomfort. Comfort is related to luxury, relaxation, or the sense of being refreshed, see table 1.

Table 1: Factors influencing (dis)comfort (Zhang et al., 1996)

Discomfort	Comfort
Fatigue	Luxury
Pain	Safe
Posture	Refreshment
Stiffness	Well-being
Heavy legs	relaxation

Designing for comfort

To be able to design for comfort, there are 4 areas that are important. These are the journey, passenger, environment and seat, see figure 4 (Jenkins and Rutter, 2019).
With the use of this model, the journey, passenger and seat will be discussed. The environment is something outside of the scope of this thesis.

Figure 4: perceived seat comfort (Jenkins and Rutter, 2019)

Context, experience and expectations

The first step in designing a car seat is to study the context and activities. This includes the journey, touch points, the positions of the different body parts, and the possibility to move and vary in body posture (Vink, 2023). The journey already starts before sitting in the car. How you experience things right now, depends on expectation and previous experiences. Van Veen and Vink (2016), asked half of the participants to sit on a luxury fauteuil and then on the test chair. A day later, they first had to sit on a hard stool and then on the test chair. The other half of the participants started on the hard stool and sat on the luxury fauteuil a day later. Sitting on a hard stool makes the test seat feel softer. Thus, precondition can influence sensation. Furthermore, our first impression influences comfort and the influence of design should not be underestimated. De Looze et al. (2003) showed that 49 experienced office workers evaluated one out of four office chairs negatively based on visual information.

The context will also influence the final design; an airplane seat, train seat, or desk chair differs quite a lot from a car seat (Hiemstra-van Mastrigt, 2015). For instance, in an airplane or train you can walk in between the ride, this is not possible with car seats. Train seat pans are smaller than car seat pans, since in- and egress is faster when there is more room to stand up. This is important since a train stops often, people should be able to get in and outside the train fast. In the same line of thought, a long-haul train has bigger seat pans. For a car seat, the roofline is also important. The lower the roof is, the lower the seat pan is positioned; and the backrest must recline more.

The angle of the backrest is also influenced by the context; watching something above eye level; a more reclined backrest is preferred (Rosmalen et al., 2009). However, if the viewing angle is more downward, as for truck drivers, the backrest should be more upright.

It is possible to look downward, but it's not most comfortable. Since the preferred posture of the different joints is close to the neutral position.
Other things to consider are the users' activities. One of them is the usage of tablets or smartphones during traveling. The neck flexion while using a tablet is far from neutral, leading to discomfort (Vink, 2023).

Posture and movement
The body's optimal position in terms of comfort requires every joint and eye position to be close to the neutral position (Delleman, 1999). However, after a while of being seated movement is preferred. A significant influence on comfort was associated with adopting and changing postures (Kremser et al., 2012). It can prevent discomfort over time. Therefore, a static posture should be avoided.
Hiemstra-van Mastrigt et al. (2016) and Sammonds et al. (2017) demonstrate that walking through the airplane or walking after one hour of driving has a significant effect on feeling refreshed.
It can even have positive effects. Van Deursen et al. (2000) and Franz et al. (2011) showed that passive movement has positive effects on preventing discomfort while seated. Other studies show the importance of actively alternating seated postures (e.g. Lueder 2004; Nordin 2004). Providing legroom is important to enable the passenger to change posture to prevent discomfort (Vink, 2016).

Upright sitting vs laying
Since a key aspect seated sleeping is accommodating a lot of different postures, Hiemstra-van Mastrigt et al. (2019) introduced spacing for shoulders in aircraft seats, figure 7. In this way, the user can sleep sideways in an almost upright position. Since it is created for aircrafts, this seat can only recline a little bit.

Seated sleeping
Multiple studies show that the ideal sleeping angle is 180 degrees, a flat bed. These are in business class seats, sleeping trains and some busses. However, for cars the space is limited, therefore it is not possible to create a fully flat bed and the sleeping must be done seated. In a study (Vledder et al., 2024) the sleep comfort was tested in different backrest angles. As expected, 180 degrees gives the best sleep comfort. However 140 degrees scores higher than 150 degrees, not only on sleep comfort but also comfort see figure 5 and 6.
One of the reasons why upright sitting isn't favourable is because of difficulties to maintain the head in a comfortable position for sleeping (Roach et al., 2018). Therefore, a good headrest is preferred.
In case of sleeping, privacy is also important. In a sleeper train 'the feeling of people peeking through curtains from the hallway was very uncomfortable". This is in line with the findings of Heufke Kantelaar et al. (2022) that privacy is important in determining the passenger's comfort in sleeper trains. (Vledder et al., 2023). A car itself is already a closed environment and is often only shared with people the user knows. However, this individualisation can also be seen at companies such as Faurecia, that focusses on personalisation and immersive experiences. They have speakers integrated in the headrest; in that way it is really a personalised experience. Other passengers can't hear these sounds. They even have sensors that can 'see' how you feel; feeling stressed? The car automatically suggests spa or forest vibes. All to increase comfort.

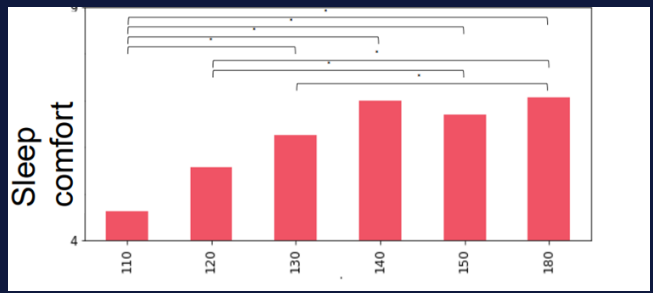


Figure 5: Sleep comfort tested with 16 participants.

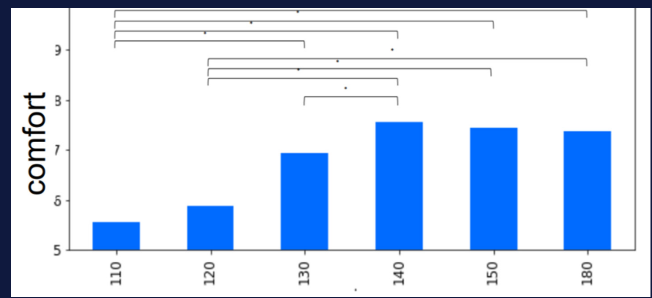


Figure 6: Overall comfort score after sleeping

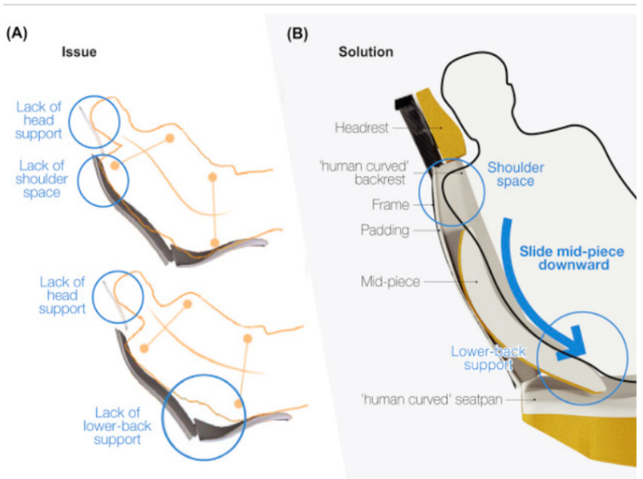


Figure 7: Concept from Hiemstra-van Mastrigt et al. (2019)

Safety
In a conversation with Jochen Hofmann (personal communications, February 8th, 2024) safety came up. A problem that occurs at an angle of 50 degrees is submarining. Submarining happens if the car has to brake very fast, therefore this is only a problem while driving and not when a user is sleeping while charging their car. It is the act of sliding downwards, as a consequence, the belt is not around the hips, but slightly above. If there is enough force in the accident, the belt will press on the organs and other soft tissue instead of the bone.
The impact at an angle of 50 degrees is a lot higher than at 25 degrees. There are already ideas to go against this submarining, such as quickly turning back the seat 10 degrees at the moment of impact, 40 degrees is still in the range of acceptable impact. Another option would be to transfer energy; the entire seat will slide back together to reduce the impact on the person. In that way, it is traveled over a longer distance. Lastly, if you lay at an angle of 50 degrees, the seat belt must be integrated into the chair. If the seat belt is connected to the B-pilar there would be too much impact on the shoulder.

Inside a car seat

Future perspective/autonomous driving

That autonomous driving will be accessible in the future, is no doubt. This will give people a lot more time. The way they use their time, has been investigated (Horváth & Partners et al., 2018). China and the USA are important target markets, due to the size of the market, long travel times, and high level of importance on private vehicles. A large demand for automated driving functions is expected. Therefore, 500 users from the USA, France, Germany, China and Japan were surveyed. In general, they expect residents of large cities, younger age groups up to 45 years old, and households with higher incomes to use autonomous driving vehicles. Sleeping and relaxing are of most interest to the participants, 46.6% of participants prefer sleeping and relaxing (figure 9 and 10) (Horváth & Partners et al., 2018). However, this is only one study, other studies give different percentages.

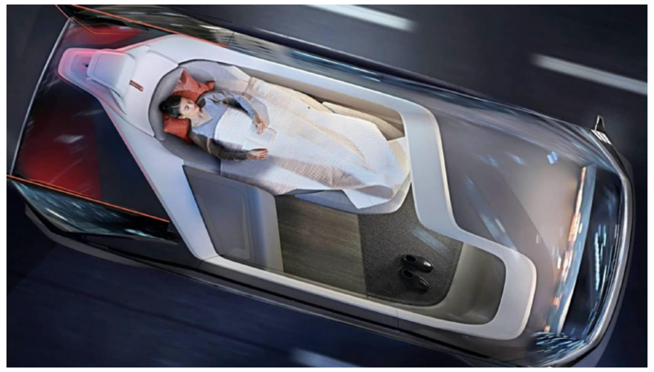


Figure 9: Sleeper car (Laging, 2019)

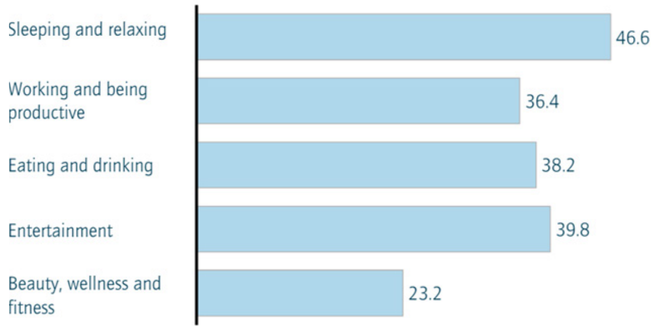


Figure 10: Acceptance values for different use types (Horváth & Partners et al., 2018)

Backrest support

In a study executed by Carcone and Keir (2007), lumbar supports of 3, 6, and 9 cm thickness were tested in an office word-processing task for 15 minutes. They tested 15 males and 15 females and kept track of the seat pan pressure, lumbar angle, and asked them to fill in a discomfort questionnaire. Individuals tend to adopt a 'passive' or slumped posture when seated for a prolonged duration, which may lead to low back pain. They found that the addition of supplementary backrest significantly reduced average backrest pressure, mean peak backrest pressure, and mean contact area on the backrest. In addition, a 3cm lumbar pad tested provided lumbar support and prevented flattening of the lumbar spine.

Participants preferred a lumbar pad of 3cm thick (smallest in the study) or supplementary backrest only regardless of anthropometrics, suggesting an optimal amount of lumbar support exists. Future studies under longer durations and different seating conditions are needed. (Carcone et al., 2007).
Backrest density plays an important role in lumbar load and comfort during seated work. Backrest density at 10 kg/m3 got the lowest contact pressure, peak contact pressure, and largest contact area. Backrests with low density can reduce lumbar pressure and increase the support contact area, which could raise comfort feeling. Backrest density at 10kg/m3 is better to maintain a balance between providing effective support and alleviating excess lordosis. (Huang et al., 2012)

Anthropometric design

Seat width

The European guideline NEN EN 1335 for office chairs states that the office chair seat width should be adjustable between 460-510 mm. In practice, this means the arm rests should be adjustable with a range of 50 mm in left right direction.

Seat pan length

For long-term sitting in a car seat, Zenk et al. (2012) and Zenk (2008) established that about 6% of total bodyweight should be carried by the part of the upper legs close to knees for a drive of more hours. An adjustable seat pan length can offer support under the thighs and behind the knees for multiple users (Vink, 2023).

Seat height

The seat height is dependent on the popliteal height. The seat height is based on P5, to prevent them from not being able to put their feet on the floor, often car seats can adjust the seating height. The roofline often determines the available vertical space for a person. Often that means that the seat is positioned lower and therefore a user needs more space in front of them to be able to stretch their legs. (Vink, 2023)

H-point

In seat design, many standards are related to the rotation point of the hip joint. This is called the H-point, which is the pivot point between the torso and upper leg of the body. The H-point is based on old, male P50 anthropometric data, Meaning that this can be quite different for females and males of other sizes, but they haven't been included in the data. The H-point is used in many international vehicle design standards. Sometimes it is also called SGRP, but this is not the same as the seat reference point. (Vink, 2023)

Seat Reference Point

The seat reference point, known as SRP, refers to the intersection point of the midplane of the seat, the backrest plane and the seat pan plane. Although it is derived from the seat geometry, it is associated as well with the occupant's sitting posture. So, it differs per person.
The SRP should coincident with the theoretical intersection point between the occupant midplane, the theoretical plane coincident with the occupant upper back and lower back and the theoretical plane coincident with the occupant buttock and hip. (Mobius, 2022).
As can be seen in figure 11, the H-point and SRP are not aligned.

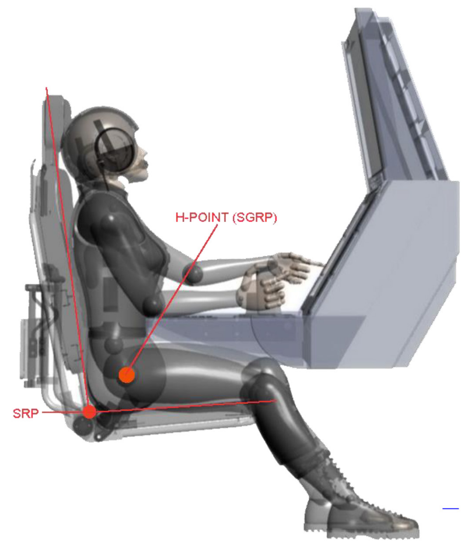


Figure 11: H-point vs SRP (Sun Group Design, n.d.)

2.2 Market research

To be able to design a new interesting relax seat, a look is taken at car brands that sell luxury cars and limousines. The entire interior is taken into account and includes interesting features.

One of them is Audi, which has two categories that are interesting for this project; business and limousines. Cars that they scale under the category of limousines are A3, A4, A6, A8, S3, S8 and RS3. Cars that they put in the category business are Q3, Q4, Q5, Q6, Q7, SQ6, SQ8, A3, A4, A5, A6 and A8.

Audi A6 limousine
Selling points according to their website (Audi, n.d.-a)

- Spacious legroom
- Quiet interior (even when driving fast)
- Massage function front seats
- Ambient lighting

Audi A8 (Audi, 2022)(figure 12)

- Cooling compartment with 2 glasses
- Espresso mobil; espressomaker
- Seat heating
- Memory function seat ergonomics (the keys store the seat configuration)
- Four direction lumbar support
- Cooled glove compartment

Mercedes Benz has a category called limousine. In this category EQE limousines, EQS limousines, A-class, C-class, E-class, S-class (Lang) and Mercedes-Maybach S-class are included.

S-Class (Mercedes Benz, n.d.-c)(figure 13)

- Cupholder with temperature regulation
- Wireless charging
- Folding table
- Cooling compartment

C-Class (Mercedes Benz, n.d.-a)

- Energizing programs such as vitality, freshness
- More leg space than ever before
- Wireless charging

Maybach (Mercedes Benz, n.d.-b)

- 4D surround sound system van Burmester
- Audiomassage by 8 speakers
- 3high-end surround speakers and subwoofer inside seats
- Massagefunction for calfs in rear seats
- Wireless charging
- Foldable footrest
- Silver champagne flutes
- Automatic seatbelt hander when entering the car

Figure 12: Audi A8 (Audi MediaCenter, 2022)

BMW has a category called sedan, which include the BMW i, X, M, 7, 5, 3 and PHEV.

BMW 7 SERIES SEDAN (figure 14)

- Entertainment Experience; 31,3 inch BMW Theatre Screen
- Glass panoramaroof Sky Lounge
- Comfortable relaxing position with extra leg space in the backseat
- Integrated touchscreens in the backdoors that control the Theatre screen, automatic airco and seat adjustments
- Digital car key (phone)

Lucid Air (Lucid Motors, n.d.) (figure 15)

- A lot of legroom
- Heated steering wheel
- Massage seats
- Sunscreen in rearwindow to keep heat out and to create a nice ambience

Genesis G90 (GENESIS, n.d.)

- UV-C storage; kills 99,99% of bacteria
- Ten adjustable cushions and inbuilt massage function
- Mood-enhancing environments that include sound, massage, ambience and fragrance
- Scent-diffusing system
- Footmassage in the 4-seater, foorest can also warm or cool your feet for extra comfort

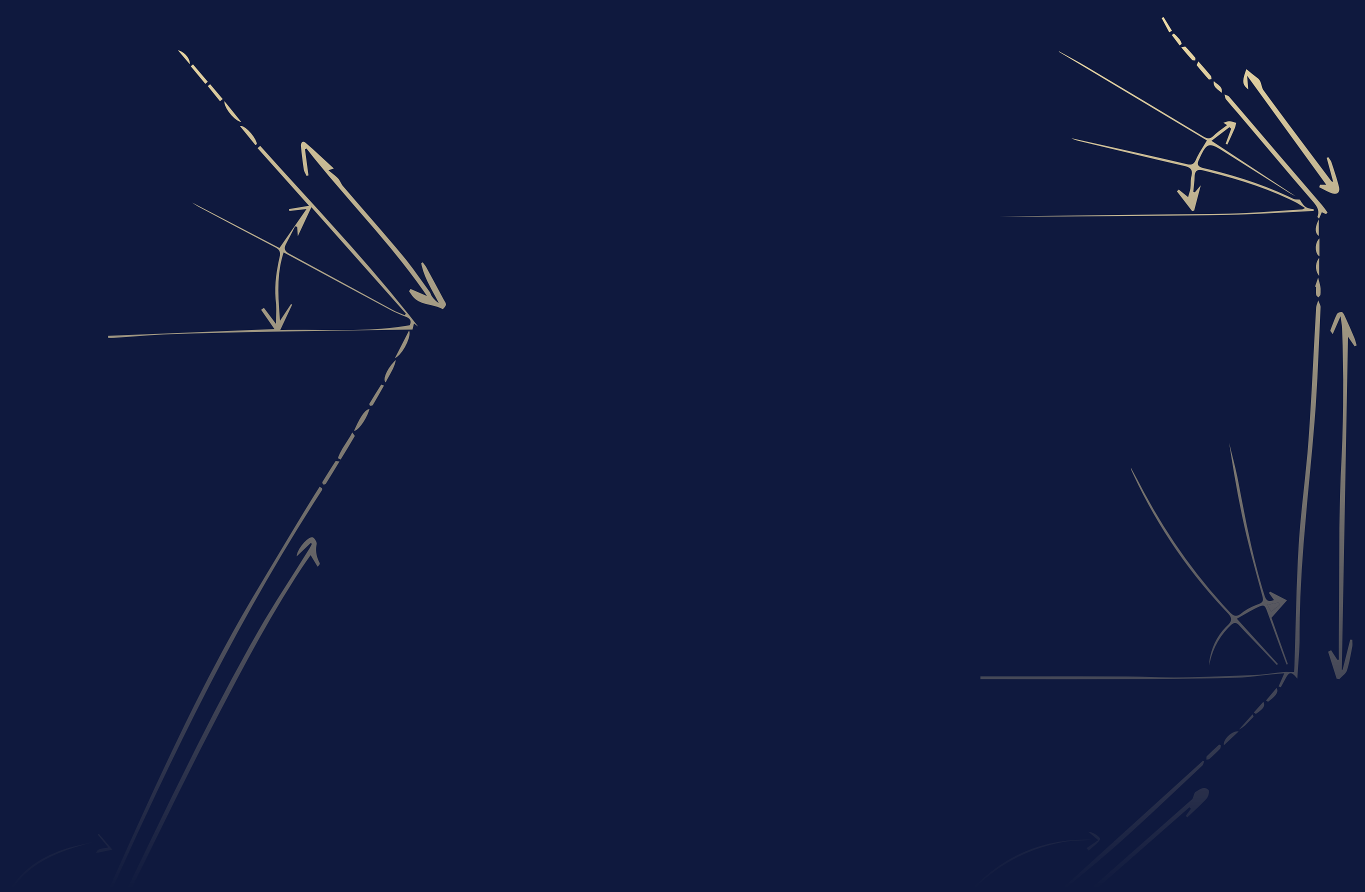
Figure 13: Climate control in backseat of S-Class

Figure 14: BMW 7 Series with Theatre Screen

Figure 15: Lucid Air

2.4 Brose moodboard

Since Brose's work is focused on the technical aspect, the design is kept clean (Jan Peukert, product designer, personal communication, April 24th, 2024). The products are designed for different OEMs, which need a clean look that can fit multiple OEMs.The identity of Brose is modern, streamlined, and purposeful aesthetic (Brose Fahrzeugteile Se & Co., n.d.). Since there are no guidelines for product design, a look is taken at their corporate identity, where the font Helvetica is chosen for its clarity and functionality and it combines a timelessly modern visual appeal with a hint of technology. With these terms in mind and their color system (red, black, and white) a mood board is created. A lot of these images are from Polestar, their brand identity is quite similar with the aim of Brose.



RESEARCH 03

3.1 Introduction

In this thesis, I will use the approach of anthropometric design. Anthropometric design will help you to design and make decisions on adjustability, size, and shape throughout the design based on human size (van Boeijen et al., 2020).
The following study is a quantitative, cross-sectional study. This study consists of 36 participants, whose anthropometric data and spinal curvature have been measured at one moment in time. The consent form can be found in appendix 3.

Target group

The anthropometric approach has different steps. The first one is the definition of the target group and considering demographic variables (van Boeijen et al., 2020). The original plan was to look at markets from the US and China since these are big markets on the global scope. Therefore, the questionnaire included a question about participants' ethnic origin. However, the data didn't show enough people from East and Central Asia (2 out of 36) and North America (0 out of 36). This meant that the target group changed according to the received data; 31 people are from Western Europe and 33 people are Dutch.

Research angles

As mentioned before, in a study from Vledder et al. (2024) the sleep comfort was tested in different backrest angles. As expected, 180 degrees gives the best sleep comfort, however, 140 degrees scores higher than 150 degrees. Also, the overall comfort was at 140 than 150 degrees. The space in a car doesn't allow to put the chair at 180 degrees, therefore the choice was made to research at an angle of 140 degrees.

To be able to find the difference between upright sitting and sleeping, it should also be measured at an upright angle. In most research, this is stated at 120 degrees. However, Brose suggested 25 degrees (torso angle), which is equal to 115 degrees.

I choose to do the tests at 115 degrees because it is a standard for them, the difference would most likely be bigger than at 120 degrees which hopefully gives better insights. Furthermore, Park et al. (2000) shows that the mean angle for Korean drivers is 117 degrees. He let 43 subjects (24m, 19f, age 25-50) adjust the seat to for their own comfort.
For a full overview of all the suggested research angles, see appendix 2.

Backrest angle

For clarity, professors at TU Delft talk about the angle from the horizontal plane to the backrest of the seat. Whereas Brose talks about the torso angle; the angle from the vertical plane to the backrest. This means that a torso angle of 25 degrees is equal to 115 degrees from the horizontal plane and that a torso angle of 50 degrees is equal to 140 degrees from the horizontal plane (figure 20). These terms are both used in this thesis.

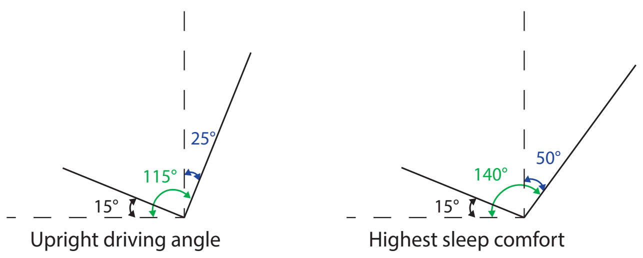


Figure 20: torso and vertical plane angles

The kyphosis measurer was built for standing measurements. Testing with a torso angle of 50 degrees was not possible with the intentional set-up. Therefore, the kyphosis measurer was put on crates, to be able to reach all the way to the participant. A schemetic of the set-up can be seen in figure 21.

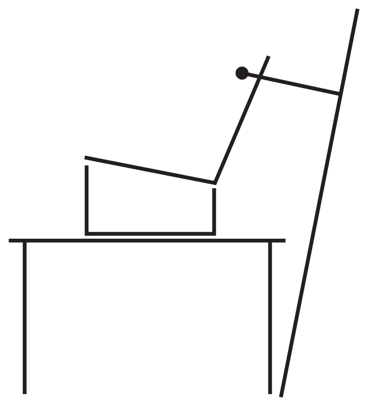


Figure 21: Schematic set-up

3.2 Method

After establishing the research angles, the kyphosis measurer with corresponding wooden chair were adjusted. First the participant is being measured on the measuring chair; popliteal height, sitting height, hip width are all measured. Then he sits on the wooden chair at 25 and 50 degrees torso angle. At 25 degrees, the participant has to look at a point on the wall, to mimick a driving position. While the person was sitting like this, I rolled a wheel over their back, which measured a point every centimeter (figure 22). These together made graphs of the curvature of the spines of participants. Afterwards, participants are asked to stand up, while the seat is adjusted to an angle of 50 degrees. The participants are asked to relax as much as possible, while the wheel is again rolled over their back (figure 23).

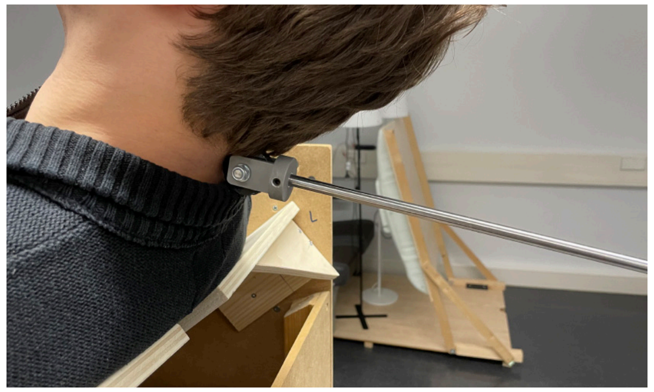


Figure 22: Measuring point on participant

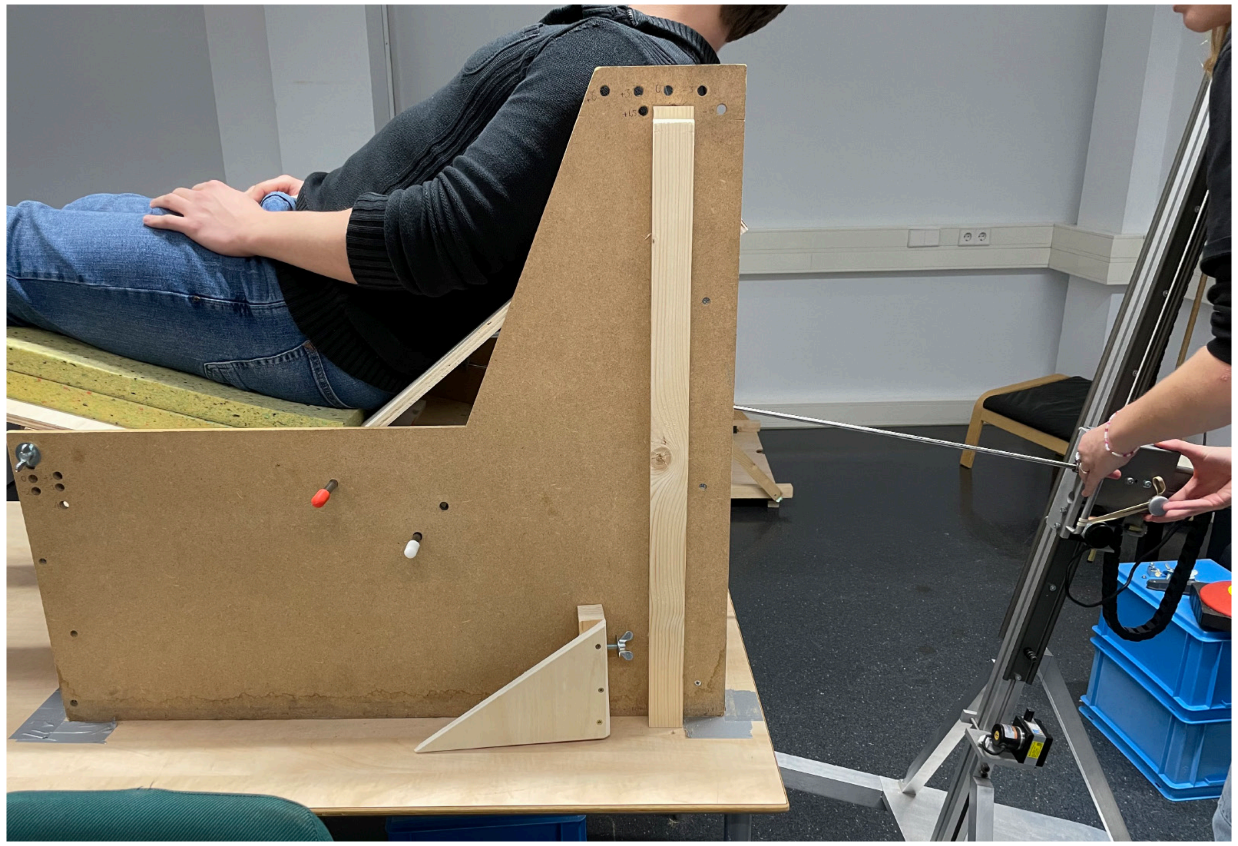


Figure 23: Actual set-up

3.3 Results

In total 43 participants were involved in this research study, held at TU Delft. From those 36 had useful data (sometimes data was to wobbly or not complete), from which 31 have ancestors from Western Europe, see table 2 for the full overview. Since this is not a representable sample size for China or the US, a look was taken at the people who had a Western Europe background. This group consisted of only Dutch people (except for a few that had double nationality). There were also two Dutch people, who had no Western European ethnic origin. The Dutch subgroup includes 17 females, 15 males and 1 other. Making a total of 33 participants. Therefore, chosen is to focus on Dutch people.

Table 2: Ethnic origin of participants

Ethnic origin	
Western Europe	31
South and Southeast Asia	4
East and Central Asia	2
Eastern Europe	1
North Africa	1

To be able to see differences in the curvatures at 25 and 50 degrees, they were layed on top of each other. This translation includes also the kyphosis measurer that was put under an angle of 11 degrees. This has to be taken into account for trainslation of the curvatures (figure 24).

From both 25 and 50 degrees curvatures a two-segmented polyline, three segmented polyline and a three segmented curve were created. Not only the entire group was evaluated, but also individual differences. Within the group evaluation 25 vs 50, P5 and P95 sitting height and male vs female were compared.

In appendix 4 an overview of all participants with their corresponding anthropometric data is given.

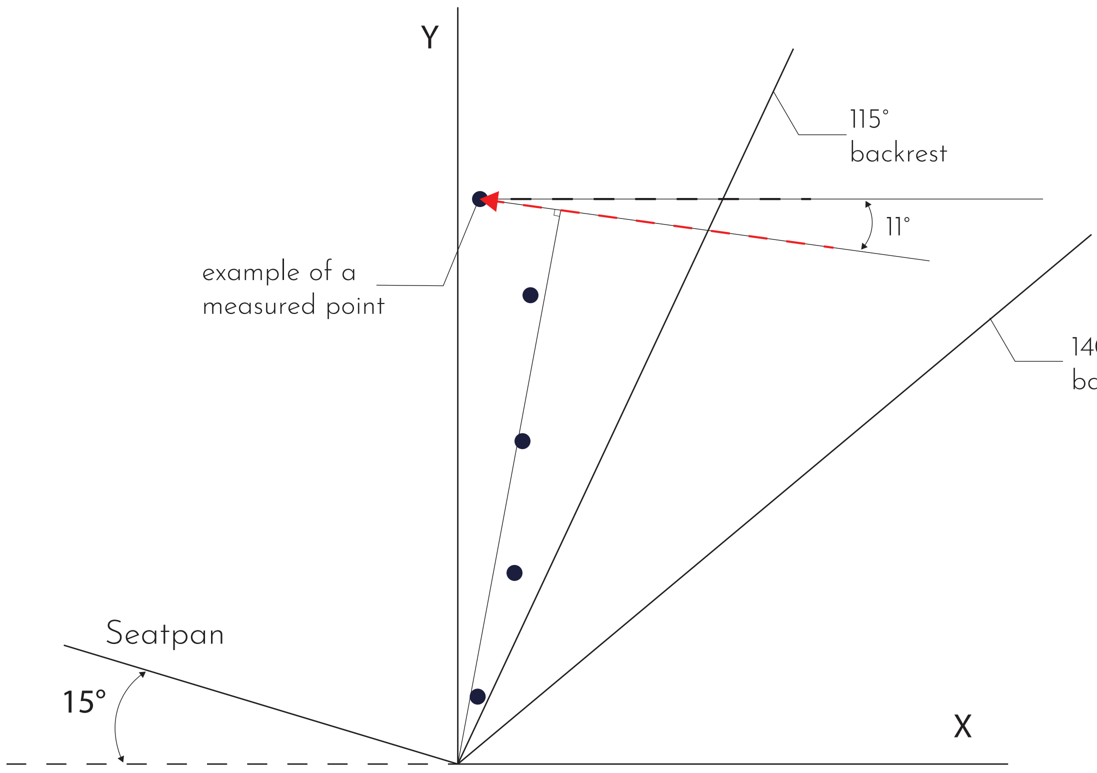


Figure 24: Measurement points compared to the angles of the seat

3.3.1 25 vs 50 curvature

There is a clear difference in curvature at a torso angle of 25 degrees and a torso angle of 50 degrees. The entire back is more rounded at 50 degrees. The results consist of multiple curvatures per person; a few at 25 degrees and a few at 50 degrees. Four participant graphs can be seen in figure 25. The black lines indicate the curvature at 25 degrees and the red line at 50 degrees. There are multiple lines because the measurements were done nomorous times, to prevent outliers as seen as a regularity. All the curvatures per person can be seen in appendix 5.

Interesting to see is that the curvatures at 25 degrees all appear to be quite similar, while the curvatures at 50 degrees sometimes have more roundings on the top and others more rounded or straight on the bottom.

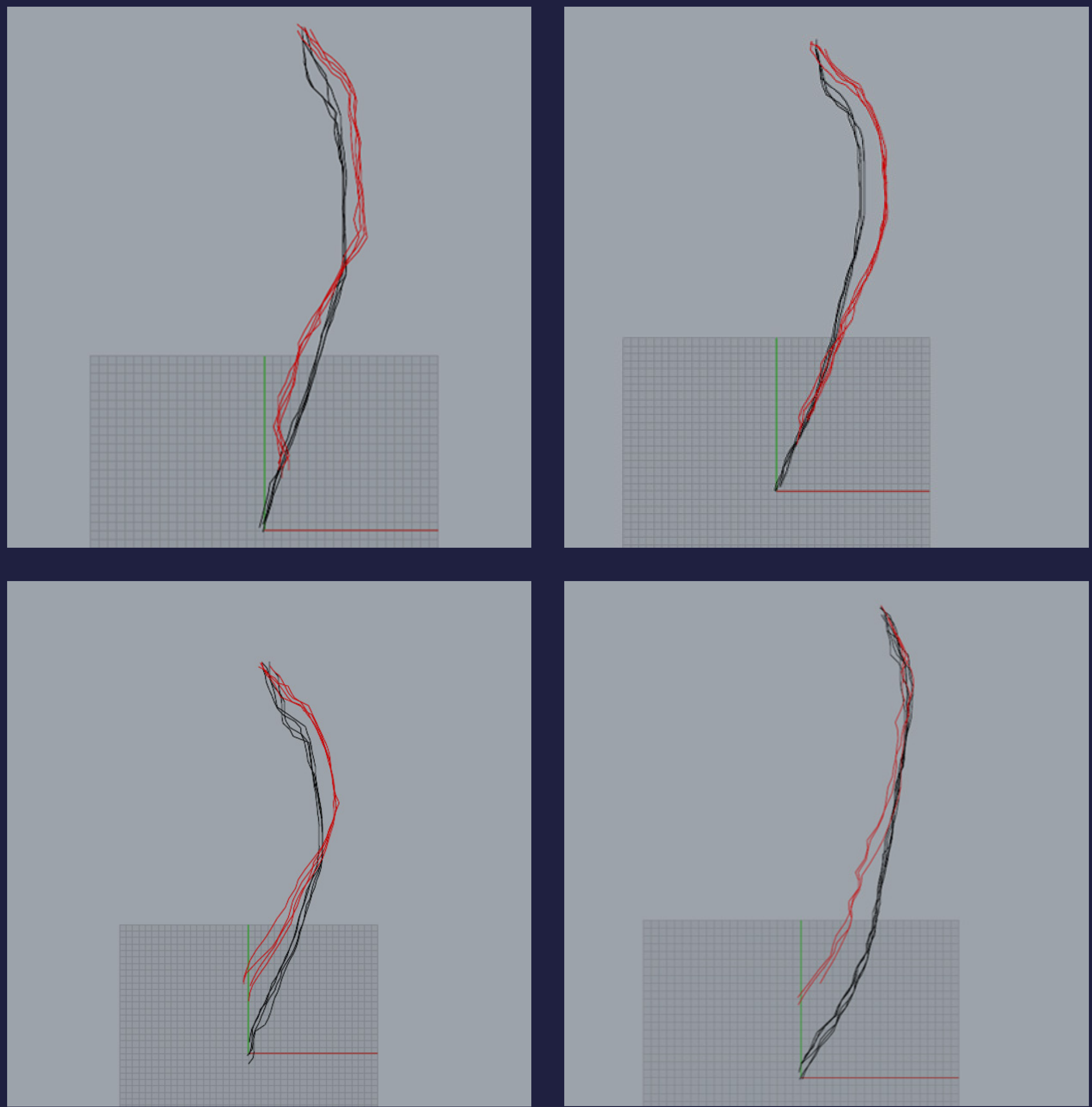


Figure 25: Four participants curvature graphs at 25 and 50 degrees

3.3.2 Male vs female curvature

In general, I found two options for the curvature at 50 degrees: a more S-formed curve, with a lordosis at the bottom of the spine and kyphosis at the top of the spine. And a more flattened curvature, with less lordosis at the lower half of the spine. Some participants had a clear difference compared with their curvature at 25 degrees, while others were closer together. Figure 26 shows two participants, one with a more S-shaped curvature and one with a more flattened curvature.

In a study from Hay et al. (2015), with 81 subjects, age 18 to 84 years, average age 41.5 years a clear difference between a male and female spine was found. The female spine manifested a statistically significant greater curvature, a caudally located lordotic peak, and greater cranial peak height (Hay et al., 2015), figure 27.

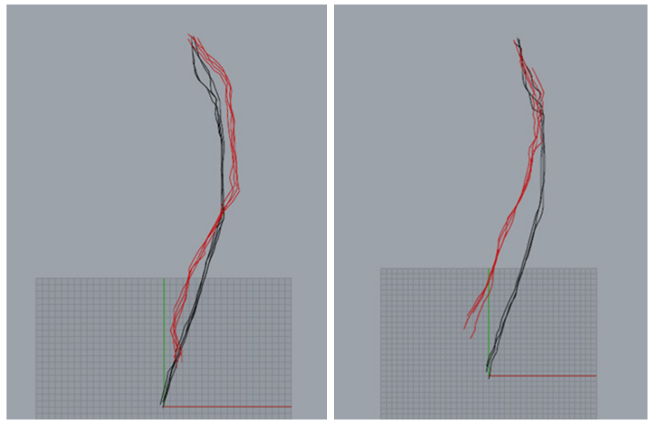


Figure 26: Left: a more S-shaped curvature (f), Right: A more flattened curvature (m)

Even though my research shows that lordose might be sex dependent; 13 out of 20 of the S-shaped curvatures (lordosis) was female and 10 out of 15 of the more flattened curvature (no lordosis) were male, Hay et al. (2015) states that the amount of inward curving (lordosis) is sex independent.

The architectural differences in lumbar lordosis shape between the sexes are due to dissimilarity in the conditions and constraints under which the male and female spines operate (Hay et al., 2015). They tested 81 male subjects, with an average age of 41.5±15.8 and 77 female subjects with an average age of 41.3± 15.5 years. Their sample group is bigger and more spread out as mine, where the average age is 26, ranging from 19 to 66 years old. That gives me confidence to trust their data and analysis.

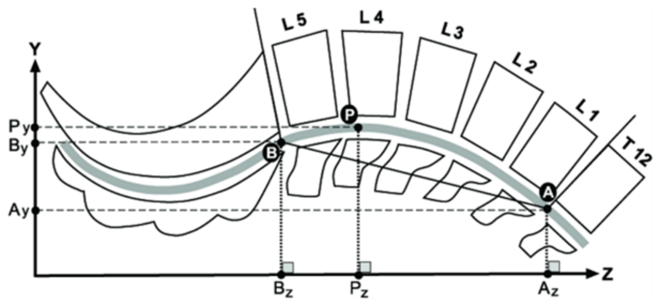


Figure 27: Cranial peak height (Hay et al., 2015)

3.3.3 P5 vs P95 curvature

To be able to establish the difference between P5 and P95, participants were categorised. Table 4, 5, 6 and 7 show respectively the Dutch population, 4 participants that fit P5 the best, 4 participants that P50 the best and 4 participants that fit P95 the best.

Table 3: p5 and p95 of Dutch population 20 – 60 years old

(DINED)	Dutch 20 – 60 years		
	P5	Mean	P95
Popliteal height	39.7	46.3	52.9
Buttock-popliteal height	45.7	50.5	55.3
Sitting height	82.7	91.1	99.5
Hip width	33.6	38.5	43.4

Table 4: P5 comparison with data

	M/F	Age	Ancestors	Stature height	Popliteal height	Buttock-popliteal height	Sitting height	Hip width
Participant 7	F	25	Western Europe	158.6	42.6	48.1	83.7	44.5
Participant 9	F	22	South and Southeast Asia	158.1	42.5	45.8	81.9	33.4
Participant 23	F	22	Western Europe / South and Southeast Asia	169	47.5	49.5	83	35
Participant 34	F	23	North Africa	159.5	41.6	49.1	83.8	41.4

Table 5: P50 comparison with data

	M/F	Age	Ancestors	Stature height	Popliteal height	Buttock-pop. height	Sitting height	Hip width
Participant 1	M	20	Western Europe	158.6	42.6	48.1	83.7	44.5
Participant 6	M	26	Western Europe	158.1	42.5	45.8	81.9	33.4
Particiant 11	M	23	Western Europe	169	47.5	49.5	83	35
Participant 22	M	24	Eastern Europe	159.5	41.6	49.1	83.8	41.4

Table 6: P95 comparison with data

	M/F	Age	Ancestors	Stature height	Popliteal height	Buttock-pop. height	Sitting height	Hip width
Participant 16	M	66	Western Europe	191	52.5	55	96	40.5
Participant 20	M	24	Western Europe	187.1	50	53.5	97.5	39.5
Participant 28	F	23	Western Europe	179.4	46,8	49,6	95,2	37,2
Participant 33	M	19	Western Europe	185.2	53	48.4	95.9	36.2

Per category (P5, P50 and P95), a average curvature diagram was created. These then were translated into an angle of 115 degrees and at starting point (0,0,0). Figure 28 shows the final diagram.

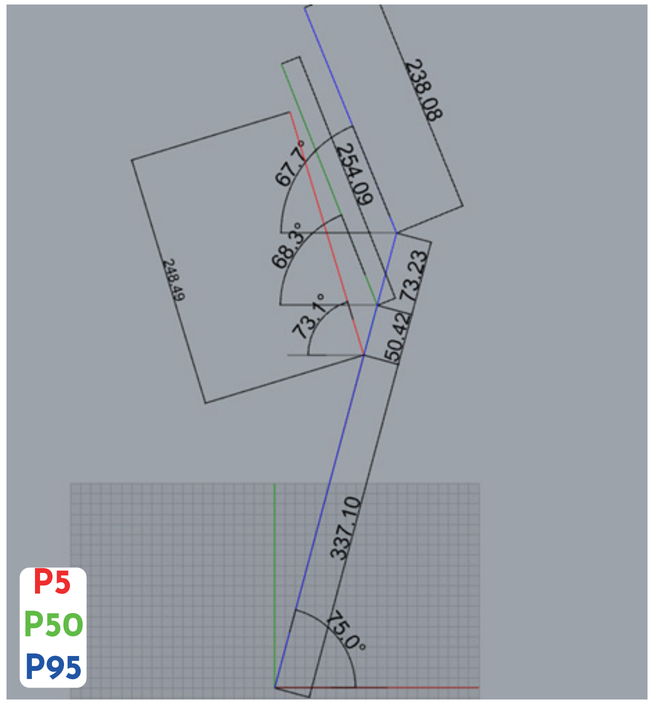


Figure 28: The different percentiles overlapping at 25 degrees

To be able to have all the input at 25 and 50 degrees in one image, the following sketches were made (figure 29). These include P5, P50 and P95 at both angles. In the left image, one hinging point is thought off, in the right image, 2 hinging points are incorporated.

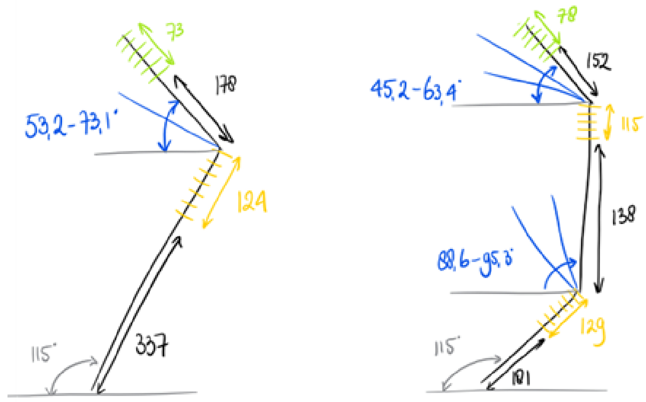


Figure 29: The different percentiles overlapping at 25 degrees

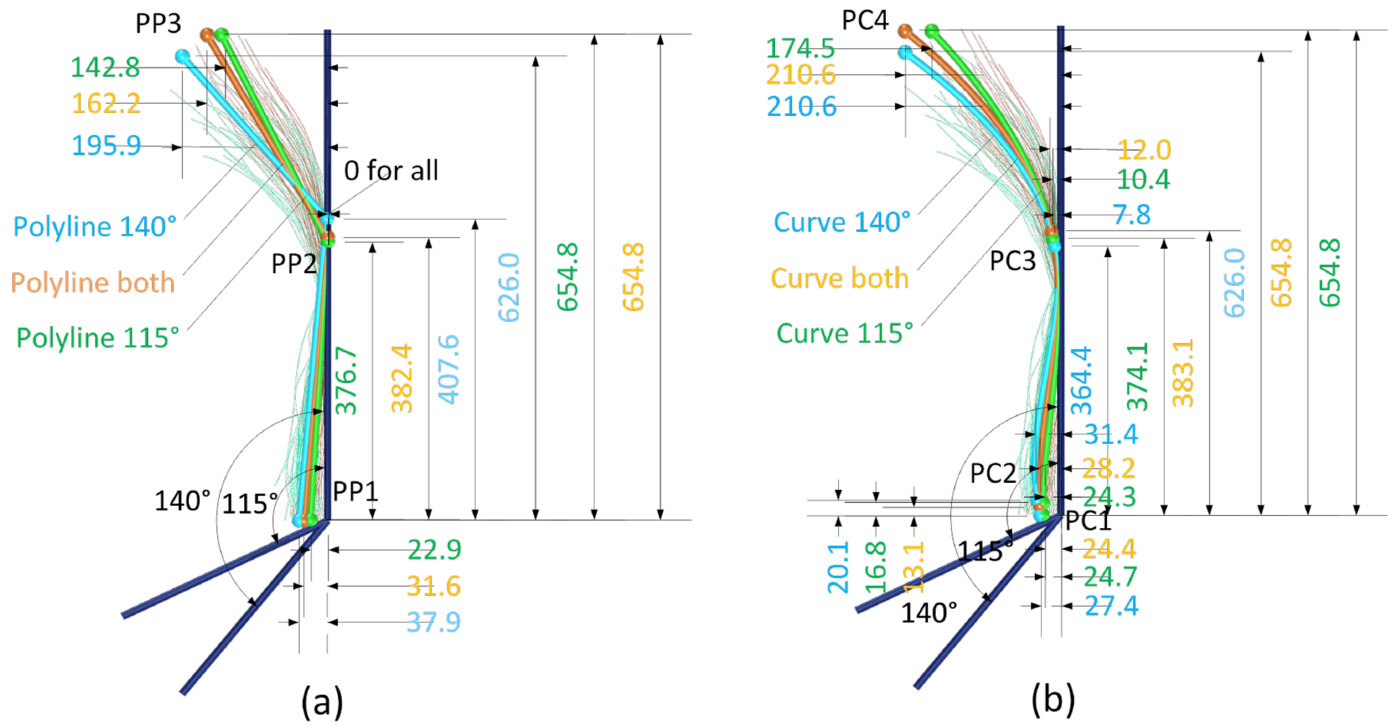


Figure 30: Overview for a polyline and curve for all data

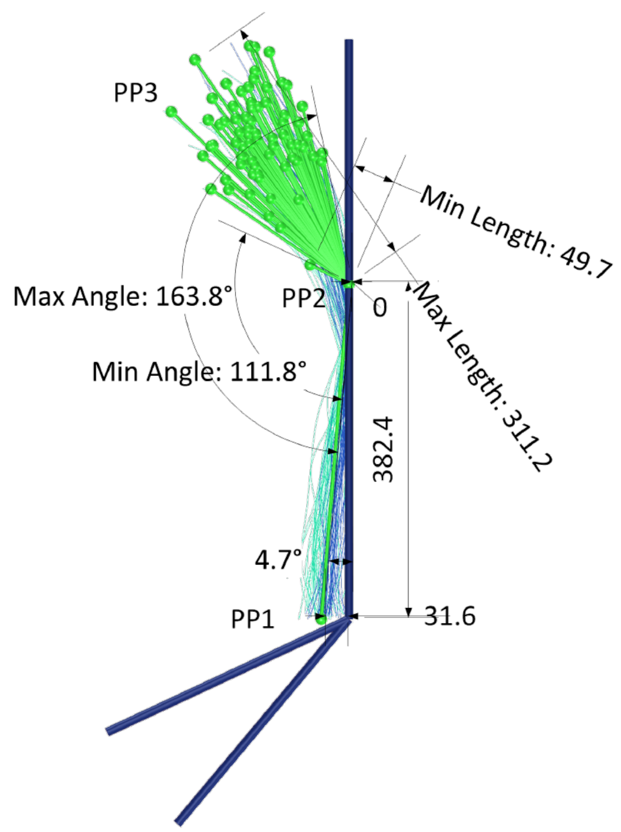


Figure 31: Length increase for one hinging point

After creating my own conclusions, dr. Wolf Song helped me optimise the measurements in Grasshopper. Figure 30-a shows the average polyline with one hinging point at 115°, 140° and combined. Figure 30-b shows the average curvature at 115°, 140° and combined.
Lastly, figure 31 shows that the minimum length from PP2 to PP3 is 49.7mm and maximum length 311.2mm. That means that if chosen to put in a length increase in the final design, this should be 261.5mm.

3.4 Conclusions

To conclude, it is hard to determine one shape that fits all. The use of hinge points and vertical translations might help to create one optimal chair that fits 90% of the end-users. Important difference with current shoulder hinges (which are exactly at 38 cm, which can be concluded out of data (b), is that the range is not that big. The optimal range would be 52°, from 111.8° to 163.8°.

3.5 Recommendations

The kyphosis measurer is created for standing positions. Therefore, it was quite hard to get it to work for laying positions. This was fixed by elongating the probe and putting the kyphosis measurer on crates, to be able to reach the spine. However, it still didn't fully work as can be seen in figure 32; the bottom part of 50 degrees was not reachable every time.

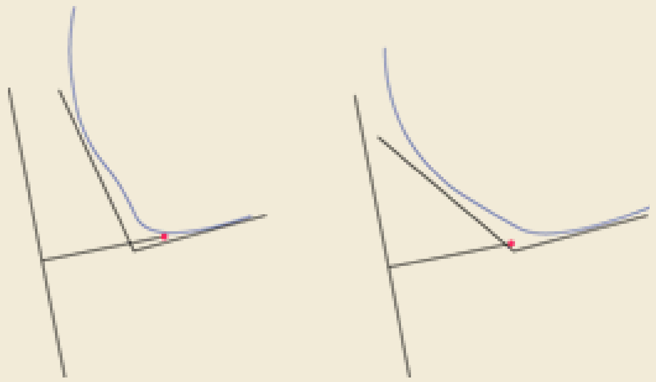


Figure 32: Schematic overview of the reachability difference in 25 and 50 degrees

Head posture

The chair was made for upright sitting, it would have been nice to add a headrest for the laying angle. This would make it more comfortable for the participants and might make the MSRE a bit lower. Right now, some participants had to hold their head up. This was not comfortable and could have influenced the results (figure 33).

Figure 33: How the head posture might influence the spine

Shoes or no shoes

In the beginning, a few pilot tests were done. I asked people to take of their shoes for measurements such as stature and popliteal height. Then, they could put their shoes back on and sat in the chair. After a short discussion with Bertus Naagen, I decided to let people do all the tests without shoes. However, I think in the end it would have been more logical to keep the shoes on. When driving, people also wear their shoes.

TARGET GROUP 04

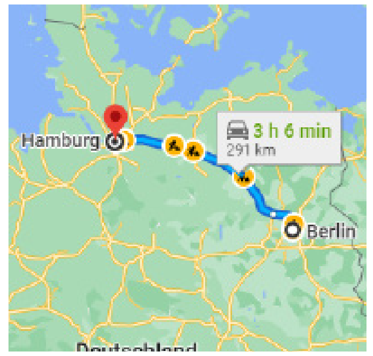
The target group of this design project is young urban professionals. People who have to travel for work and are in the age between 25 and 35 years old. They fit in the group that is most likely to use autonomous vehicles in the near future; residents of larger cities, younger age groups up to 45 years old and households with higher incomes (Horváth & Partners et al., 2018). Furthermore, the majority of this group has a high income and is willing to spend more on luxurious products,
The context for these travelers is therefore long distance (>3 hours). They either drive manually or autonomously, it could also be that they have a driver. They sometimes drive alone or with colleagues. And lastly, they live in big cities, therefore not owning a car is very common and they are open for car sharing opportunities or services like Uber.

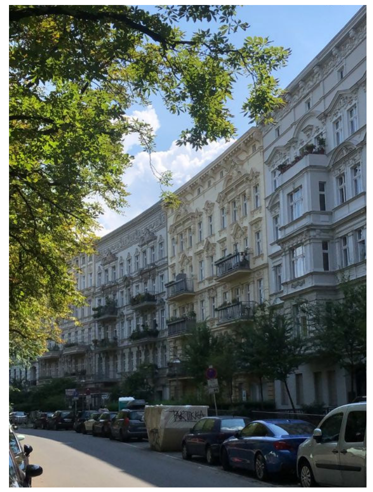
4.1 Persona 1: Emma

Emma is 28 years old, lives in Berlin, and is a Global Communications Manager. She is always in a rush with her coffee to go. She doesn't own a car and uses Uber regularly. She is willing to pay extra for a luxurious experience.

Usecase
She has to go to the office in Hamburg 1 to 2 times a week. She often drives together with colleagues or uses Uber. She likes to work on her way to the office. She prefers to be home late instead of sleeping in a hotel, therefore she often sleeps on the way back home.

Wants and needs
She wants a seat that has multiple configurations; working, talking, and sleeping mode. She wants a luxurious way of transportation and sometimes wishes for a bit more privacy during her trips.

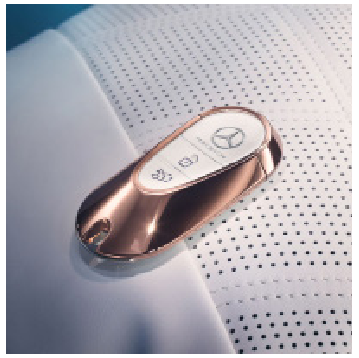
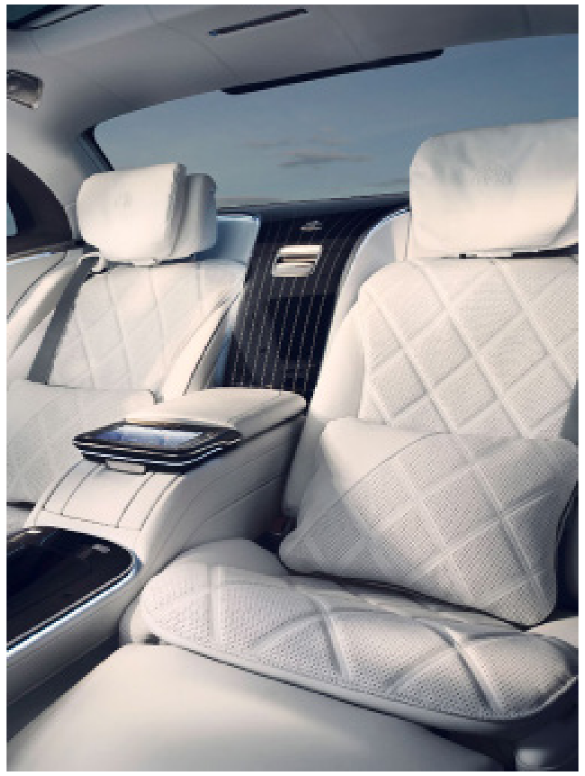




Context
Emma's use case has different options for vehicles, the Mercedes Benz S-class fits her way of traveling. The S-class comes from the German word Sonderklasse, which means 'special class'. It is a series of full-sized luxury sedans and limousines.
One of them is the Maybach. This luxury car has a spacious backseat, including a middle console, with a cupholder, champagne flutes, refrigerator compartment, and folding table. That means she can relax, travel together with a colleague, but also work.

Future perspective
In the future she could be driving in an autonomous vehicle, probably privately owned. This should be a vehicle that takes more than one person, to be able to travel together. The seat itself has still the same requirements; to be able to work, talk and sleep.

Mercedes Benz Maybach

4.2 Persona 2: Alex

Alex is 29 years old, lives in the suburbs of Sacramento, California, and works as an electrical engineer in the R&D department of a big prosthesis company. He likes personal contact with end-users, to optimize their needs. He is interested in cars and he owns a brand-new Audi Q6 e-tron. He gets excited about new technologies and is idealistic; he always looks for ways to improve the world around him. He is always interested in new technologies and products and therefore is willing to pay extra for an interesting experience.

Usecase
Alex drives every day to the office, which takes him about half an hour. Once a week he has meetings in San José (Silicon Valley), which takes him around 2 to 2,5 hours.

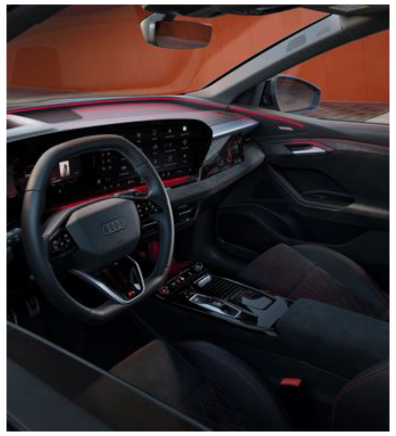
Wants and needs
He prefers a car seat that can be used for driving and sleeping. The car is a relaxing spot for him, so he wants to be able to enjoy his car rides but sometimes is a bit too tired to drive.





Context
A car that fits Alex' persona is the Audi Q6 e-tron. This car will be on the market end of 2024 or beginning of 2025. The car is the first production model on the Premium Platform Electric, that is created by the Volkswagen Group.

Future perspective
In the future he could be driving in a semi-autonomous vehicle, since he is interested in new technologies. He will still own a car privately and sometimes wants to drive himself. The seat itself has still the same requirements; to be able to chill and sleep.

05 REQUIREMENTS

To design a car seat that is comfortable, follows the spinal movement, fits the user group and Brose, some requirements were established. Afterwards they were categorised in performance, environment, maintenance, target product cost, production facilities, size, aesthetic, ergonomics, safety and reuse. Lastly, some wishes were added.

Performance
1. The seat should be able to be used for both driving and sleeping or other relaxing activities. This means that the seat should move from 115 to 140 degrees.
2. It should keep the user in place while driving.

Environment
3. The seat should be able to be produced locally, to avoid shipping.
4. The seat should be able to be cleaned properly, to keep a long lifespan.

Maintenance
5. The seat should be made in such a way that maintenance can easily disassemble broken parts.

Target product cost
6. The costs of the seat should not be more than 200% of regular car seats.

Production facilities
7. It should be able to create the new seat in-house at Brose's already existing facilities.

Size and weight
8. The seat should be as light as possible, to reduce the environmental impact.
9. The size can't exceed the size of current car seats, since it should be able to fit in current cars.
10. The structure shouldn't exceed 20 kg.
11. The weight shouldn't exceed 30 kg, the weight of a highly equipped seat (there are also seats up to 50-70 kg) (Jochen Hofmann, personal communication, 21 February 2024).

Aesthetic, appearance and finish
12. The seat should look luxurious and comfortable.
13. The appearance of the seat should show that it is meant for future purposes.
14. The seat should outperform on comfort; experience, emotion, unexpected features and luxury, compared to current seats.
15. The seat should be able to find in different configurations of cars.

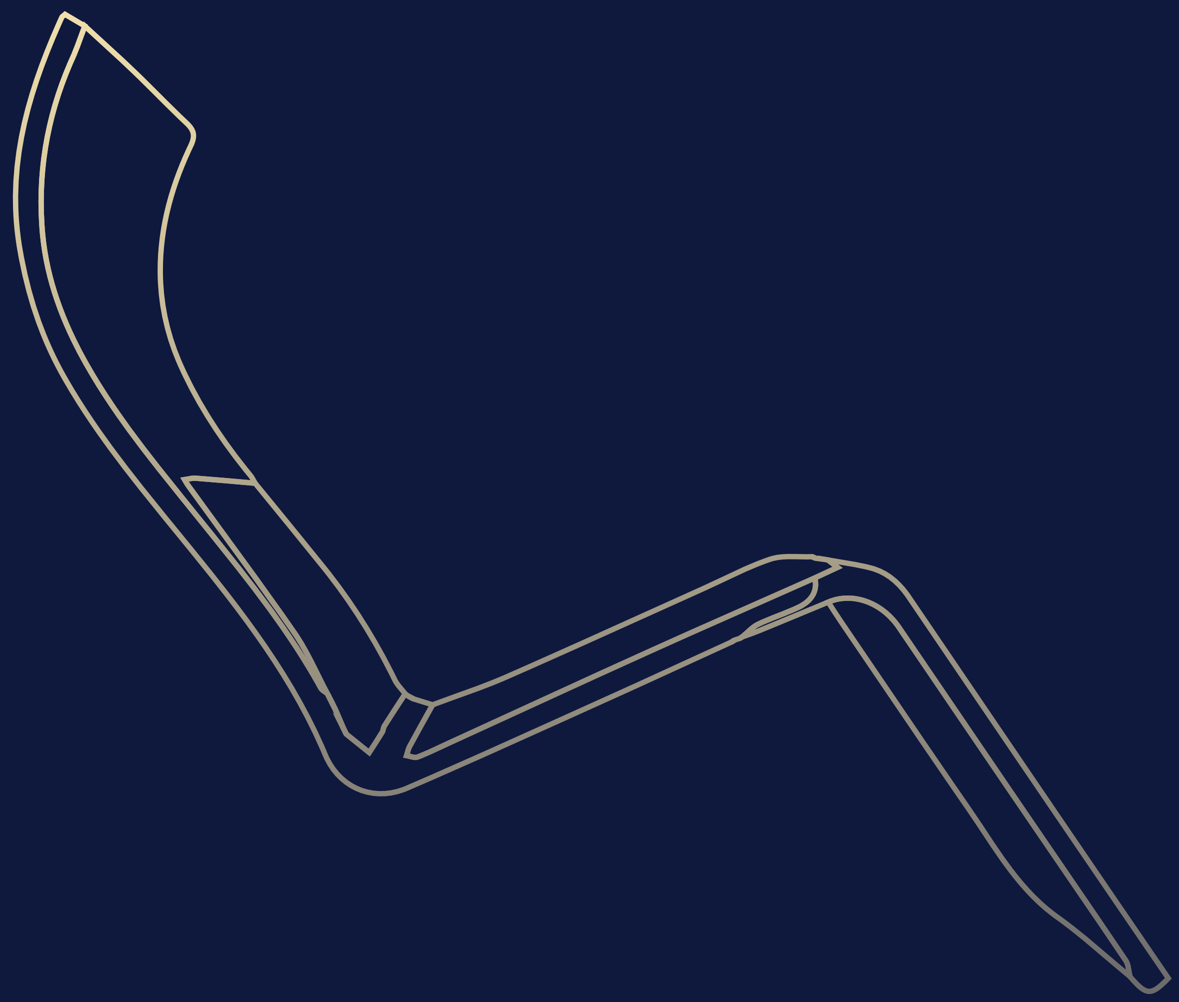
Ergonomics
16. The seat should be comfortable for 5^{th} up and till 95^{th} percentile males and females.
17. The seat should have a lower discomfort; physical characteristics, compared to current seats.

Safety
18. All moving parts should be covered.
19. The user should be kept in place in case of an emergency, in the laying position.

Reuse, recycling
20. The seat should be able to disassemble in a way that products or parts of products can be reused or recycled.
21. The final seat should have a recyclability of at least 50%.

Wishes
22. The production of the seat should have 5% less energy usage than current seat production.

23. In the sleeping position submarining should be prevented.



IDEATION 06

After the research study, the focus was on diverging with as many possible solutions. Starting with some backrest and bolster ideas, where flexibility and movement were kept in mind. The solutions were not only focused on the backrest and bolsters but also incorporated different seating options. Such as a bigger headrest, the use of different materials such as a net weave, and passive movements such as turning the seat pan.

Hammock (figure 34)
A hammock is relaxing and comfortable. If the seat is made out of one shell where the seatpan and the backrest are connected, this could reduce discomfort around the hip rotation point. The gap that normally is created in a laying position, is not there. This might be increasing the discomfort.

Figure 34: Maybe stretch the back in a laying position; hammocks feel comfortable

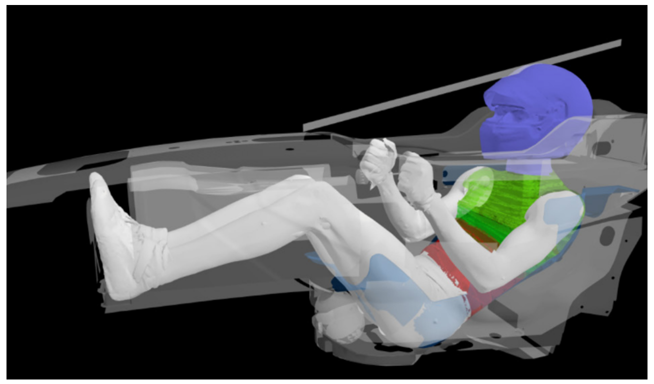


Figure 35: F1 seat is manufactured from carbon fibre and honeycomb structure that makes it incredibly strong but also very light

F1 seat (figure 35)
F1 seats have an interesting body posture. The feet are high enough to not get fatigued. Furthermore, the seat is manufactured from carbon fibre and honeycomb structure that makes it incredibly strong but also very light (Parker, 2020).

Gamer and office chairs (figure 36)
Gamer chairs are often praised for their incredible comfortability. They are made for multiple hours of seating. The same goes for office chairs. Office chairs have a netweave in their beckrest, that is quite flexible and moves with the body.

Figure 36: Left: Gamerchair, known for ergonomics and long periods of use; Right: netweave

6.1 Mechanism

During the ideation phase a look was taken at the mechanism to change the curvature from upright sitting to laying, figure 38.

Some options are a curved backrest, made from multiple slots that can be stretched and curved. Figure 37 shows some hinging ideas.

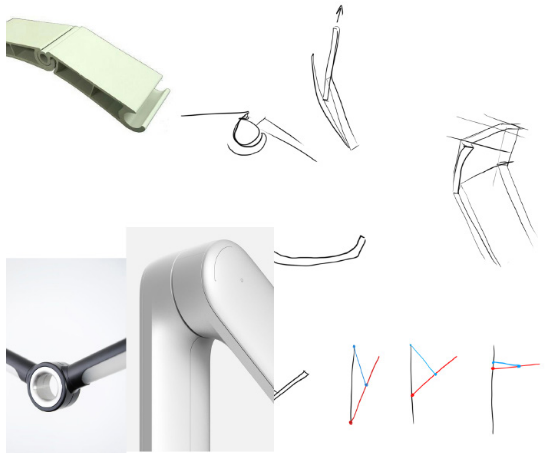


Figure 37: Hinging ideation

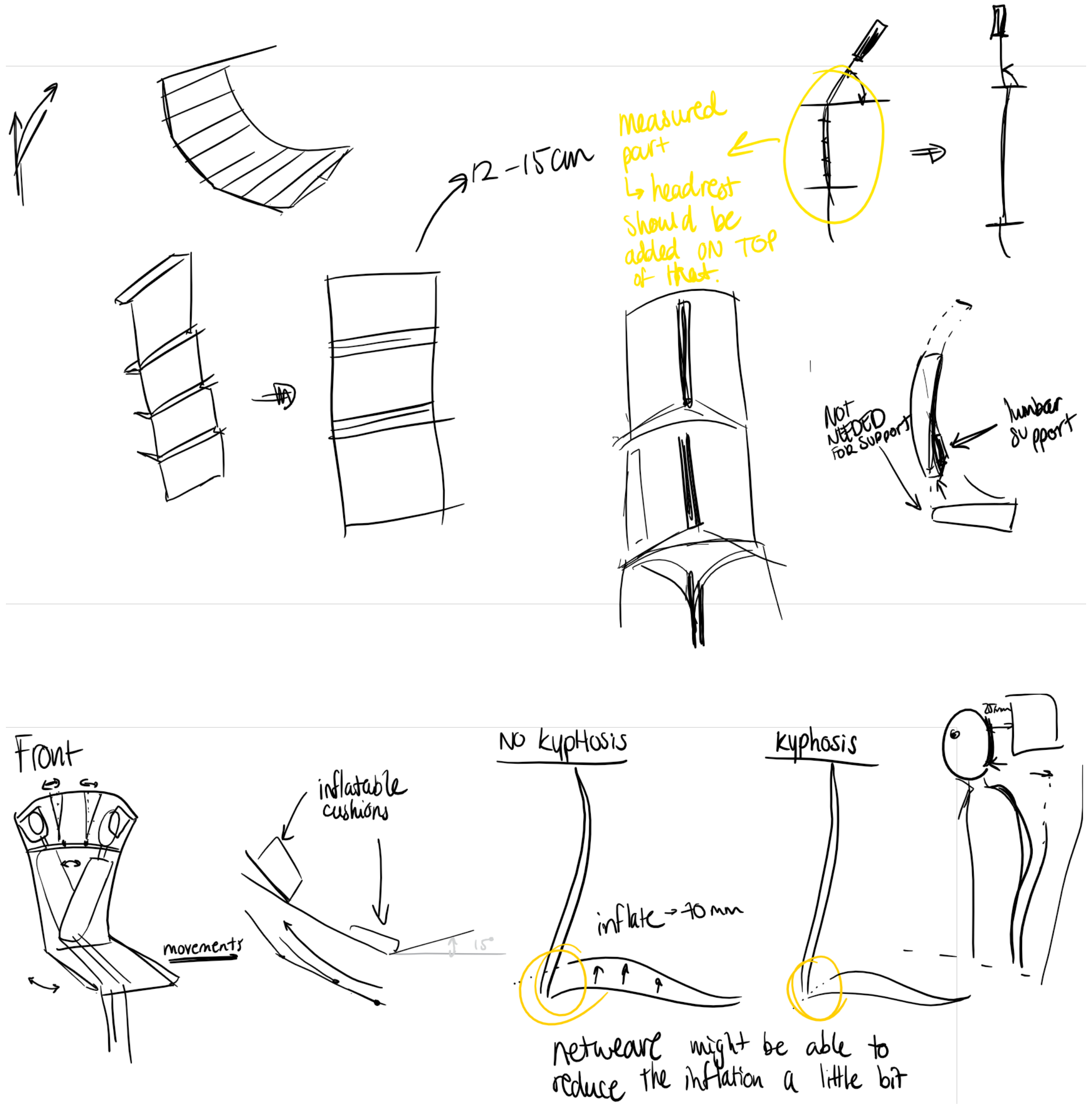


Figure 38: Ideation backrest

Movement

From the literature study it became quite clear that movements and the option to change posture while being seated is very important. Sammond et al. (2017) shows that when a driver (tested in a driving simulation) feels discomfort increase, the seat fidgeting and movements are increasing correspondingly. These movements can also be done passively, for instance by internal massage points. There are multiple options for passive and active movements. Hence, a small mindmap with options for both passive and active moments was created (figure 39).

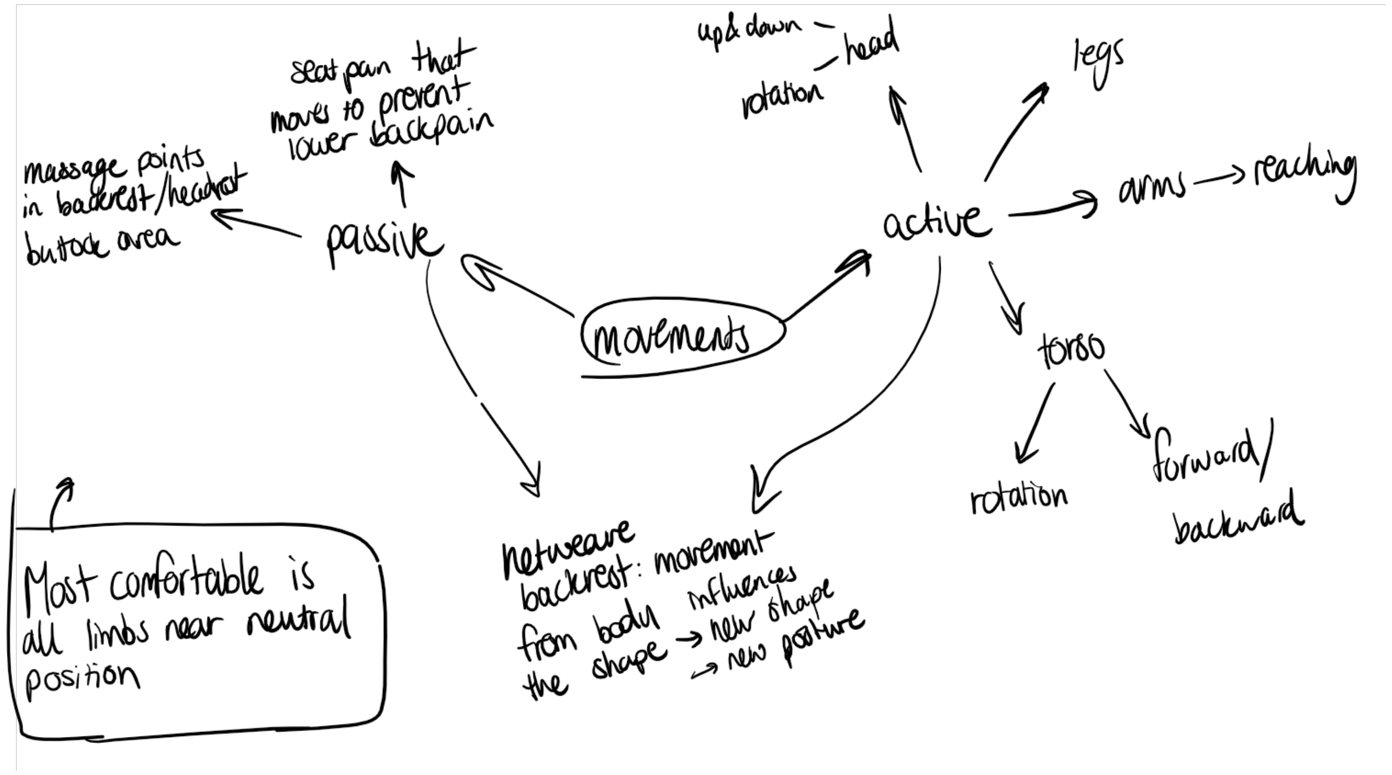
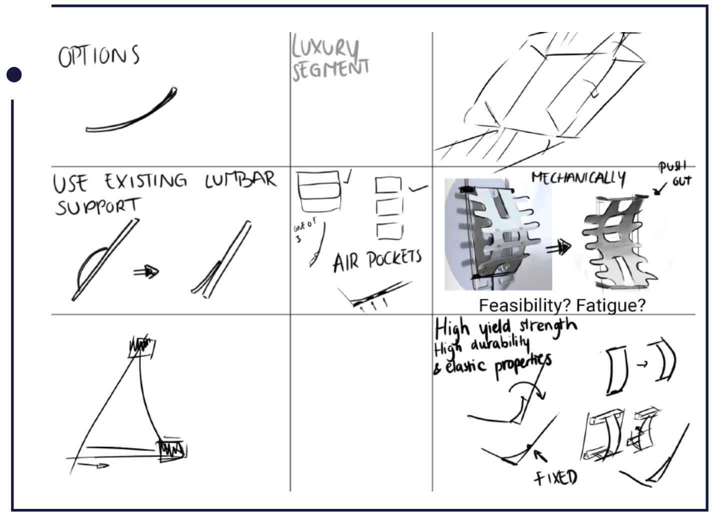


Figure 39: Mindmap movements

1.



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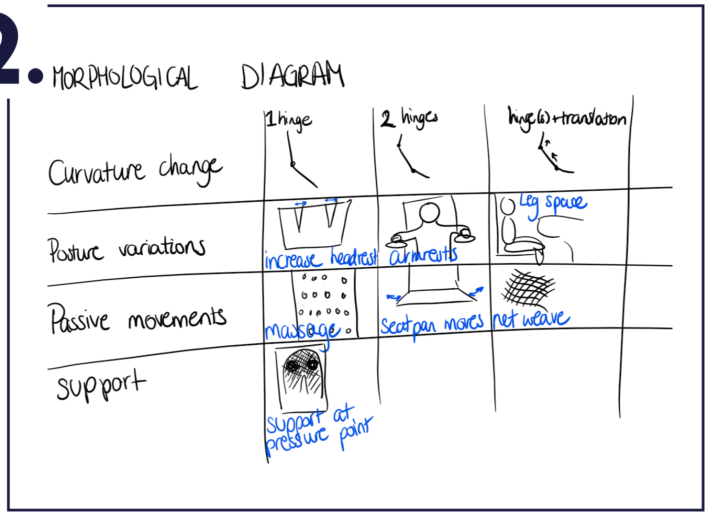

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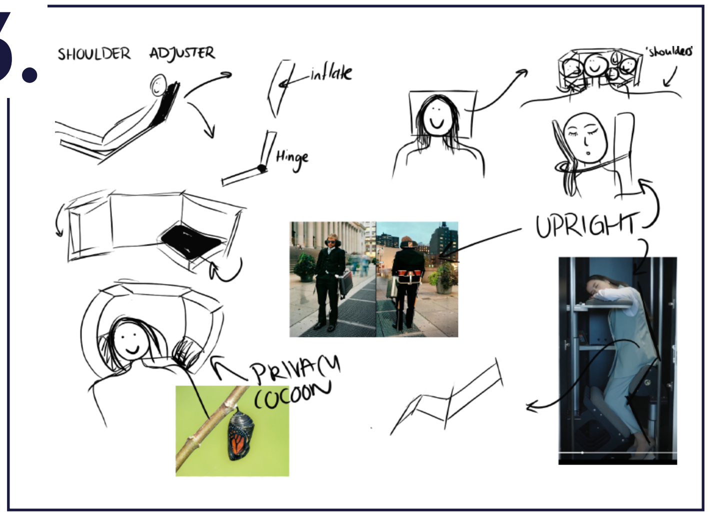

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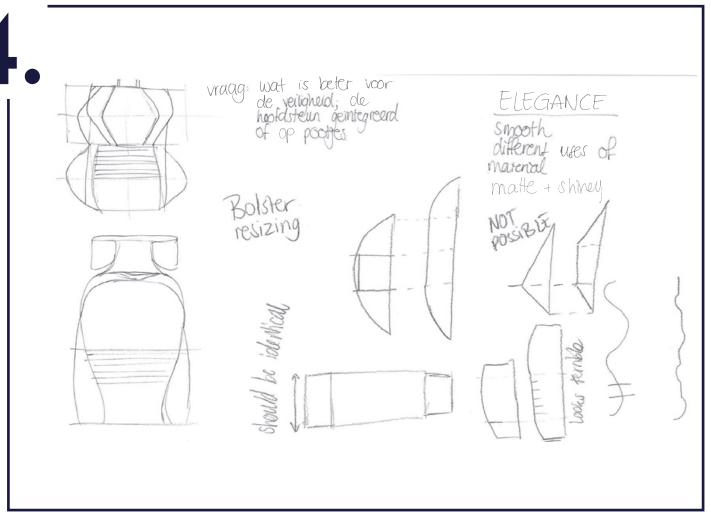

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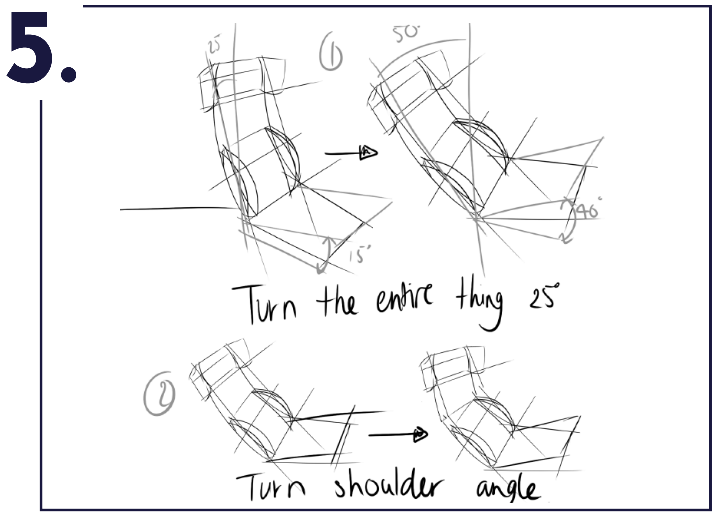

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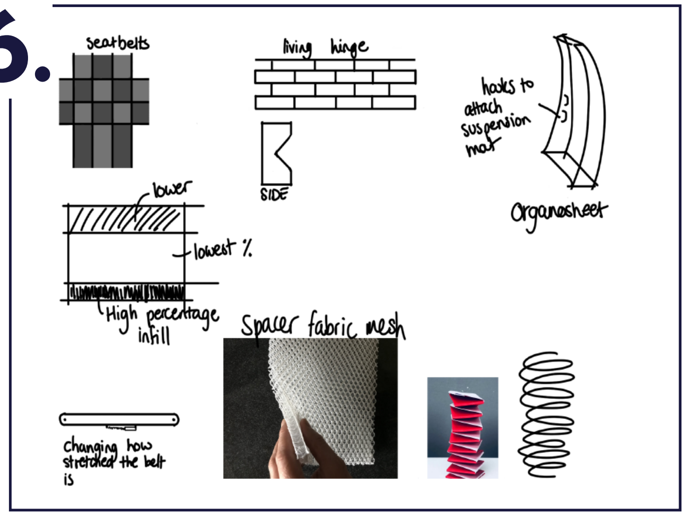

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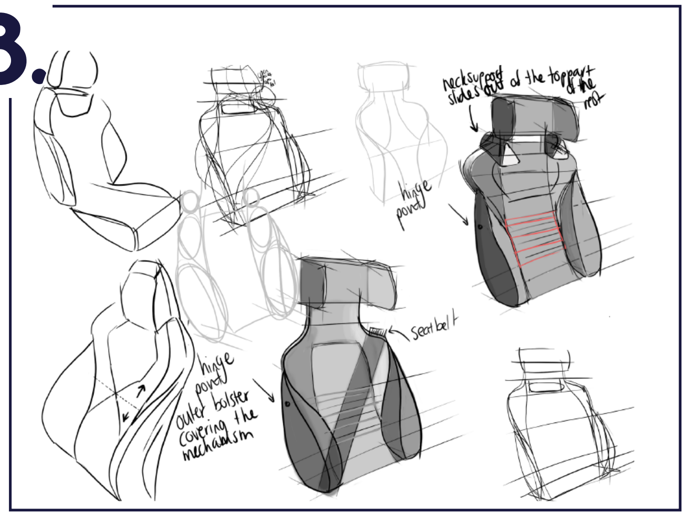


Ideation process

On the left side the ideation process can be seen. The numbers indicate the order of the process.

1) Started was with some ideas for a lumbar support, to follow the curvature.

2) After that a morphological diagram was made with curvature changes, posture variations, passive movements and suport.

3) From there I looked more into the shoulder adjuster and head rest. In this part of the ideation, I examed other options for upright relaxing and sleeping.

4) Then I looked into the length increase and how that would work for the side bolsters.

5) There is quite a big gap between the backrest and seatpan if the back rest is on its lowest position, this is not comfortable; the user needs some support in their lower back, but doesn't get this. It is not ideal either, but by turning the entire seat over 25 degrees (from 25 degrees torso angle for driving, to 50 degrees for sleeping), the problem of the gap is gone. For the experience it would be nice that the seat automatically goes in the laying position and a little bit delayed, the shoulder angle would turn.

6) The options until now; woven seatbelt as movable material, different infill percentages of a printed material to make a hinging point, motorised seatbelt material that will be stretched on different points, living hinges, a frame of organosheet as seen in Coburg, spacer fabric mesh for air permeability and very flexible to increase comfort and lastly some type of spring or folded material to increase the length of the fabric.

7) The current seat that has a translation in the Y-axis. Options could be to have a compressable honey comb foam covered with a lycra sportsfabric that can stretch a lot and is still breathable. The fabric can then be tensioned with some kind of torque.

8) Some first ideas for the looks of the seat, with an integrated seatbelt and neck cushions for extra support.

In image 5 (see page 44), the idea is to turn the entire seat. This ideas was further explored in a simplified SolidWorks model, figure 41. The same is done for the hinging part, figure 42. To get a bit of an understanding of how that would look and move. Figure 40 shows an idea for the frame structure. An other option would be to use topology optimization for the frame. The possibility depends on the final design.

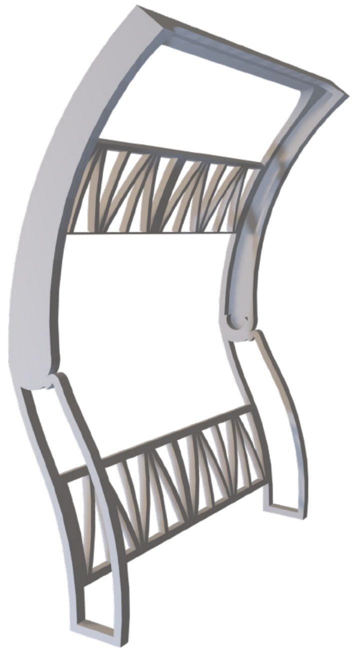


Figure 40: Simplified SolidWorks model of frame

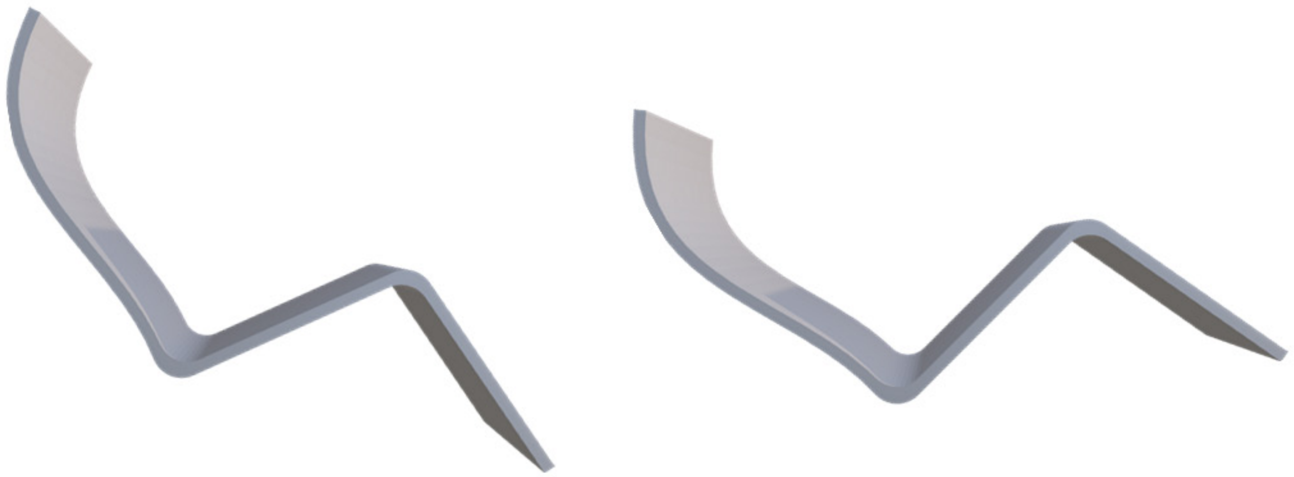


Figure 41: Simplified SolidWorks model of envisioned movement

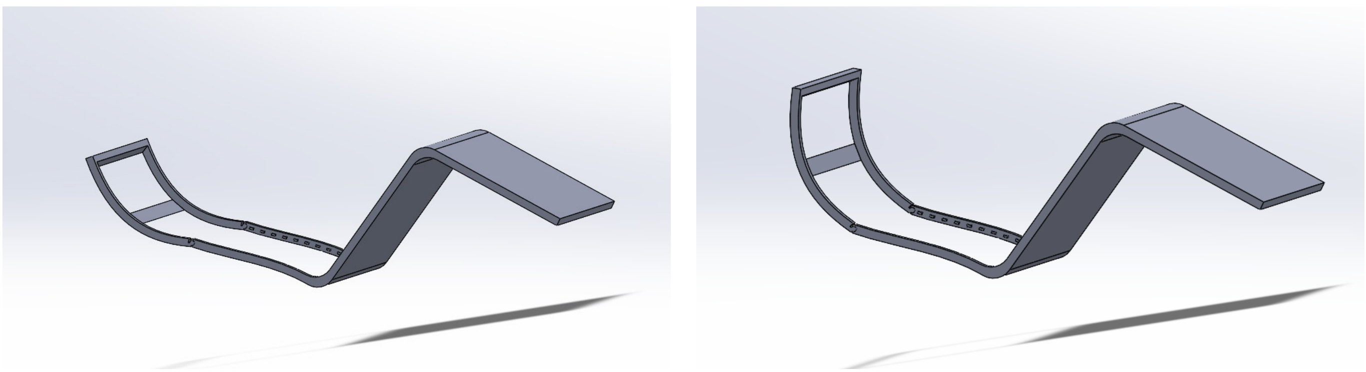
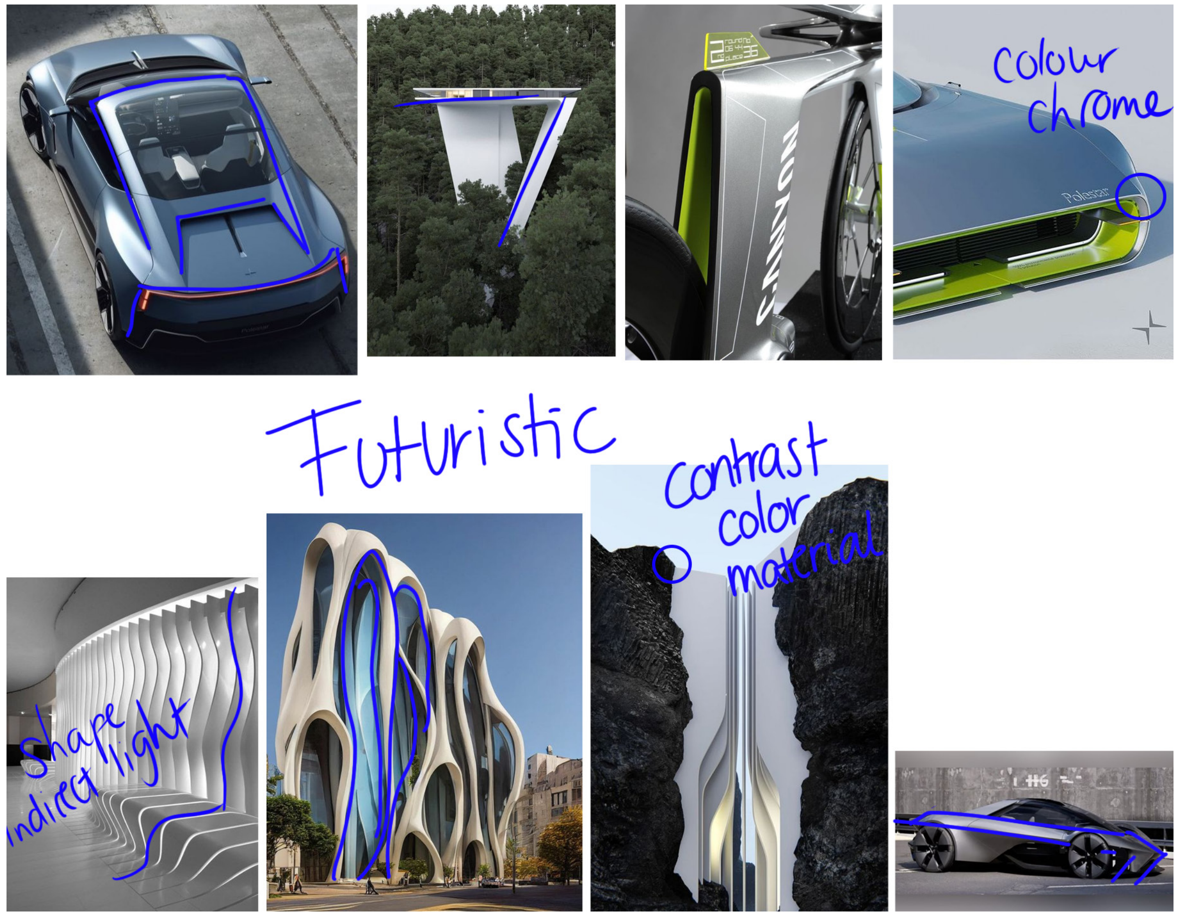
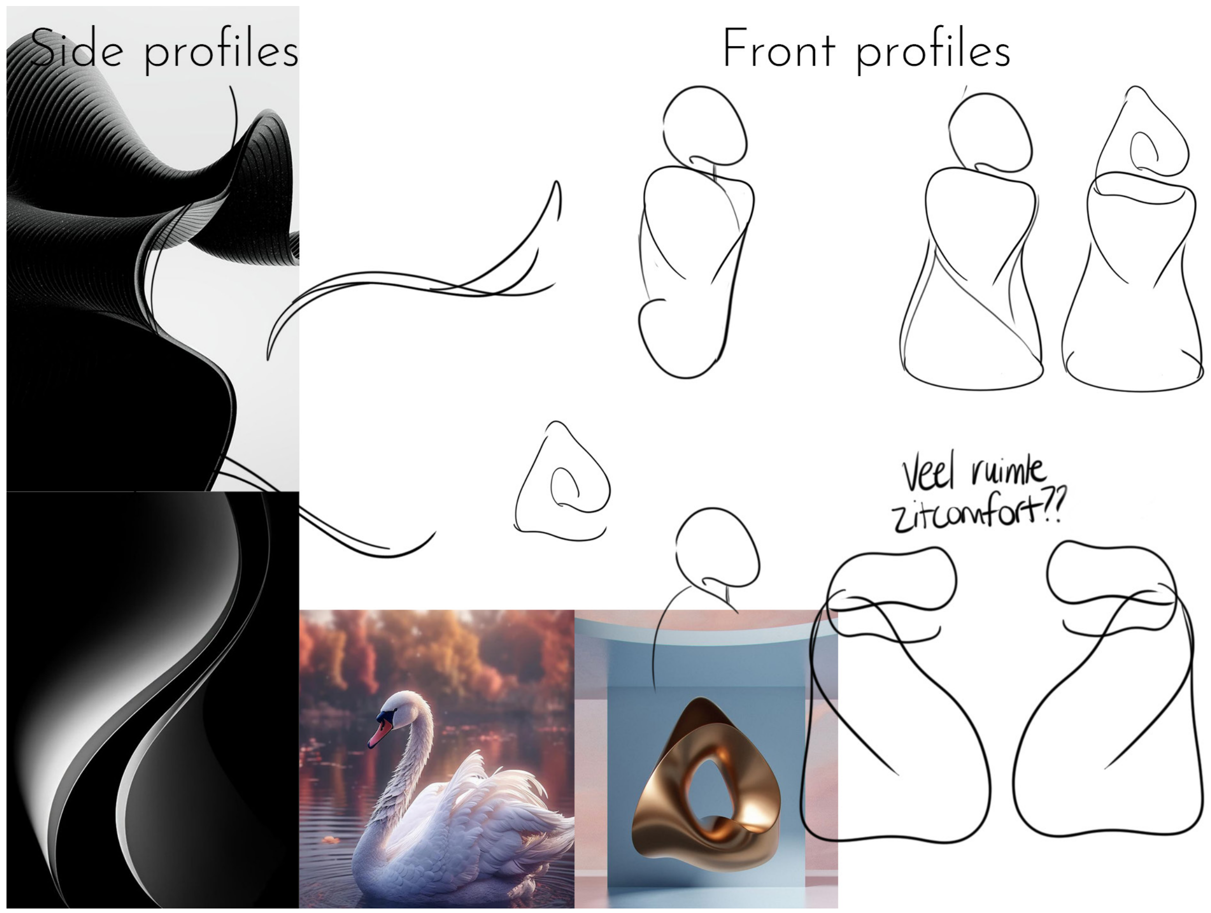


Figure 42: Simplified SolidWorks with hinging part

6.2 Design

Not only the mechanism is important, but also the design. Especially since the design influences the level of comfort a user experiences. Comfort is, as said before, associated with luxury, relaxation, well-being, safeness, and refreshment. Therefore, luxury is a word that has to fit the final design of the car seat. The seat should also look futuristic, since it is preferable to use the seat for future purposes, such as autonomous vehicles. Lastly, the target group is determined to be young urban professionals, these people are interested in luxurious and elegant products. A few products that these people use daily could be Apple or Dyson products, such as the iPhone or the Dyson Airwrap. These products have a certain amount of elegance. Therefore, moodboards of luxury, futuristic, and elegance were made.





6.3 Comfort vs. feasibility

After the initial ideation phase, the research results were evaluated. Simplified, I gave myself 5 options, from fixed to free++, see figure 43.
On the far left side, the option is just a lumbar support and no shoulder hinge. This has a low comfort and is not really an innovation. On the far right side, the option with a lumbar support, shoulder hinge, shoulder translation, lumbar hinge and lumbar translation is mechanically very complex, but gives the user a lot of freedom, making it more likely to improve comfort.
The choice was made to use on shoulder hinge, a lumbar support and a shoulder translation. The reason for this is that it will optimize the comfort, without complicating it mechanically. This exact combination was already made before within Brose. Mechanically it worked, but it was quite complex with around 30 motors in it. This also explains that the chair was really heavy. And lastly the OEMs thought the design itself was just not nice, see figure 44.

Fixed	Partly fixed	Free	Free+	Free++
lumbar support no shoulder hinge	lumbar support shoulder hinge	lumbar support shoulder hinge shoulder translation	lumbar support shoulder hinge shoulder translation lumbar hinge	lumbar support shoulder hinge shoulder translation lumbar hinge lumbar translation

Not an option to improve comfort —— Mechanically very complex

Figure 43: different directions to move forward in

Figure 45: Sketches based on the material moodboard

6.4 Finalizing ideation

When I knew what direction mechanically I was going towards, I started to sketch (figure 45). I made a fabric and material moodboard (figure 46). This was based on the guiding words elegance, futuristic and luxurious. A few things that immediately came to mind where the shape of the chairs, the trim, possibly with embroidery brand names and options for interesting stitching in the backrest.

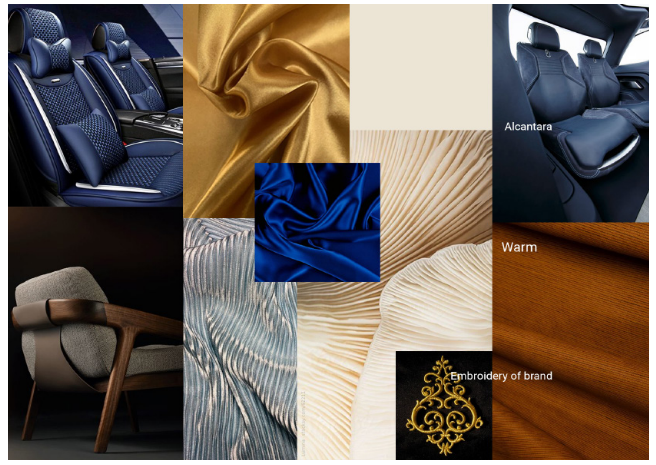


Figure 46: fabric and material moodboard

6.5 Final ideation sketch

When I showed my sketches to Jan Peukert, product designer at Brose, he told me that the sketches were not connect to the context (the car, the ride) and the user.
Therefore I choose to leave the blue and wood theme for now and look at the cars that I have assigned to the personas. These were a Mercedes Benz Maybach and an Audi Q6 E-tron. Since there is just limited time, the focus was on the Maybach (figure 47 and 48). The final ideation sketch can be seen in figure 49.

Figure 47: Collage made with images from mercedes-benz.de (n.d.)

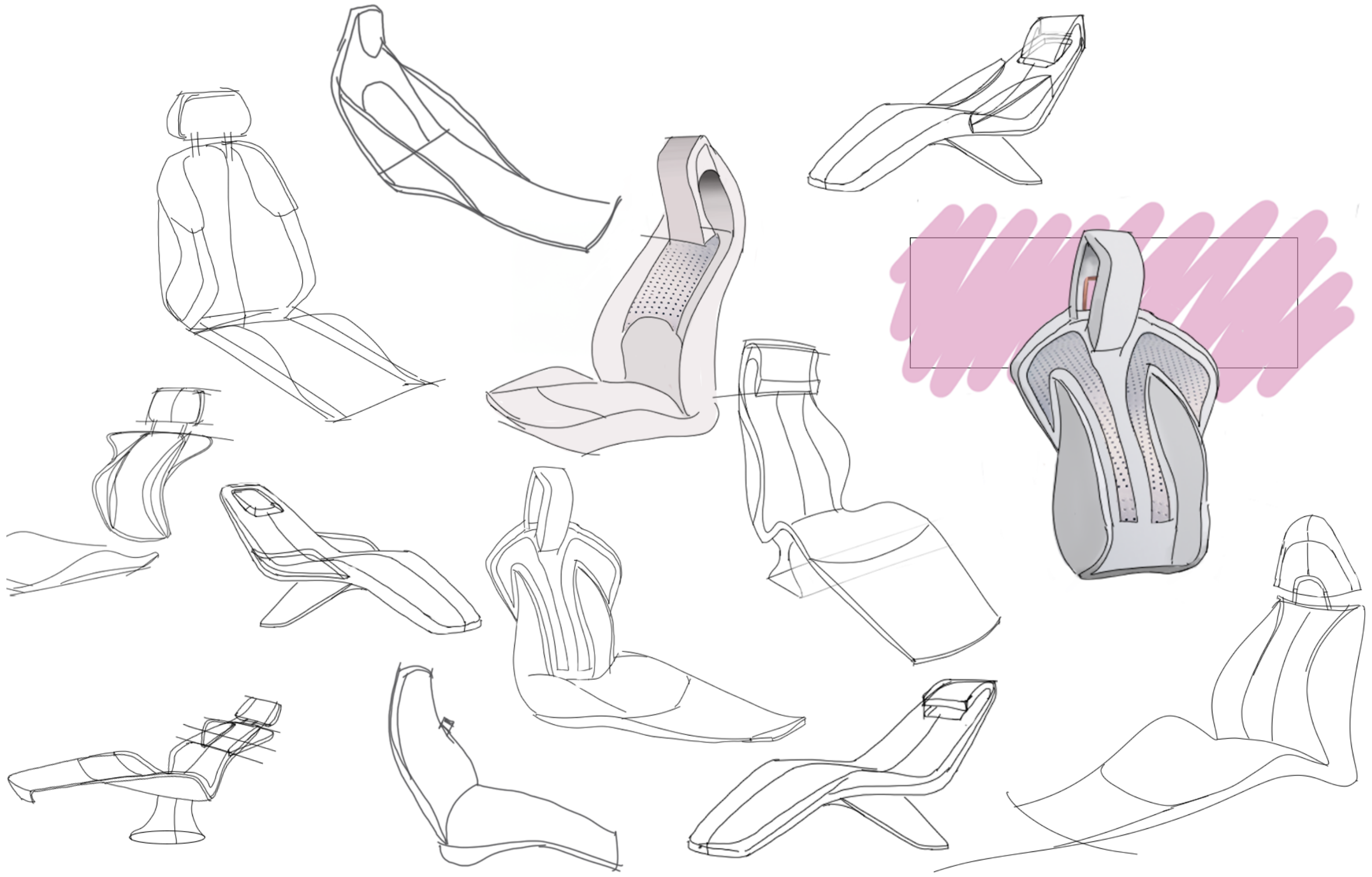


Figure 48: Ideation for Mercedes Maybach

Figure 49: Final concept sketch

IDEATION RESULTS

07

After establishing that the seat should have a shoulder hinging point and lumbar support, concept directions were created. This was done on the hand of some preliminary prototyping, which can be seen in figure 50. Based on the sketches and research on hinging mechanisms, some test pieces for a suspension mat and side bolster were printed. On the top right image, an auxetic piece can be seen; when this is stretched the material also expands in the perpendicular axis. For the concept directions, the focus is on the suspension mat. The concept directions are the beach chair, which is inspired by a hammock, and a hinging point, a bit similar to a shoulder adjuster (figure 51).

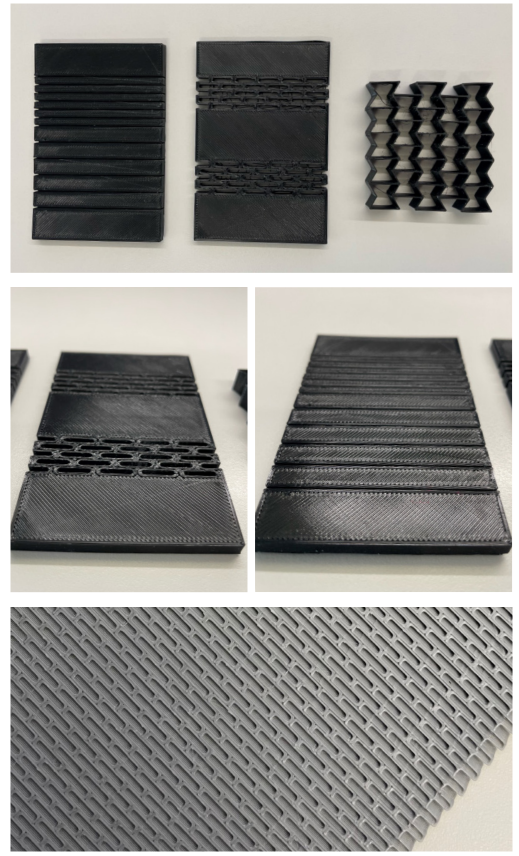
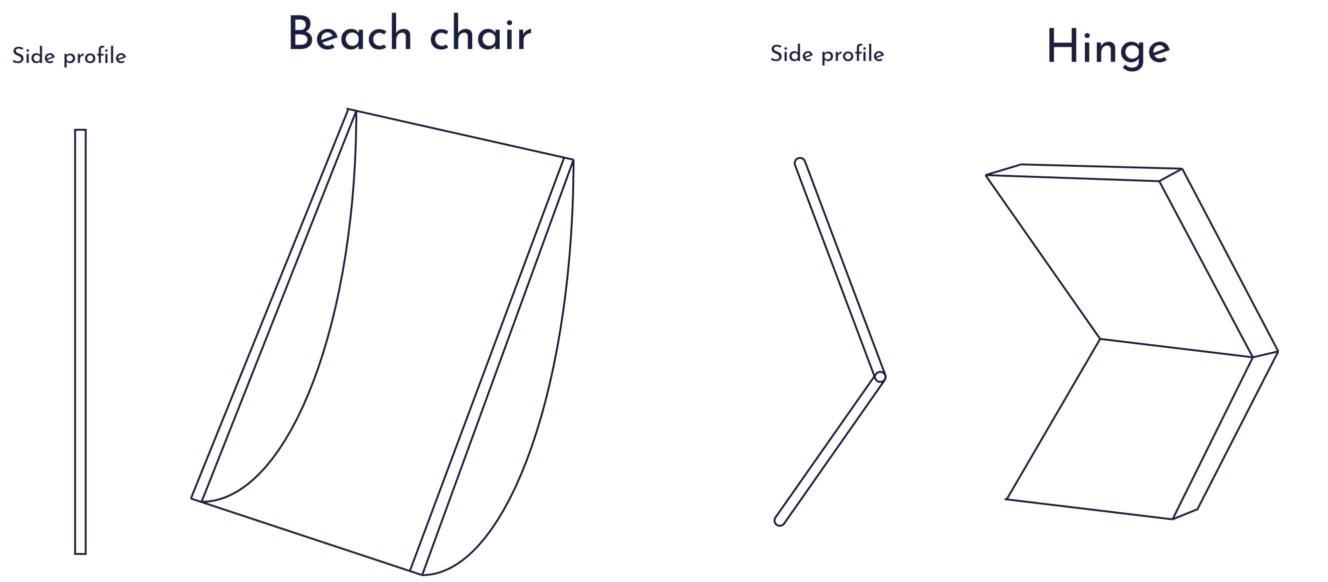


Figure 50: 3D test prints



Beach chair

- Translation is easily incorporated
- Should be a lot of stretch in the material
- How does that work with foam?
  - Side bolsters?

Hinge

- Translation will be on the bottom part of the hinge
- Little bit less stretch needed

Figure 51: Concept directions

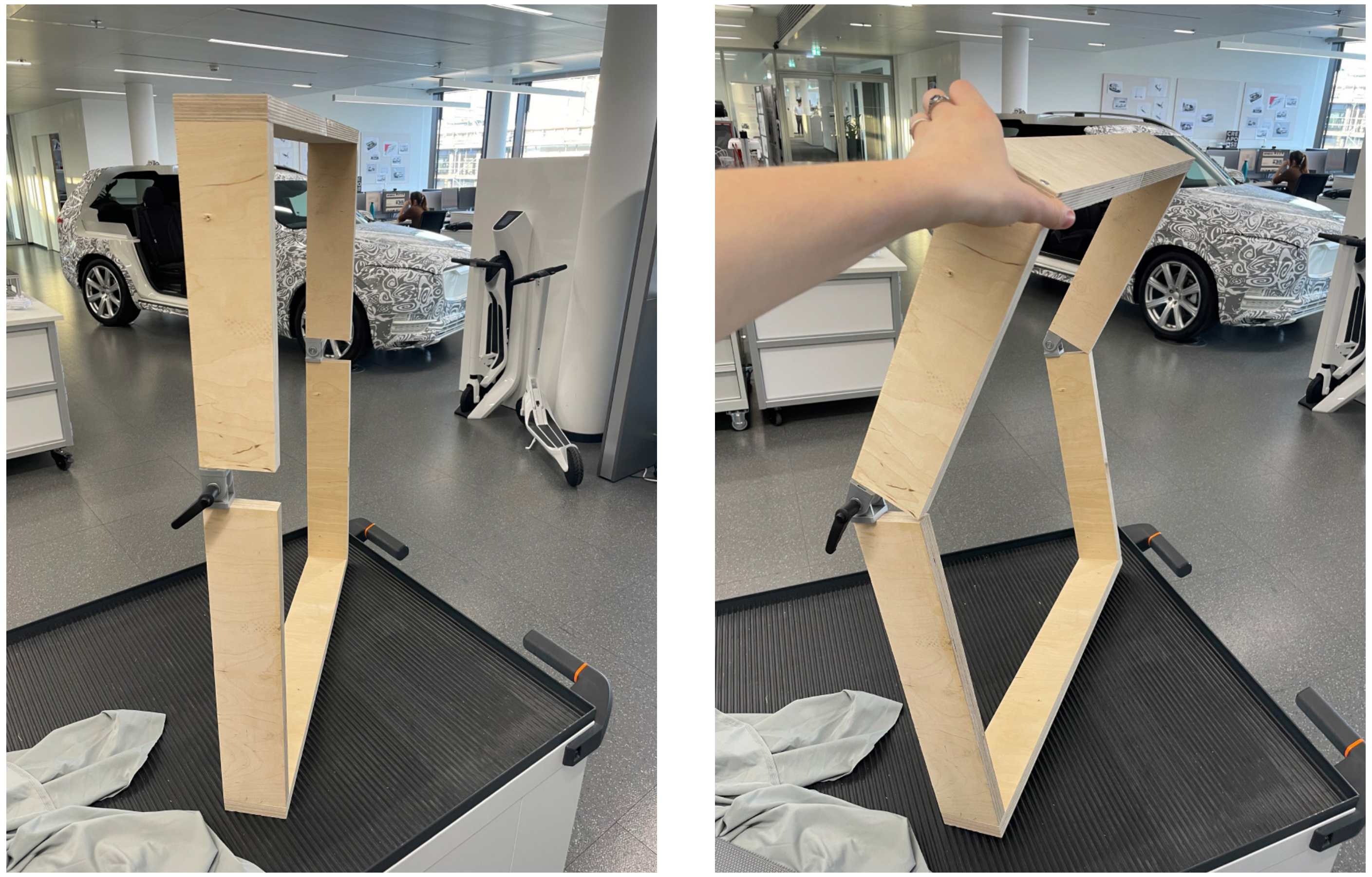


Figure 52 and 53: Hinging frame can also be locked straight

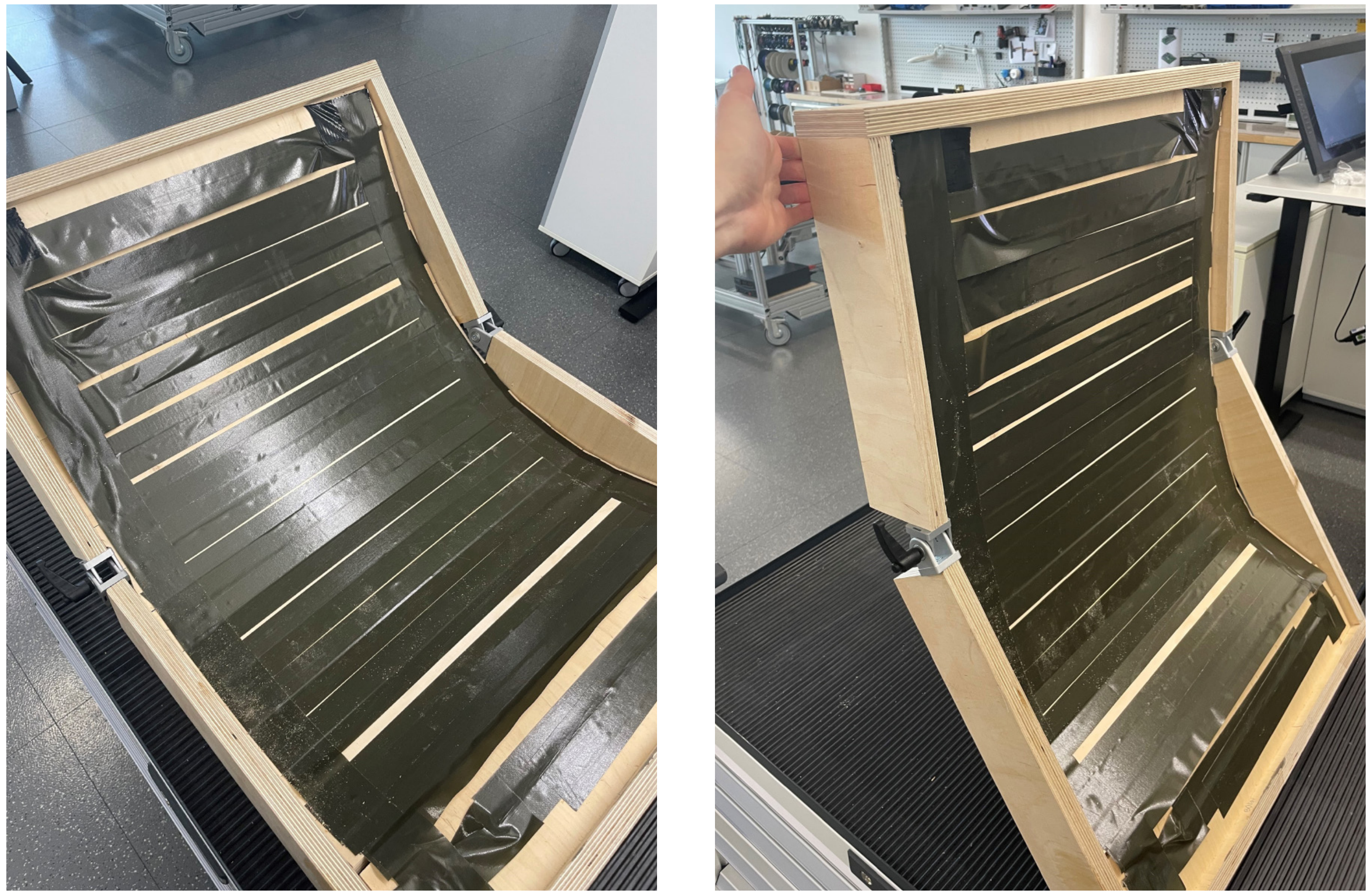


Figure 54 and 55 Hinging frame can also be locked straight

Before choosing the concept direction, some prototyping was done. With a wooden frame, with a hinge that can be locked, some tryouts were made (Figure 52, 53, 54 and 55). One of them is a wooden piece that can be locked at certain angles. In that way I can try both a hinging part and straight frame.

Concept choice

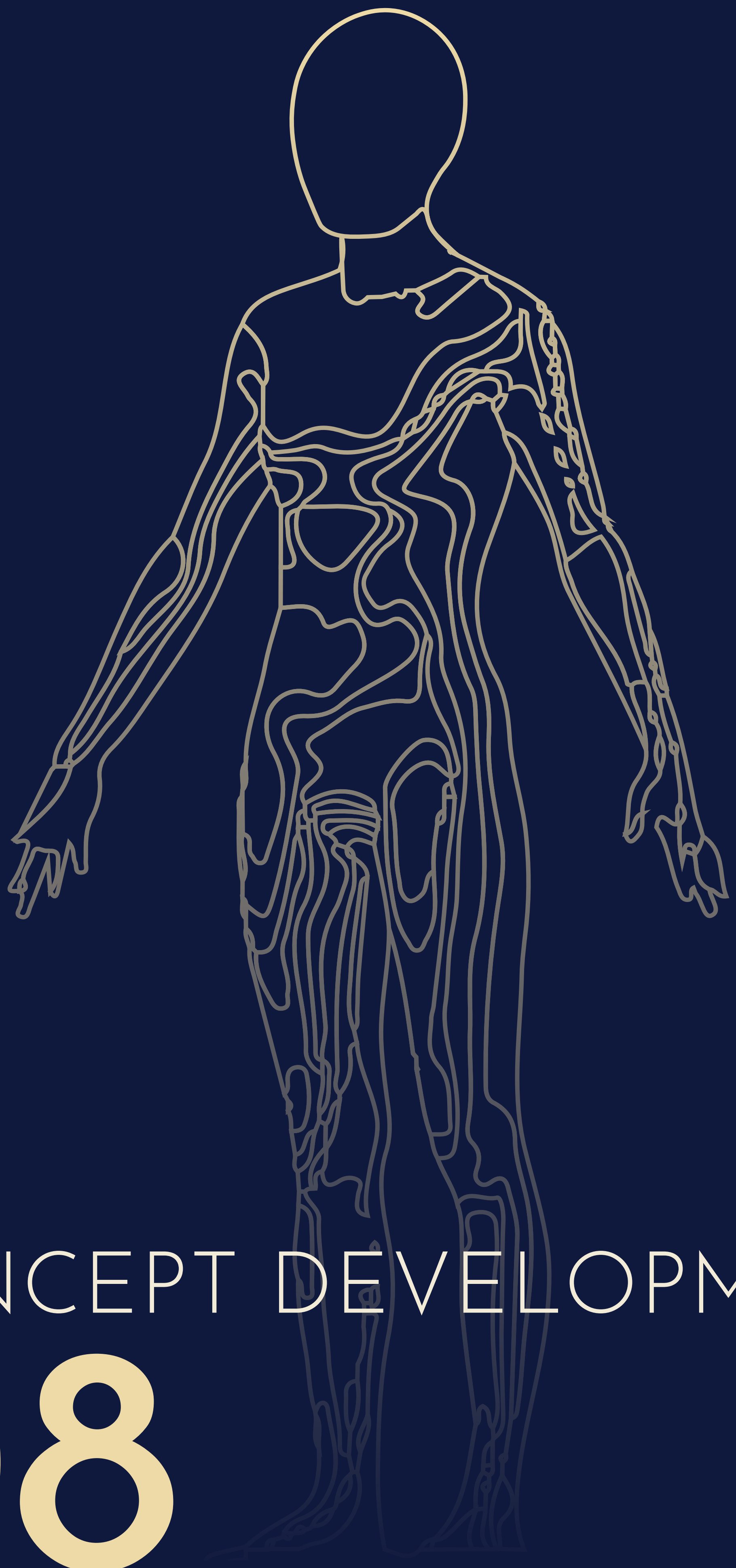
The concept choice is being made using the weighted objects method. The wish of the company is to create something interesting to show at design fairs. Therefore the weight of interesting new design is set at 5 and feasibility at 2. Table 7 shows an overview of the requirements that lead to this choice. It is chosen to use the beach chair principle. It is new, but feasibility is low (lower than the hinge principal at least).

Concept advantages

The chosen concept has a few advantages. It is something new and interesting, it should be easier to disassemble because the principle is quite simple. And lastly, there are options for the reduction of discomfort in the lower region of the back, when moving to the laying position. This is due to the hip rotation point. If the fabric is connected to the seatpan, in combination with rotating the seatpan, could reduce discomfort.

Table 7: Weighted objects method for concept choice

		Beach chair		Hinge		Combi	
Requirements	Weight (1-5)	Score (1-5)	Weighted score	Score	Weighted score	Score	Weighted score
Should be able to sleep, work and drive	5	5	25	5	25	5	25
Local production	2	4	8	5	10	4	8
Cleanability	1	5	5	5	5	5	5
Disassembling	2	5	10	4	8	3	6
Cost should not exceed 200% of a regular seat	1	3	3	3	3	2	2
Lightweight	3	5	15	3	9	3	9
Size can't exceed current seats	2	5	10	5	10	5	10
Should look luxurious and comfortable and futuristic	5	5	25	4	20	5	25
Should be comfortable for 5th till 95th percentile males & females	5	4	20	5	25	5	25
Should outperform on comfort; experience, emotion, unexpected features and luxury compared to current seats	5	4	20	4	20	4	20
All moving parts should be covered for safety reasons	2	5	10	5	10	5	10
Interesting new design for design exposition	5	5	25	3	15	4	20
Feasibility	2	1	2	5	10	4	8
	40		178		170		173



CONCEPT DEVELOPMENT 08

8.1 Suspension mat

Since the concept so far was just an idea for a mechanism, the following chapter is going deeper into this concept.

Big scale

Until now, all prototypes were done on a small scale. To get a feeling of the bigger picture, a wooden plate of 60x40cm was lasercutted (figure 56). Ofcourse, the final material won't be from wood, but it gave some insights in the scale.

Prototyping

From the earlier printed options two new options were created. Figure 58 shows a suspension mat from PLA, that is sewn together with fishing wire. Another option was a moveable part of TPU with the use of living hinging (figure 59). There was also thought about the idea of a length increase of the fabric (figure 57), which is also an option for the suspension mat, with some torque to tension the mat in the upright position.

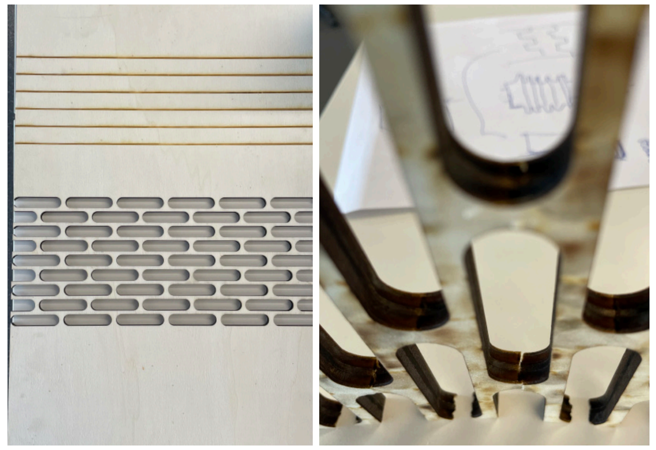


Figure 56: lasercutted suspension mat

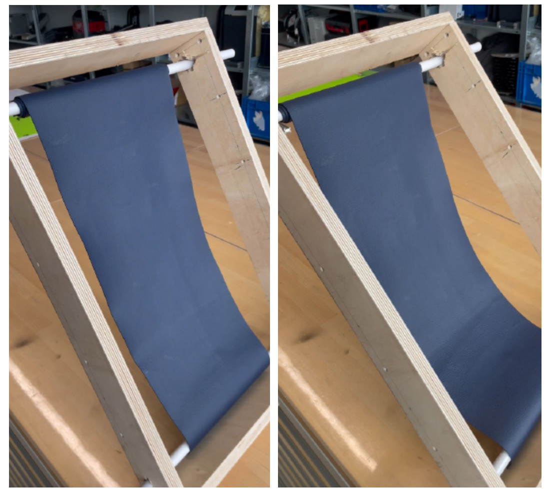


Figure 57: Length increase of fabric

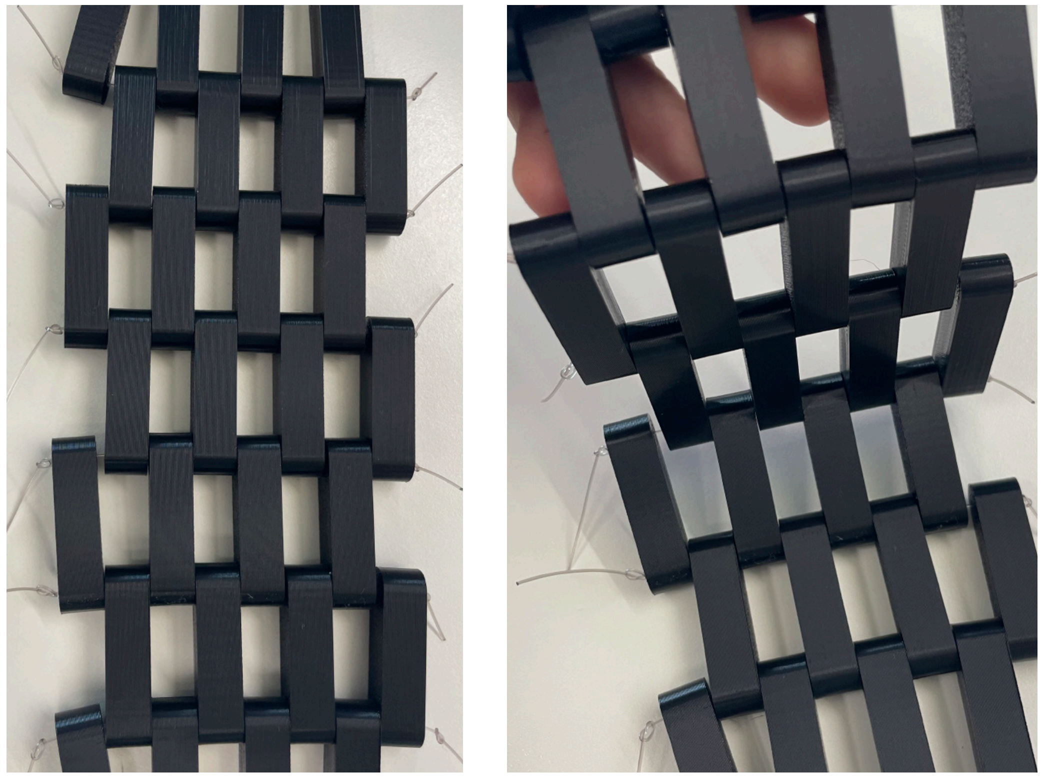


Figure 58: suspension mat PLA

Figure 59: suspension mat TPU

Material choice

After creating the suspension mat from PLA on a bigger scale (figure 60), the movement looked good. However, I had big doubts about strength. Since it has a lot of weak spots. Therefore a new print from TPU was created (figure 61), it was really flexible, however chosen was to go further with the pattern on figure 59.

The final choice for TPU over PLA is based on two reasons. The first one is that PLA wears out faster and the quality is a bit worse. Besides that, the design I created for PLA has a lot of weak spots. Due to the fact that the material itself is stiffer, movement had to be created in a different way, which gave the design weak spots.
The second reason is that TPU is really versatile, you can adjust the hardness at place where you need more support. Furthermore it has excellent bearing capacity, impact resistance and shock absorption. It can handle oil, water and funghi and it's recyclability is great. (Odin Mould Co. Ltd, 2019)

Final hinging choice

The vertical hinging works perfectly, but hinges over the entire mat. While the concepts before had the hinging parts in a horizontal direction (Figure 59 and 62). The area that should be hinging is only 20 mm and needs to hinge for 52 degrees. It will be a bit weaker if the hinging part is horizontal, but it will also hinge more. Therefore that is the final choice.

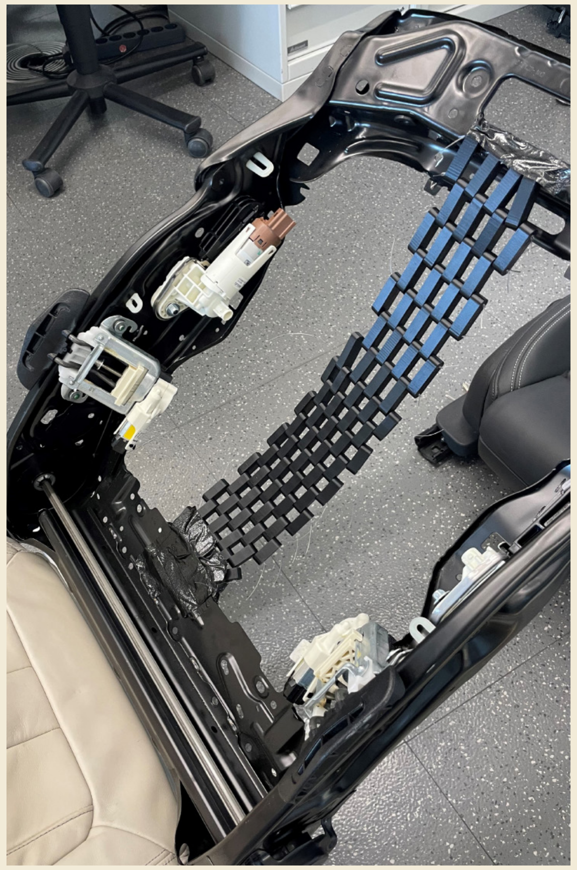


Figure 60: Suspension mat PLA on big scale

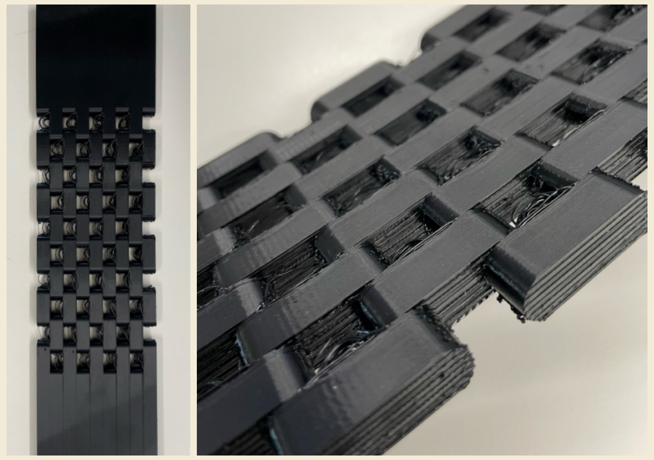


Figure 61: Suspension mat TPU

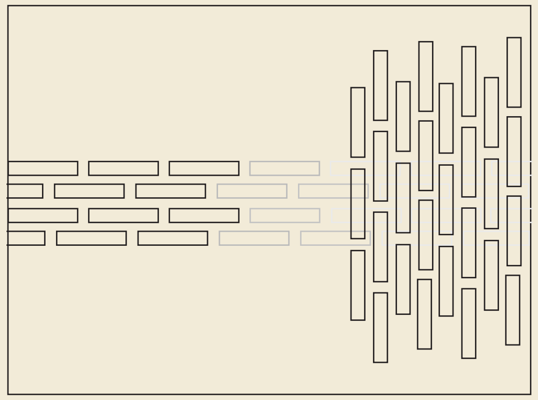


Figure 62: Living hinge direction

8.2 Anthropometry

After understanding that the principle worked, a look was taken at the horizontal cross-section contour of the backrest. Therefore the data of the participants in the study was used and put in DINED.

Unfortunately, DINED doesn't support sitting height and hip breadth in its mannequins. To still be able to get some information on expected curvatures of the back, the statures of the persons were used and the hip circumference was 'calculated' on the hand of hip breadth.
For example, the person with the smallest hip breadth was 334mm. This was filled in, in DINED and gave percentile 1.25. This was then used to get a hip circumference (so p1.25 give a hip circumference of 780mm). This is not fully accurate; someone can maybe store more fat in their belly, making the circumference bigger than the hip breadth, but it gave some insights.

I established three groups; group 1 are all the participants from the research study, group 2 participants with smallest hip breadth and group 3 with widest hip breadth (table 8 and 9). Figure 63 shows the sample sizes distribution based on their stature and hip cirumference.

Table 8: Participants smallest hip breadth

P0 - P1	F/M	Hip breadth	Sitting height	Stature
Participant 8	M	34.9	93.8	176.1
Particpant 9	F	33.4	81.9	158.1
Participant 21	F	34.3	88	168.4
Participant 22	M	33.4	90.5	180.6

Table 9: Participants widest hip breadth

P93 - P99	F/M	Hip breadth	Sitting height	Stature
Participant 7	F	44.5	83.7	158.6
Particpant 13	M	48	92	176.5
Participant 14	M	43	93.5	189.5
Participant 17	F	43	88	165.5

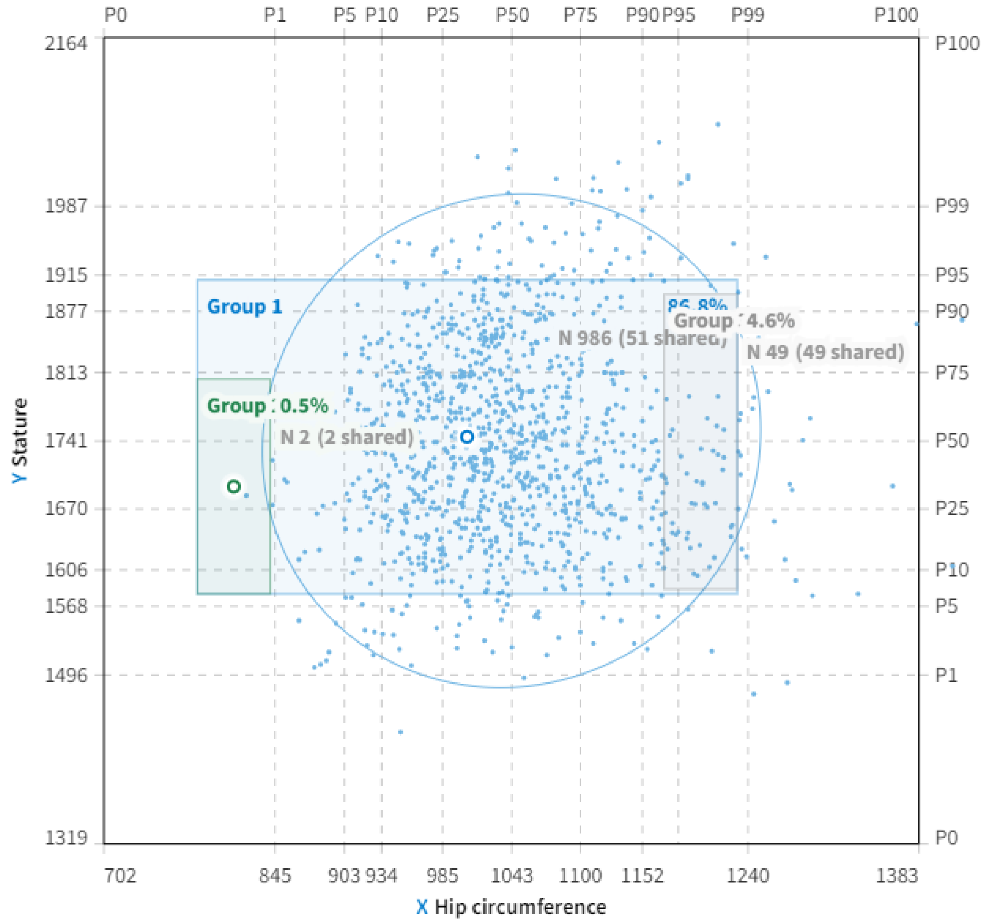


Figure 63: participant compared to DINED database

Since the groups are part of the sample group and are actually P0-P1 and P93-P99. DINED was used to create a P5 model, both P5 stature and hip circumference, and P95 model (figure 64). These models were then reversed engineered in a horizontal curvature. The process of this can be seen in figure 65 and 66.

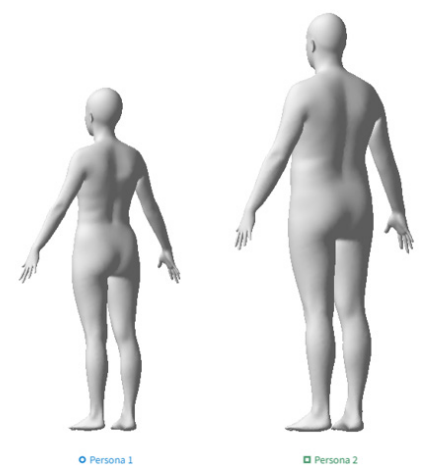


Figure 64: Back of P5 and P95

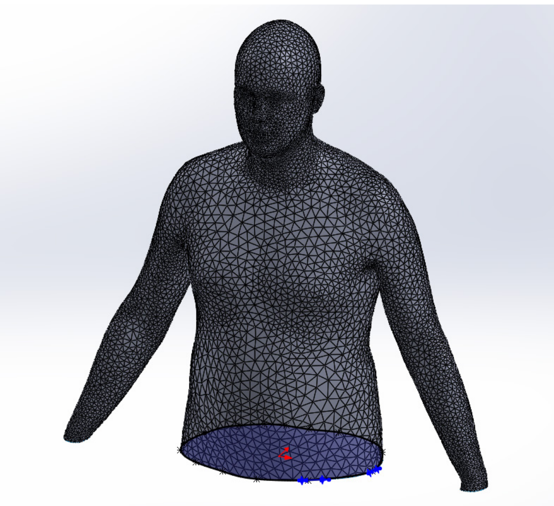


Figure 65: P95 reverse engineering the curvature

These horizontal cross-section contours were compared with the research from Hiemstra-van Mastrigt (2015), figure 67. For both areas (buttock and shoulders), the width is set on 450mm.

As said earlier, it is important to have enough freedom while sleeping in a seat, therefore the circumference around the hips is a bit wider than P95.

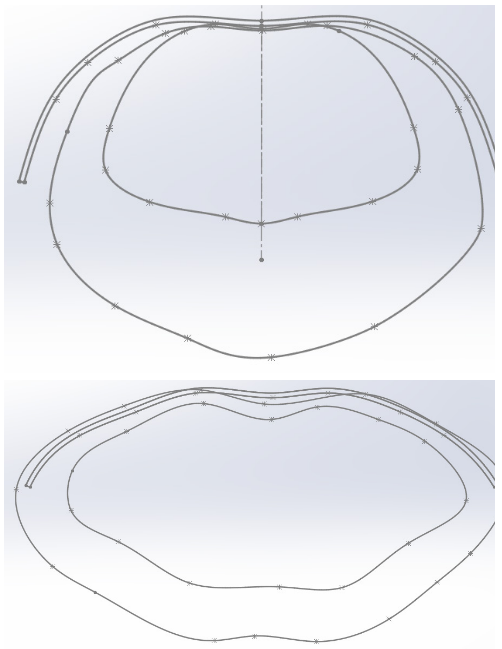


Figure 66: Top: P5 and P95 around the hip area, bottom: P5 and P95 around the shoulder area

Then the curvature that was researched is also incorporated. Figure 68 shows those results, at 114 and 140 degrees. These results were compared with what Hiemstra-van Mastrigt (2015). While there is no angle at the shoulder area, the height seems to be a lot smaller. However, Hiemstra-Mastrigt's priority was the thickness; not the length. The lumbar area seems relatively similar. Chosen was to follow

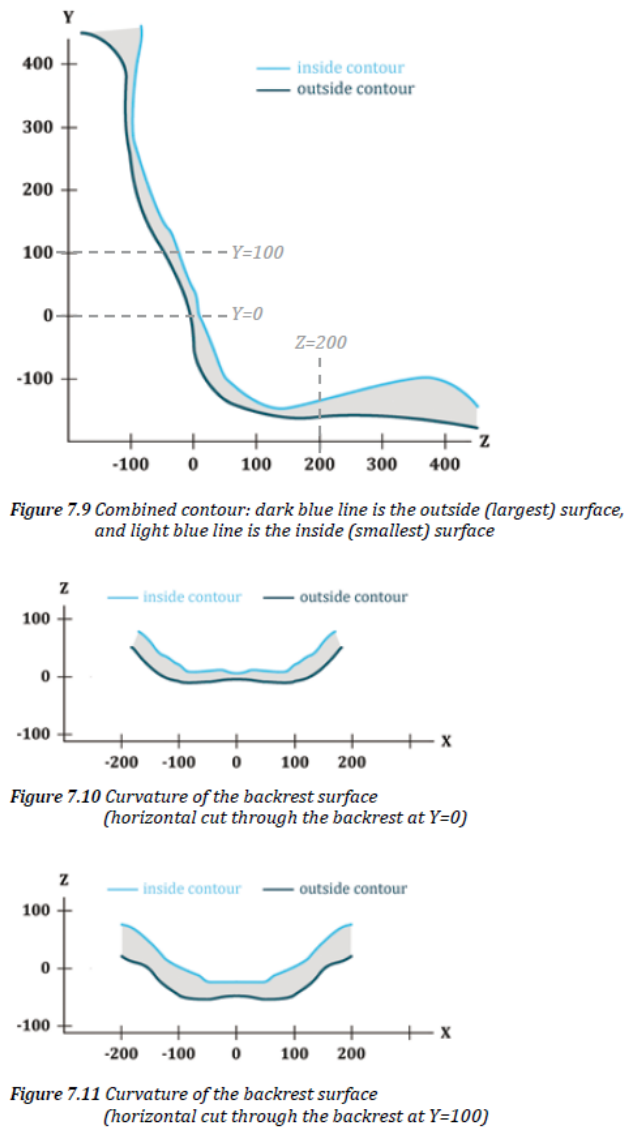


Figure 67: Curvature of backrest surface at Y=0 and Y=100 (Hiemstra-van Mastrigt, 2015)

the results of the research. This horizontal curvatures and vertical curvatures were together lofted into the final design as can be seen in figure 69.

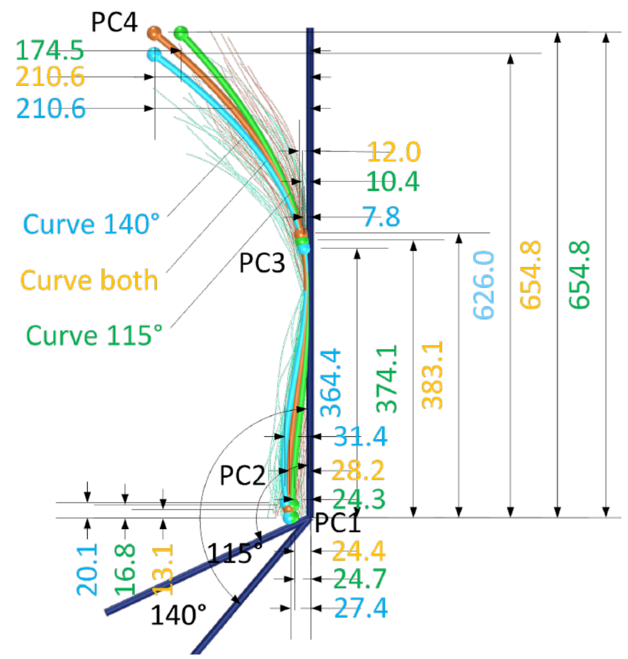


Figure 68: Back of P5 and P95

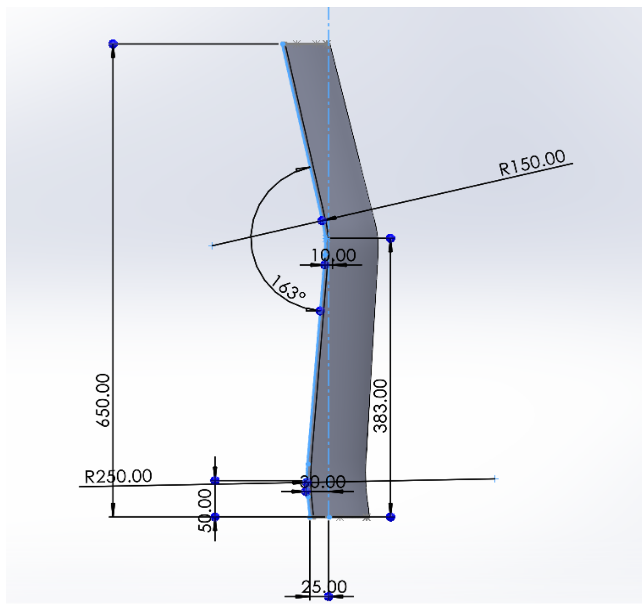


Figure 69: Loft follows the curvature established in the research study

8.3 Materials

Organosheet

When visiting the production facility in Coburg, Jochen Hoffman showed me organosheet. Organosheet is a fiber-reinforced composite made of carbon or glass fiber fabric embedded in a thermoplastic matrix. It can save up to 60% of weight compared to metals (Ensinger Plastics, n.d.). Organosheet has a lot of good mechanical properties and is very lightweight, however not environmentally friendly (Jochen Hoffman, personal communication, 21st of February 2024).

TNO is a Dutch company that looks at the end of life of wind turbine blades, which are made of glass and carbon fiber, just like organosheet. Wind turbine blades can go for around 25 years. Each year there are around 4 million tons of blade waste. Glass and carbon fibers are suitable for reuse, however mechanically or chemically recycling has disadvantages. Therefore, TNO and Brightlands Materials Center use pyrolysis, which is heating the material at 500 degrees Celsius, which releases the fibers. The fibers are then usable in thermoplastic composite which can be used in recyclable products (TNO, 2022)(figure 71).
TNO expects that the first demonstration can be done in 2026 (TNO, n.d.). It will probably take a few more years to set up a production facility. Therefore, I expect that in 2030 it might be possible to use this material. I want to use the carbon fiber-reinforced composite for the frame.

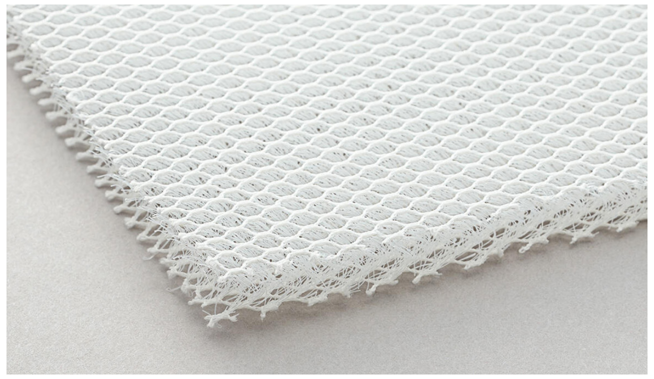


Figure 70: Cubit™(Asahi Kasei, n.d.)

Figure 71: Reusing windturbineblades to create new products with carbon fiber (TNO, 2022)

Cushioning

There is no such thing as a standardized foam. There are thousands of options if it comes to foam (Caroline Lederle (Ziegler), personal communication, 18th of April, 2024). Avek (2024) shows the different ISO norms, such as density, hardness, stiffness, elongation and tensile strength, elasticity, plastic deformation, and dynamic fatigue. The higher the density of the foam, the longer the expected lifetime is. And the level of hardness is for example higher in a chair than in a mattress (Avek, 2024). For the backrest, it makes most sense to use multiple layers of foam, one layer for initial comfort feeling and one layer of longer duration, which will just added on top of eachother. Ziegler creates nonwoven 'foams' that are made from fibers (figure 72). They are put together thermally or needled. Nonwoven foams are more sustainable than traditional foams, however non-woven is not durable enough without an extra layer of foam and can't just cover a structure (Caroline Lederle (Ziegler), personal communication, 18th of April). This is another reason to put two levels of foam on top of each other. Furthermore, complex molding of nonwovens is not possible, this is too complex. There is also a risk of durability; it is just not as good as normal foam. Nonwovens do have a very good air permeability. To try out this principle it makes most sense to put a thin, soft layer of a few millimeters on top of a more hard layer of foam. However, foam is not sustainable at all so a look was taken at spacer fabric. It has good air permeability, is flexible, the middle layer of the spacer fabric is quite stiff, which keeps the shape and bounces back after use. Car seat cushions made of warp knitted spacer fabrics can offer good mechanical support and physical comfort to the driver's body, and are stronger than polyurethane foams (Gokarneshan & Velumani, 2018). It is importanted to note that Krumm et al. (2020) concluded that the use of war knitted spacer fabric is prefered in backrest cushioning, but not in seat pan cushioning, where foams are prefered. This has to do with the fabrics inability of reducing seat transmissibility.

Figure 72: HACOsoft (J.H. Ziegler GmbH, n.d.)

Spacer fabrics are already used in the automotive industry, since they are lightweight, stay in good condition and have good air permeability which makes it ideal as comfortable cushioning material.
A company that creates this is Asahi Kasei. Their branded spacer fabric is called Cubit (figure 70) and is made from 3 layers of PET, with a thickness of 3.0 to 20 mm. PET-PET-PET is best for recyclability, compared to other spacer fabrics.
The weight is somewhere beween 250-1.200 g/m^3 (Asahi Kasei, email, April 17, 2024)

8.4 Evaluation with experts from Brose Sitech

After constructing this idea for cushioning, I contacted Patrick Konkiel, who works as *Modulkonstrukteur* for Brose Sitech, which focuses on concept development of complete seats.
Together with five of his co-workers, we talked about my ideas.

There is no system for seats that is really sustainable and comfortable. He suggest to choose one of the two; if you go for comfort, go with the classics. A seat that at the moment has great comfortability is The VolksWagen Tiguan. The shape of the foam is important, especially the backrest.

The B-side of the foam is stiff for support. However, some cut out slots on the back make it possible to let the foam move. Interesting is that the A-side of the Tiguan seat is almost flat. The position of the channels of the trim cover are on a really great spot, making it appear that the trim is one piece. With a small hook the trim is connected in such a way that it doesn't wrinkle.

In general, the important facts are:
- Cold cured foam / MDI
- Gross density
- Compression stress

(Patrick Konkiel, Modulkonstrukteur at Brose Sitech, personal communication, 3rd of May, 2024)
Cold cured foam has durability as its main benefits. Because it is cured at a lower temperature the foam cells are compact and makes the foam less prone to break down over time. It also has the ability to return to its original shape after being compressed (*Cold cured HR foam*, 2023).

8.5 Final choice

As ludicrous it might be to go against people with a lot of knowledge, I decided not to go with the VW cushioning and will focus on the spacer fabric with a layer of nonwoven on top. One of the reasons is that different studies (Gokarneshan & Velumani, 2018; Krumm et al., 2020 and Guo et al., 2021) show that there are benefits from using spacer fabric compared to polyurethane foam. Cushions of warp-knitted spacer fabric (figure 73) are better at reducing peak pressures (Gokarneshan & Velumani, 2018), excellent performance in breaking strength, tearing strength and air permeability (Guo et al., 2021).

Important to note is that Krumm et al. (2020), who researched seat transmissibility, concluded that the preference of warp knitted spacer fabrics over foam is just for the backrest cushioning. The seat pan cushioning should prefer foams, unless spacer fabrics were redesigned and proved their ability to reduce seat transmissibility (Krumm et al., 2020).

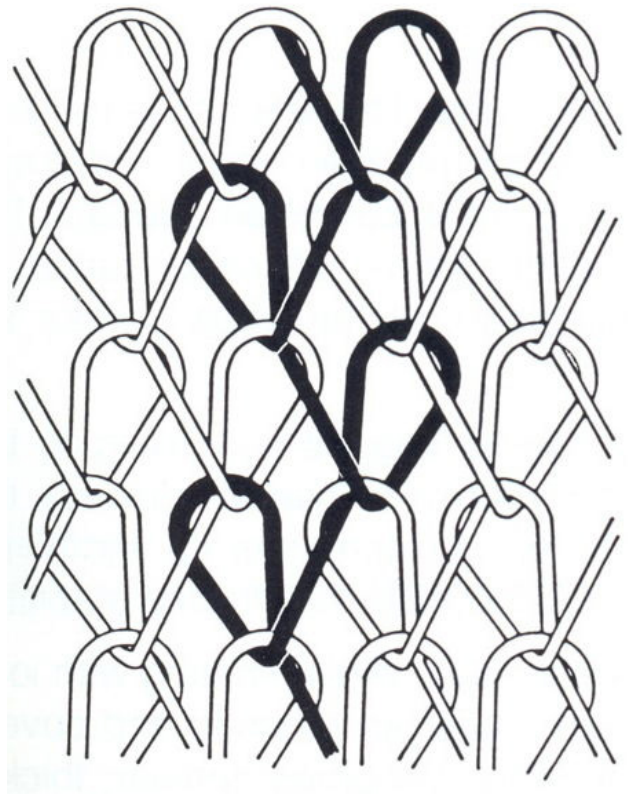


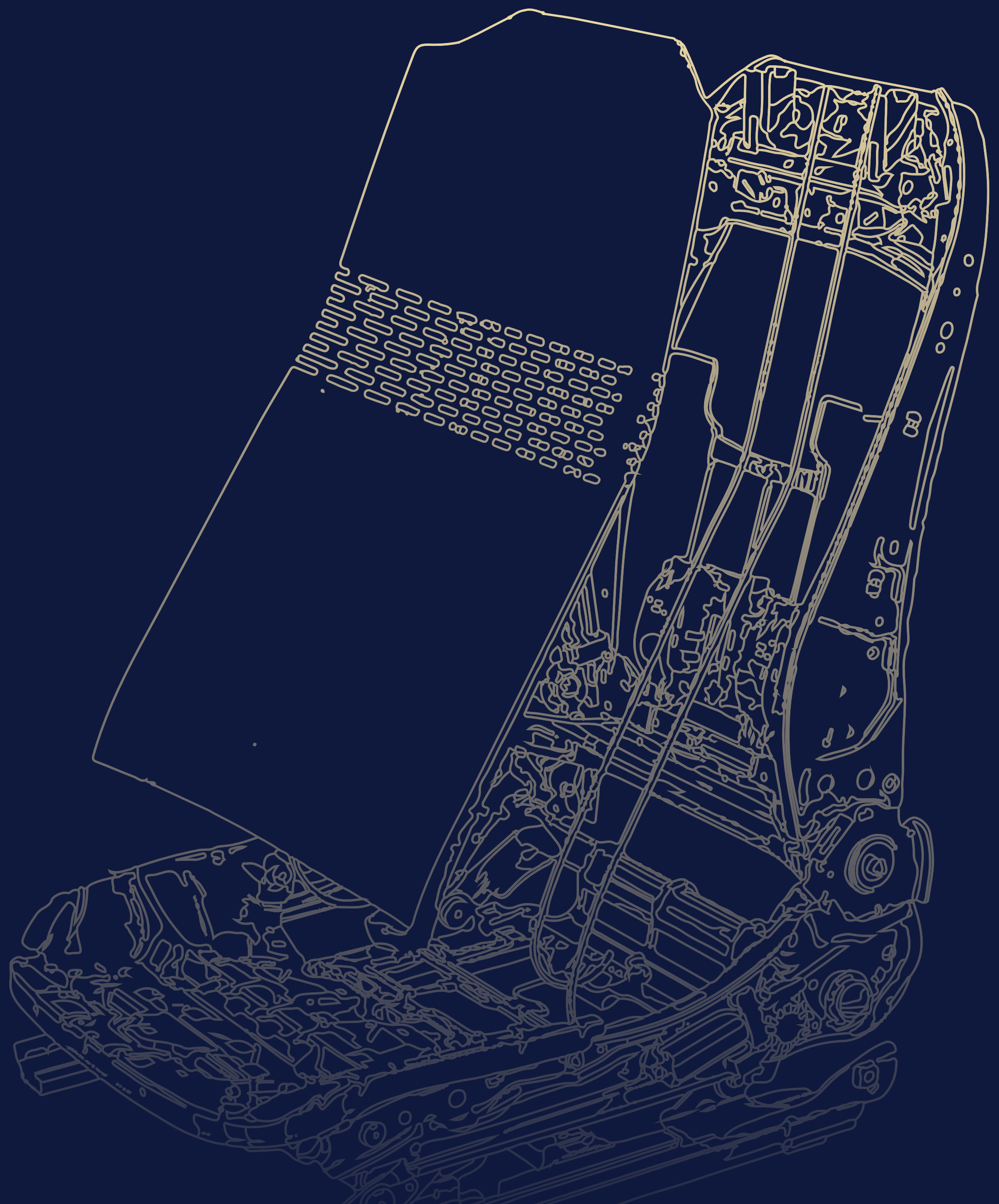
Figure 73: Warp knitting pattern (Wikipedia contributers, 2024)

Thicknesses and dimensions

A second conversation with Caroline Lederle from Ziegler, gave some insights on comfortability. She suggested, to drop the spacer fabric since it is quite expensive. Unless it is a climate seat. Most comfortable seats have a massage function and cooling system. So for the future I think it makes sense to keep the spacer fabric.

In general the thicker the foam or nonwoven, the better the comfortability (Caroline Lederle, personal communication, May 16, 2024). It makes sense to have a harder layer on the bottom and a softer layer on top. 75mm is the thickest they can offer. The options are a one-layered construction and a two-layered construction. If there is only one layer, it is important to take a hard foam or nonwoven. If a two-layered construction is used, she adviced a 50mm thickness with a density of 40 kg/m^3. And on top of that a nonwoven with a thickness of 25mm and a density of 20 kg/m^3. In a personal conversation with Jochen Hofmann, we discussed the thickness of the seat. Whereas he agrees that 70-80mm of foam is needed in the seatpan, it is not needed in the backrest. Often the meat-to-metal thickness in the backrest is 40 to 50 mm, since there is less pressure.

Hofmann et al. (2023), shows that a thinner seat foam not immediately leads to less discomfort. By better distributing the regions where thicker foam is needed, a reduction of 40% of foam was done without any negative impact on comfort.
The exact regions where more or less foam is needed should be worked out in a future project.



FINAL CONCEPT
09

9.1 Final design

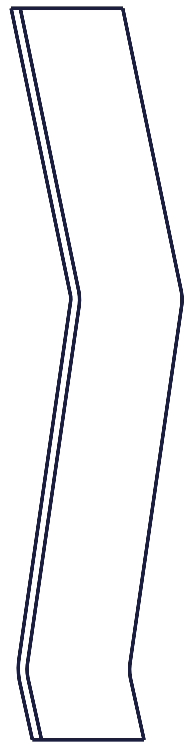
The final concept consists of a suspension mat of TPU, that is being tensioned at an upright position. As soon as the seat is moved in a laying position, the tension is released, giving the backrest a curvature. This is done on the hand of 4 wires in the backrest, see figure 74. The TPU is flexible enough to make the backrest rounded at the shoulder area.

On top of the TPU layer, a layer of spacer fabric is placed. As said before the total meat-to-metal is 40-50 mm and in general, the thicker the more comfortable.

The TPU will be 5 mm, it is just there to help guide the curvature. On top of that is 6 mm of spacer fabric. Guo et al (2021) used a thickness of 6mm which had excellent comprehensive properties and could be used in lamination car seat fabric for middle layer.
Than a 25mm layer of nonwoven with a density of 40 kg/m^3 and on top of that a 15mm layer of nonwoven with a density of 20 kg/m^3.

Shore hardness

The suspension mat will be made from TPU 70 shore A. The number gives the amount of resistance the material has when pressed. The higher the number, the higher the resistance of the material. The lettes A or D shows the scale which is used when the material is tested. Both scales go from 0 to 100. Where 0 shore A is extra soft, 0-30 shore D is middle hard (equal to 60-80 shore A) (*Wat is de Shore-hardheidsschaal*, 2024).



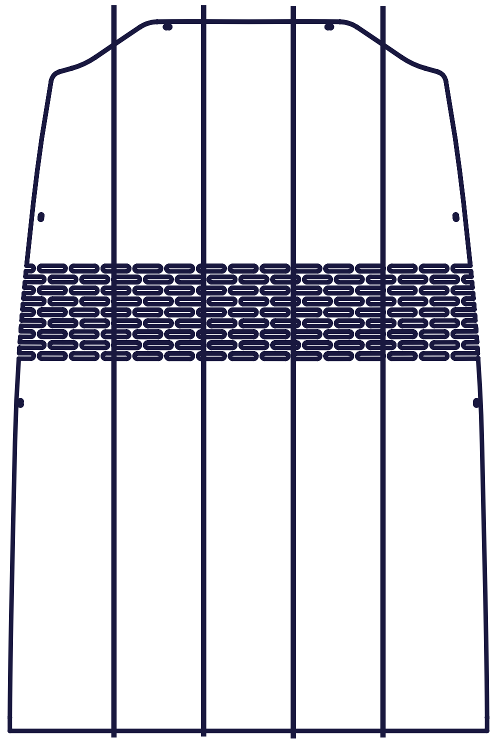
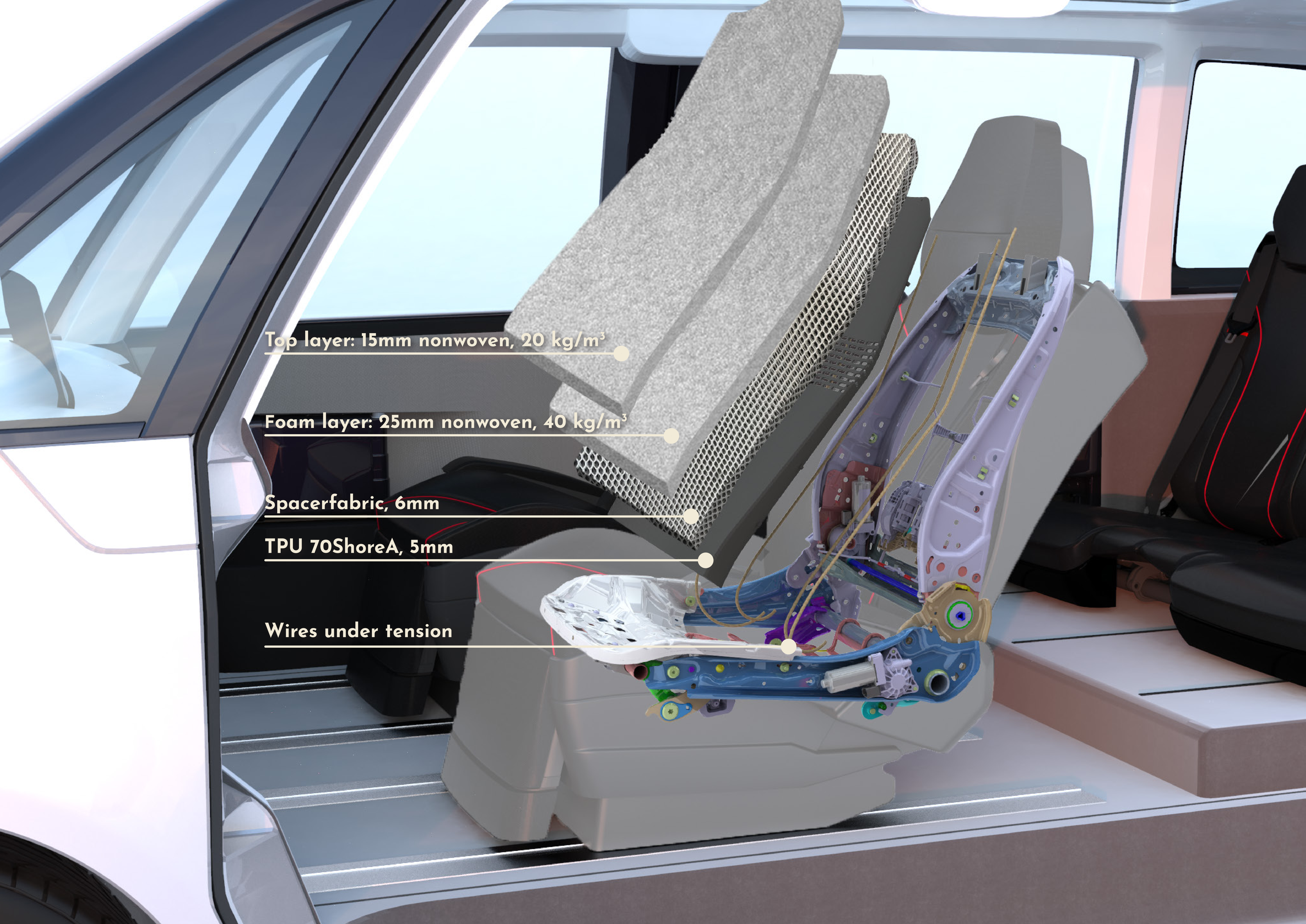


Figure 74: Final TPU design



Top layer: 15mm nonwoven, 20 kg/m³
Foam layer: 25mm nonwoven, 40 kg/m³
Spacerfabric, 6mm
TPU 70ShoreA, 5mm
Wires under tension

9.2 Requirements check

On the hand of the requirements the design of the last page will be evaluated. Table 10 shows all the requirements and wishes. If the requirement is met, yes is indicated. If the requirement is not met, no is indicated. If not sure yet, maybe is written down and explained in the next paragraph.

Table 10: Final concept check

1. The seat should be able to be used for both driving and sleeping or other relaxing activities. This means that the seat should move from 115 to 140 degrees.	**YES**
2. It should keep the user in place while driving.	**YES**
3. The seat should be able to be produced locally, to avoid shipping.	**YES**
4. The seat should be able to be cleaned properly, to keep a long lifespan.	**YES**
5. The seat should be made in such a way that maintenance can easily disassemble broken parts.	**YES**
6. The costs of the seat should not be more than 200% of regular car seats.	**MAYBE**
7. It should be able to create the new seat in-house at Brose's already existing facilities.	**YES**
8. The seat should be as light as possible, to reduce the environmental impact.	**MAYBE**
9. The size can't exceed the size of current car seats, since it should be able to fit in current cars.	**YES**
10. The structure shouldn't exceed 20 kg.	**YES**
11. The weight shouldn't exceed 30 kg, the weight of a highly equipped seat (there are also seats up to 50-70 kg) (Jochen Hofmann, personal communication, 21 February 2024).	**MAYBE**
12. The seat should look luxurious and comfortable.	**YES**
13. The appearance of the seat should show that it is meant for future purposes.	**YES**
14. The seat should outperform on comfort; experience, emotion, unexpected features and luxury, compared to current seats.	**YES**
15. The seat should be able to find in different configurations of cars.	**YES**
16. The seat should be comfortable for 5^{th} up and till 95^{th} percentile males and females.	**MAYBE**
17. The seat should have a lower discomfort; physical characteristics, compared to current seats.	**MAYBE**
18. All moving parts should be covered.	**YES**
19. The user should be kept in place in case of an emergency, in the laying position.	**YES**
20. The seat should be able to disassemble in a way that products or parts of products can be reused or recycled.	**YES**
21. The final seat should have a recyclability of at least 50%.	**YES**
Wishes	
22. The production of the seat should have 5% less energy usage than current seat production.	**NO**
23. In the sleeping position submarining should be prevented.	**YES**

In this next paragraph a further explanation of the **MAYBE** answers is given.

6. The costs of the seat should not be more than 200% of regular car seats.
Both spacer fabric and TPU are rather expensive. Especially compared to foam. Furthermore, organosheet is more expensive than a steel frame. However, no exact costs of current seats are known. So yes, it will be more expensive than currently, but how much more expensive is hard to tell.

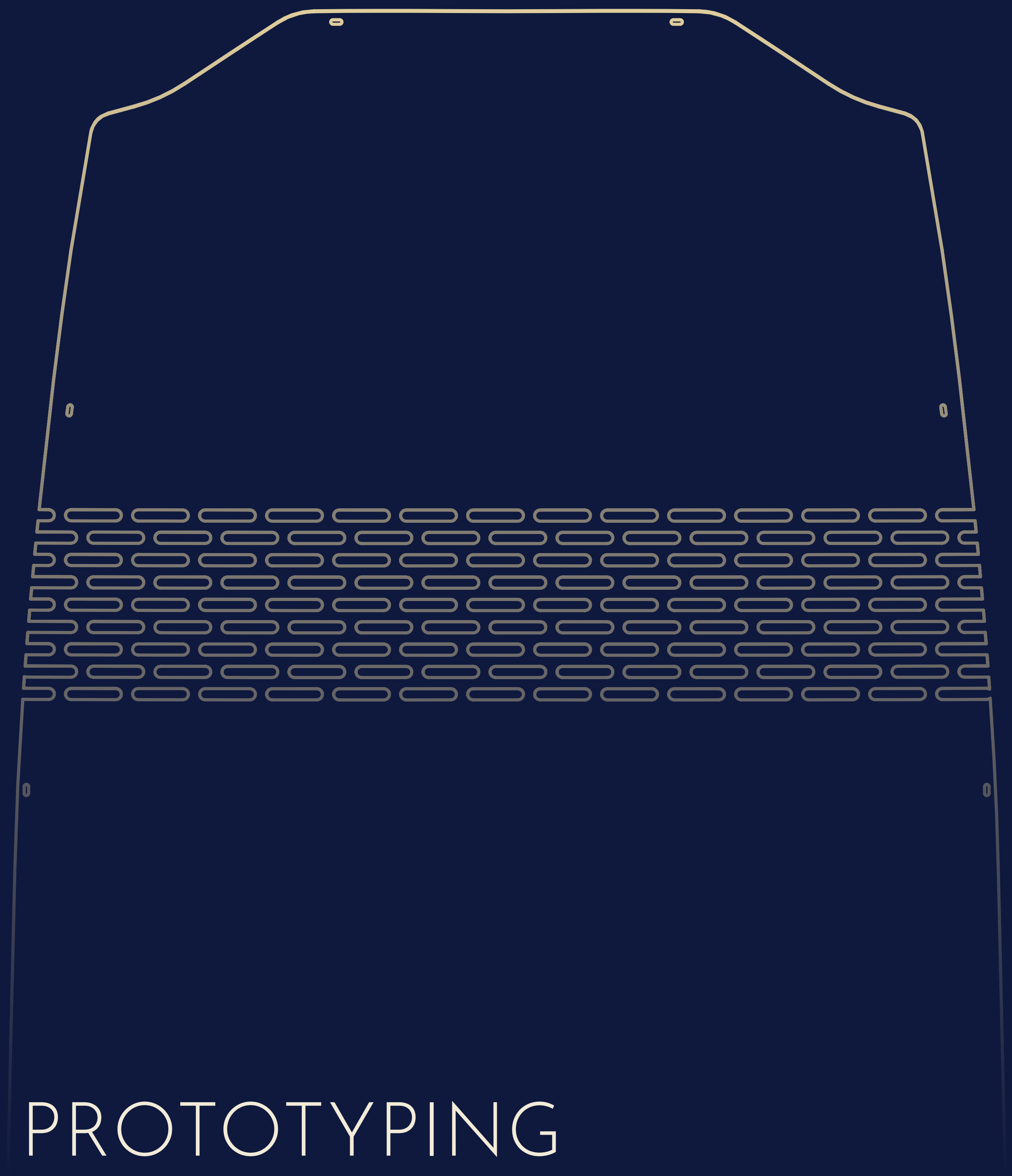
8. The seat should be as light as possible, to reduce the environmental impact.
With the use of organosheet, there is a lot less weight needed to give the same strength as steel. However, TPU is quite heavy compared to foams and spacerfabric.

11. The weight shouldn't exceed 30 kg, the weight of a highly equipped seat (there are also seats up to 50-70 kg) (Jochen Hofmann, personal communication, 21 February 2024).
This is almost the same as the answer before; the exact weights are not known. TPU 70 Shore A has a bulk density of 1110-1200 kg/m^3 (Prodways, 2015). The part created in SolidWorks has a volume of 683649.86 mm^3, which is equal to 0,75885 kg. Polyurethane foams have a density of 24 to 30+ kg/m^3. For now chosen was to put 25 mm of 40 kg/m^3. With a width of 450mm and a height of 650mm. Which is equal to 0.0073125m^3 * 40kg =0.2925 kg.
The same calculation goes for the thinner foam. Which is 0.0043875 m^3 *20kg = 0.08775kg.
The weight of the spacer fabric is not known, except for ‚being lightweight'. If we estimated it on 250 grams, the total weight would be 758,85+292,5+87,75+250=1389,1 grams.
If a medium hard foam (30 kg/m^3) of 40mm thickness is used with a top layer of soft foam (20 kg/m^3) of 10mm thickness that would be:
0.0117 m^3 * 30 = 0.351 kg
0.002925m^3 * 20 = 0.0585 kg.

Giving a total of 409.5 grams.
The weight of the foam parts is therefore increased 979,6 grams. This is a lot, but might be able to still fall in the set range. Also with using organosheet, which needs less material than steel and is also lighter. Therefore, further reserach is needed.

16. The seat should be comfortable for 5^{th} up and till 95^{th} percentile males and females.
This should still be determined from the evaluation test. However, the expectation is that the frame is a bit too narrow in this prototype. Which would mean that smaller participants probably feel more comfortable.

17. The seat should have a lower discomfort; physical characteristics, compared to current seats.
Has to still be determined in the evaluation test.



PROTOTYPING

10

10.1 Starting point

For the prototype a current seat is used, where the seatpan has a regular cushioning and trim. The backrest just consists of a frame. Figure 75 shows a quick sketch of how it should look.

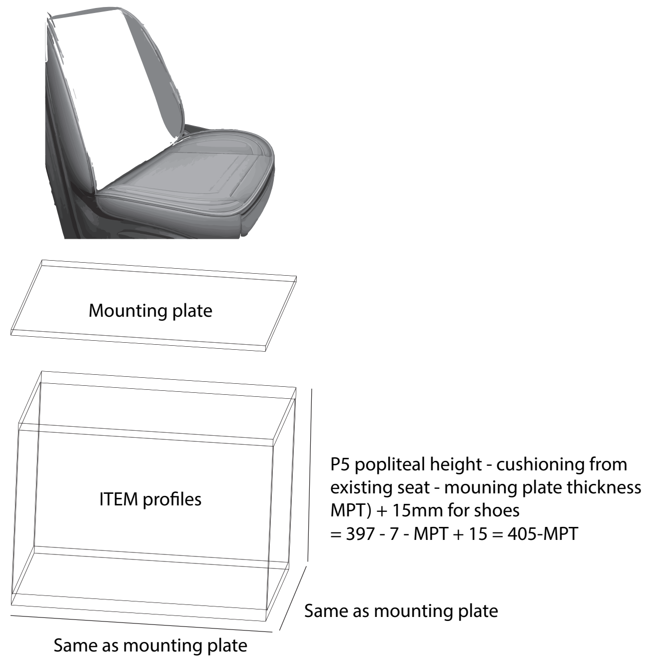


Figure 75: Quick sketch of final prototype

Adjustable angle

The evaluation test should be done at 25 and 50 degrees torso angle. As part of the idea is to also move the seatpan up as soon as the person goes in a laying position. Therefore, a frame with a hinging part on the front is used to be able to change the angle (figure 76).

Figure 76: Prototype is able 25 and 50 degrees

Suspension mat

The suspension mat for the prototype has first been created on paper to check if it would fit (figure 77 and 78).
The first try didn't fully fit, so it was adjusted to fit the shape. During concept development the areas around the buttock and shoulder both were set on 450mm. With the current frame, this does not fit, the shoulder area became smaller with a total width of 370mm.

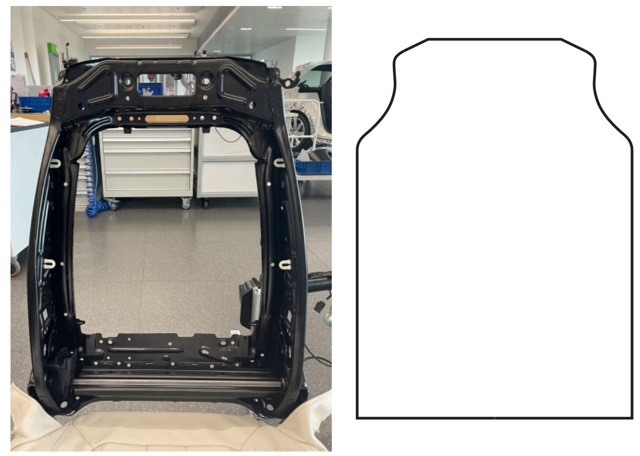


Figure 77: Shape for suspension mat based on frame

Figure 78: Try-out paper suspension mat

Attachment suspension mat
The suspension mat should be connected to the prototype. The hooks of the original suspension mat can be re-used (figure 79).
The 3D printed part therefore has small holes at the corresponding points, to fit an elastic band through to keep the suspension mat in place. The choice for elastic band is to keep as much flexibility as possible.

Tensioning
One of the problems I foresee is that the suspension mat is too flexible in the upright driving position. To prevent the user from falling through the seat will driving, some tensioning of the suspension mat could help this.

That means that the suspension mat is tensioned at torso angle 25 and completely released at torso angle 50. Together with Fabian Lang (CAD design & engineering in the InnoLab), we thought about a way to do so. For the prototype this resulted in 4 threads that will be attached to the suspension mat and will be tensioned at 25 degrees., see figure 80.
After trying out the first 4 threads, it became clear that participants would sit against a metal beam in the lumbar area. Therefore, chosen was to put also 4 horizontal threads; two at the height of lumbar support and two around the shoulder area (there is another beam).

Hammock
The principle of the TPU mat is what I foresee in the future. However, due to time constraints this won't be possible. On May 2nd, the part was sent to the contact person, on May 13th it was not yet comfirmed that the company could make it or not. The material being printed takes probably around 50-60 hours (estimation based on earlier prints) and because of it's size, can't be done in-house. Together with shipping and contact with the company, this will take at least another 2 weeks. Since the purpose of this graduation project is to create a prototype to validate the working principle of a reclining car seat, the choice was made to use a hammock instead of the designed TPU mat. The principle of tensioning the mat will still stay the same.

Spacer fabric
As said before, a layer of spacer fabric will be added. I have chosen for a thickness of 12mm. I would have chosen 6mm if I would have had the 5mm thick TPU mat underneath it. Since I now use the hammock, the choice was to put in 12 mm spacer fabric.

Foam layer
In the final design two layers of nonwoven will be used. Since the prototype is just to figure out if the principle works, a foam that was already in the office was used. The density and hardness is unfortunately not known.

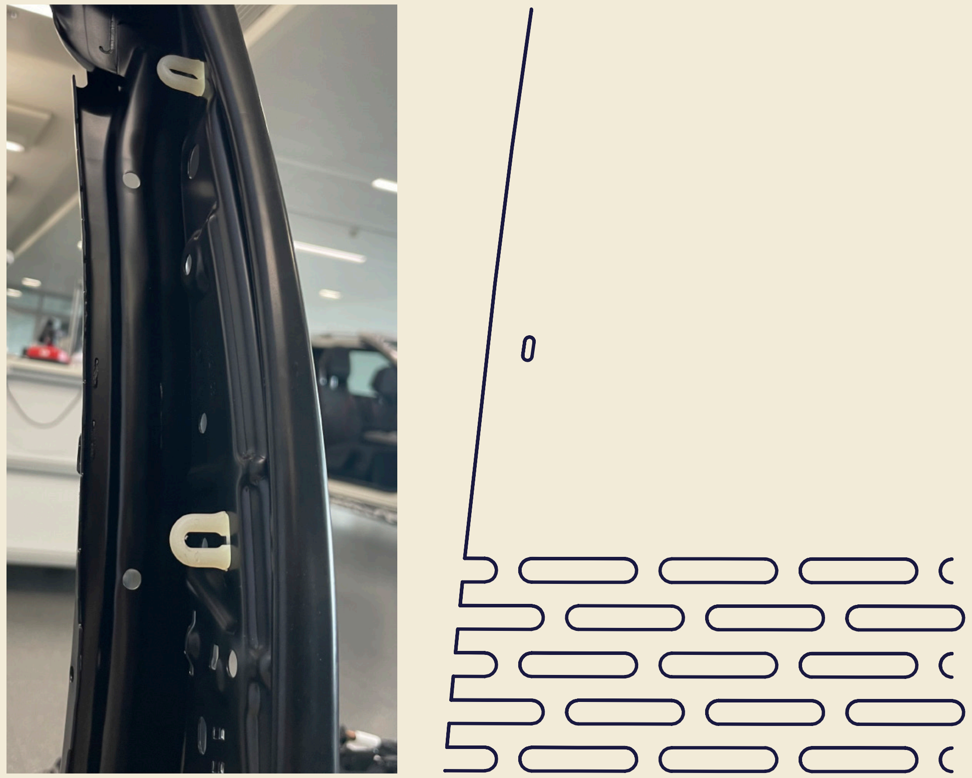


Figure 79: Hooks of suspension mat can be reused

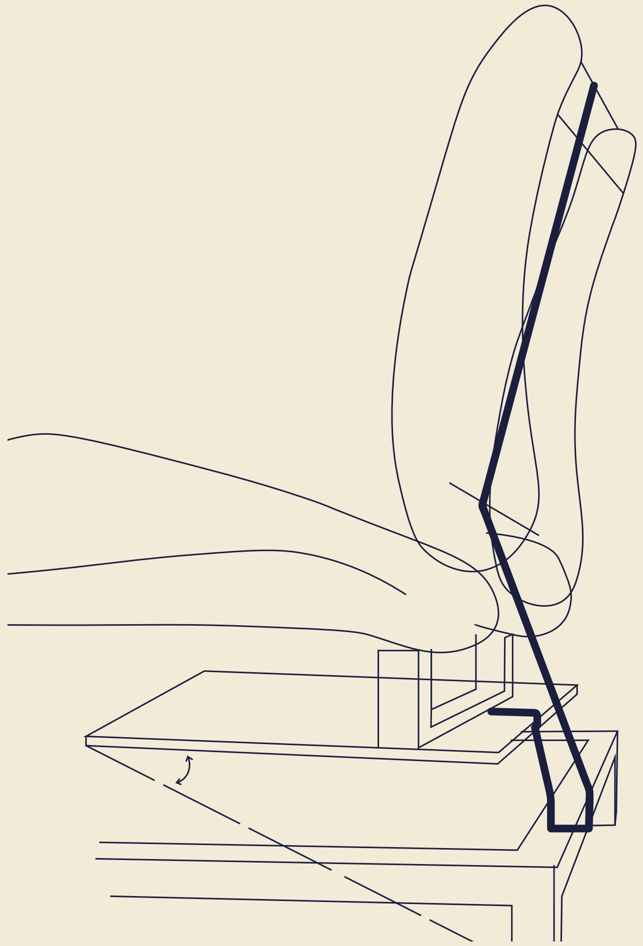


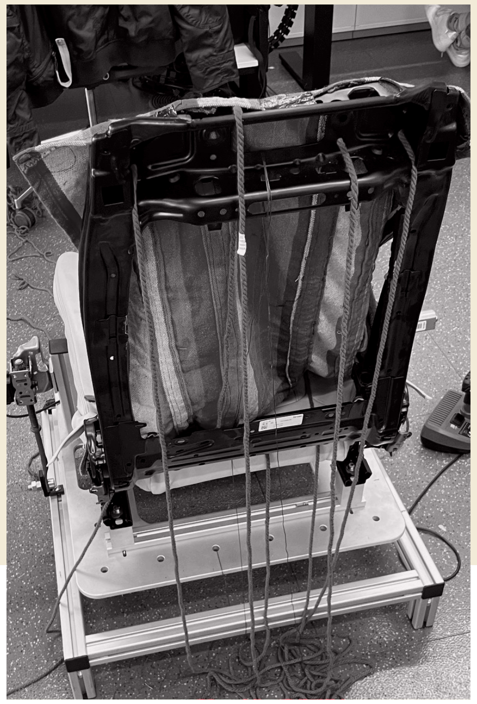
Figure 80: Tensioning wires movement

10.2 Prototyping process

Measuring the size of the hammock

Cutting the hammock

Sewing it together



Getting the rope in place

Add some wood to make the backrest a bit more forward

Adding a layer of 12 mm spacer fabric

Adding a layer of foam

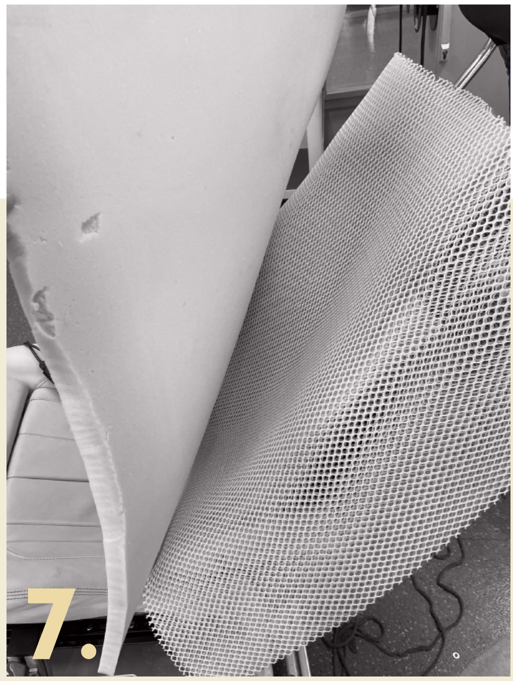


Figure 81: Prototyping process

10.3 Final prototype

Figure 82: prototype in two configurations

The prototype tensions in an upright position (figure 82) and releases in a laying position. On top of that the spacer fabric, foam and a blanket are put to not give any visual feedback to the participant.
Figure 83 shows the framework of the seat, before doing the evaluation test. The seat is mounted to a mounting plate, which is mounted on a frame. On each side a motor drives the seat up and down, being able to hold around 120kg each.

Figure 83: Adjusting the prototyped seat for the evaluation test

EVALUATION TEST

11

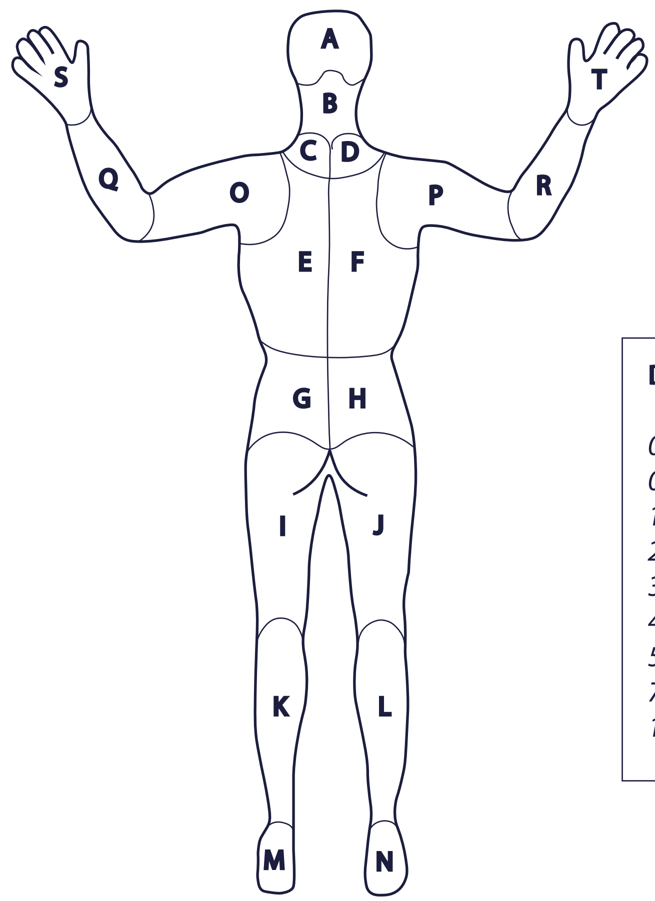
11.1 Introduction

At the end of this project I would like to test if the created concept is comfortable and preferably has an increased comfort level. To do this I choose to do an A-B test. Since the concept is only a prototype it doesn't have to have an increased comfort level. It really has to be an evaluation to see which areas should still be adjusted.

11.2 Method

The A-B test has to have 2 seats: the prototype and a 'regular' seat. It will make use of the Borg scale (1-10), in which participants are asked to hold a 1 k weight in a horizontally extended arm. First, they will feel very little discomfort, until they can't hold the weight anymore. This gives extreme discomfort. Participants are given the localized postural discomfort map (figure 84), in which areas they feel discomfort. This gives them the feeling of the scale, but also prevents that the results are influenced by earlier felt discomfort. (e.g. a person has already a hurting calf, the subject will fill this in, this reduces the errors).

After understanding the discomfort scale, participants must on the seat at 25 and 50 degrees. After each sitting, they fill in the LPD. Originally the idea was to do for 4 sittings (both seats 25 and 50 degrees, however, there was only one mounting plate available, therefore some people sat at the prototype and others at the reference seat) That means that one participant must sit 2 times. It is important that the seats look the same, considering that looks improve the feeling of comfort. Therefore a blanket was thrown over the seats. Lastly, the participant has to write down three positive and negative points of the seat, see appendix 6 for all questions. Figure 85 shows the movement of one participant.



Discomfort scale

0	No discomfort at all
0.5	Extremely little discomfort (hardly noticable)
1	Very litle discomfort
2	Little discomfort
3	Average discomfort
4	Raised discomfort
5 - 6	High discomfort
7 - 9	Very high discomfort
10	Extremely high discomfort

Figure 84: Discomfort scale

Figure 85: Participant goes from upright position to laying position

11.3 Results

In total there were 28 participants. There was only one mounting plate available, so chosen was to let the participants on Monday and Tuesday sit on the prototype in the two set-ups. And the participants on Wednesday sat on a foam seat from BMW 5-series, the control group. This means that the test groups are independent of each other. From the 28 participants, 19 sat on the prototype and 9 on the foam seat. The participants were selected randomly (not based on anthropometric data) and the seat they sat in, was only determined by the participants availability.

Figure 86: Participants sitting and filling in their sheets

Statistical power

This test is a two-tail A-B test, with 19 participants on the prototype and a control group of 9 participants, a few of them can be seen in figure 86. The actual power of this test is 0.63886, so around 63%. That is low, see figure 87. However, the room were the tests were done was only available for three days. So with this limited time and the little people I know within Brose, I think this is the best outcome possible.

For each region a p-value, based on the dicsomfort score, was calculated. These are all very high, meaning that the changes of the results being a coincidence is high. That means that the results of these discomfort levels are not fully reliable, but could give a preliminary idea of what is expected.

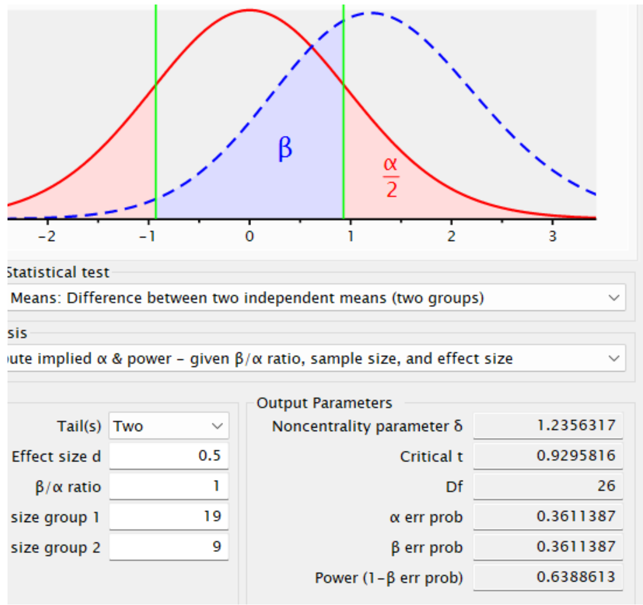


Figure 87: Statistical power (Faul et al., 2009)

11.3.1 Reference seat versus prototype

Comparison of discomfort

Considering that the numbers of comfort are quite close by, the discomfort numbers are further apart. Each participant had to fill in their discomfort in the regions A to T and the corresponding value is between 0 (no discomfort at all) and 10 (extremely high discomfort). The mean discomfort of the control seat and the prototype are best visible in figure 88.

As can be seen, the shoulder area is a problem point, both on the control group and the prototype group. Where the prototype really scored lower is the upper body, regions E and F.

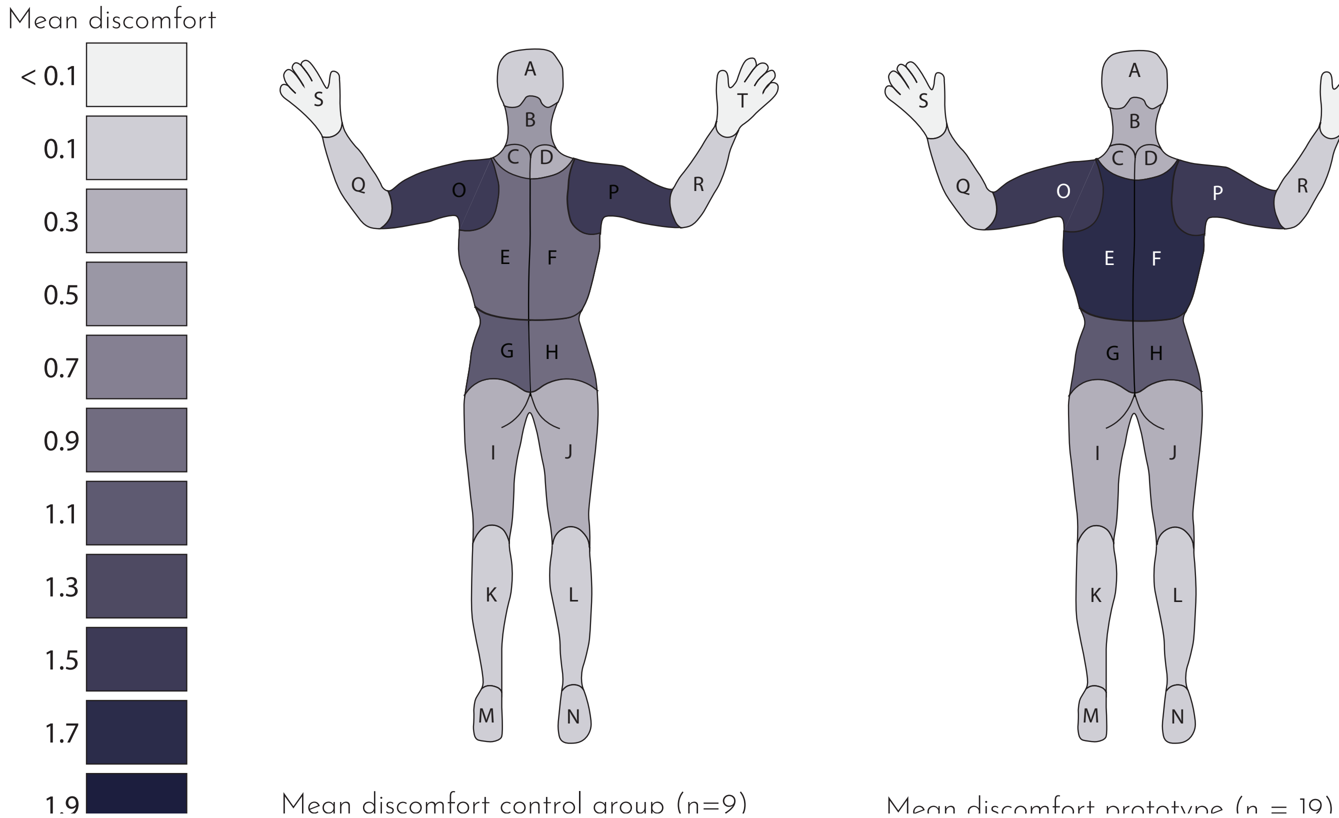


Figure 88: Discomfort mean of the control group and prototype group

Discomfort per region
The participants filled in their discomfort per region. From these, the mean and the corresponding p-values were calculated. A p-value of less than 0.05 is used as the threshold for statistical significance. This means that if $p<0.05$ there is less than 5% chance that the observed result was due to chance, assuming the null hypothesis is true; there is a low probability that the observed result is a false positive (R., 2023). The null hypothesis (H0) states that A = B; the seats are the same. The alternative hypothesis is that A ≠ B; the seats are not the same (Hayes, 2023). So, the smaller the p-value, the stronger the evidence to reject H0. In other words, if $p<0.05$ the two populations are different. However, it doesn't work the other way around. If $p>0.05$, the test fails to show a difference between the seats, but it is not the same as saying that they are the same (Ganesh et al., 2018). Lastly, it is important to consider the sample size. With a huge sample size, H0 may always be rejected even with small differences. With a very small sample size, it may be nearly impossible to reject H0. Since the sample size is quite small, recommended is to do more investigating in the future.
As can be seen in table 11, there are 2 regions where the null hypothesis can be rejected; regions O and P. The p-values are 0.0269, so statistically significant. That means that at regions O and P, the differences in discomfort from the seat have a low probability of a false positive. The mean values of O and P are the same in both the prototype group (1.618) and the control group (0.472). The prototype has a higher discomfort in those regions.

Then there are 3 regions, on which there can't be given any conclusions. These regions have p-values between 0.05 and 0.25; these are regions B (neck), E and F.

Lastly, all other regions have a p-value of 0.531 or higher. Meaning that the test fails to show a difference between the seats. However, with the very small sample size, I would advise to investigate the principle in further detail.

Table 11: Mean discomfort and p-value

Two-tail homoscedastic	Mean (prototype)	Mean (reference)	p-value
A	0.289	0.250	0.843
B	0.329	0.694	0.216
C	0.395	0.528	0.646
D	0.395	0.444	0.861
E	1.776	0.944	0.144
F	1.882	0.972	0.112
G	1.211	1.111	0.844
H	1.132	1.083	0.924
I	0.303	0.417	0.645
J	0.303	0.417	0.645
K	0.197	0.139	0.782
L	0.197	0.139	0.782
M	0.224	0.139	0.607
N	0.224	0.139	0.607
O	1.618	0.472	0.027
P	1.618	0.472	0.027
Q	0.105	0.167	0.670
R	0.105	0.167	0.670
S	0.026	0.056	0.531
T	0.026	0.056	0.531

Discomfort per posture
After each region, a closer look was taken per posture. In the regions K and L in the upright position, the p-values are <0.05. (see table 13) The prototype scores higher in these region than the control seat. The prototype has an average discomfort of 0, the control group an average of 0.11 (see table 12). These are very small differences and that in combination with the small sample size, are enough reason to see this as an outlier.

The regions O and P also have in the laying position a p-value <0.05. The average discomfort score of the control group is 0.39, while the average discomfort score of the prototype is 1.97. This is a bigger difference and worth to take a look at in the future. In appendix 7 all results on discomfort can be found.

Table 12: Means per posture for the highlighted regions

Region (posture)	mean (prototype)	mean (reference)
K(U)	0	0.111
L(U)	0	0.111
O(L)	1.974	0.389
P(L)	1.974	0.389

Table 13: P-values per posture, per region

Region	Posture	P-value
A	U	0.980
	L	0.725
B	U	0.370
	L	0.413
C	U	0.412
	L	0.819
D	U	0.412
	L	0.934
E	U	0.174
	L	0.549
F	U	0.162
	L	0.458
G	U	0.894
	L	0.689
H	U	0.894
	L	0.791
I	U	0.734
	L	0.767
J	U	0.734
	L	0.767
K	U	0.033
	L	0.587
L	U	0.033
	L	0.587
M	U	0.409
	L	0.964
N	U	0.409
	L	0.964
O	U	0.314
	L	0.042
P	U	0.314
	L	0.042
Q	U	0.667
	L	0.973
R	U	0.667
	L	0.973
S	U	0.150
	L	0.973
T	U	0.150
	L	0.973

11.3.2 Prototype

Discomfort upright or laying

Expected was that there would be a difference between upright and laying position in means of comfort and discomfort within the prototype. The biggest differences can be seen at O, P and C, D. Both regions have a significant higher discomfort in the laying position, see figure 89.

However, the mean discomfort in the laying position at C, D is at 0.711 (see table 14). On the discomfort scale that would mean very little discomfort. In the regions O and P there is a higher discomfort with a mean of 1.974; little discomfort.

Table 14: Comfortability score per position

	Upright		Laying	
	Total	Mean	Total	Mean
A	6.5	0.342	4.5	0.237
B	5.5	0.289	7	0.368
C	1.5	0.079	13.5	0.711
D	1.5	0.079	13.5	0.711
E	38	2	29.5	1.553
F	39	2.053	32.5	1.711
G	23.5	1.237	22.5	1.184
H	23.5	1.237	19.5	1.026
I	6	0.316	5.5	0.289
J	6	0.316	5.5	0.289
K	0	0	7.5	0.395
L	0	0	7.5	0.395
M	4.5	0.237	4	0.211
N	4.5	0.237	4	0.211
O	24	1.263	37.5	1.974
P	24	1.263	37.5	1.974
Q	3	0.158	1	0.053
R	3	0.158	1	0.053
S	0	0	1	0.053
T	0	0	1	0.053

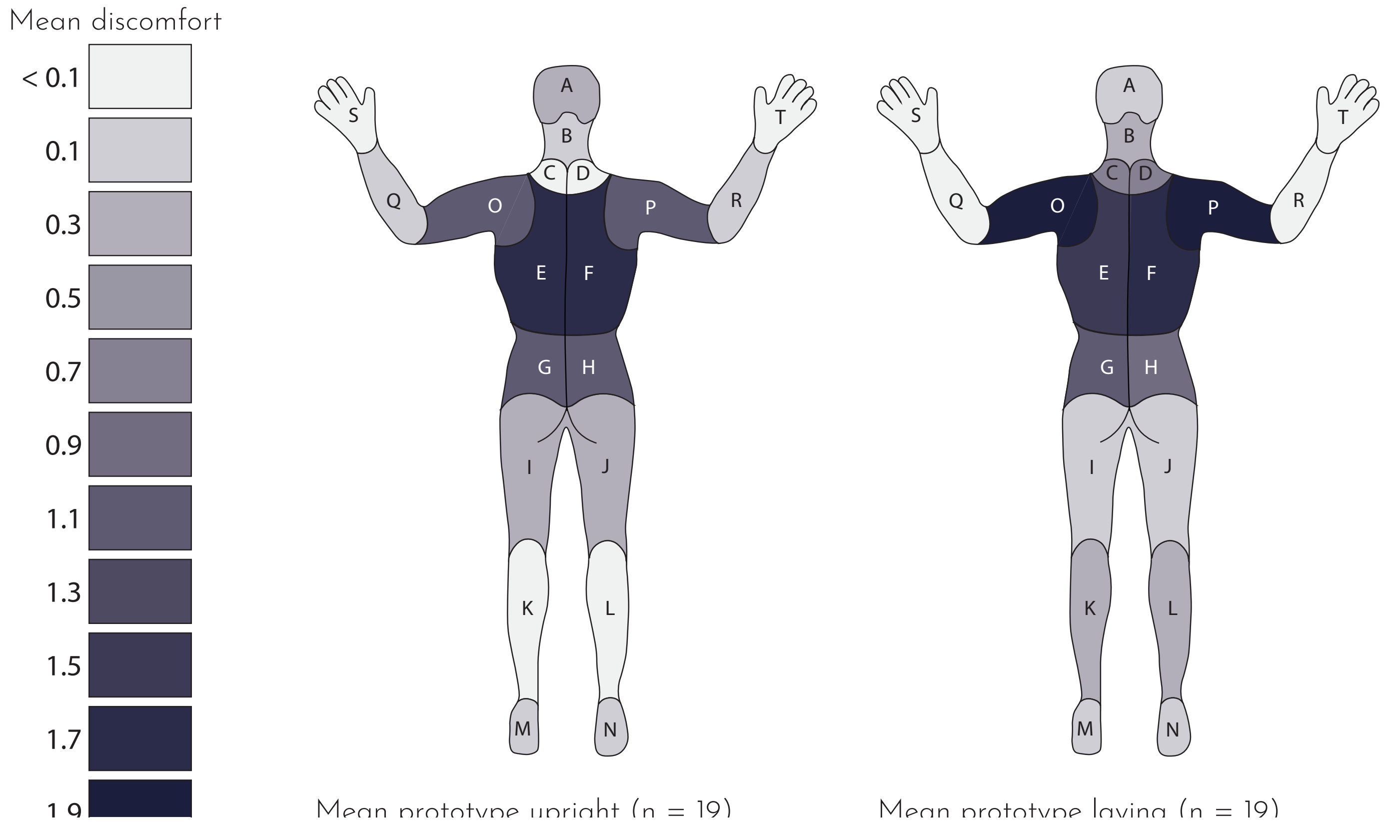


Figure 89: Upright discomfort vs. laying discomfort within the prototype

11.3.3 Comfort

Each participant gave after sitting and laying an overall comfort score. The p-value of this test is 0.017. Meaning that the probability that the results are based on a coincidence are quite low.

The average comfortability score that the prototype got is 6.99. For the comparison seat, the comfortability score is rated as 7.88. In table 15 you see the scores per position. Where upright sitting was experienced more comfortable in the prototype, in the control seat laying was experienced as more comfortable.

Table 15: Comfortability score per position

Comfortability score	Upright	Laying
Prototype group	7.184	6.789
Control group	7.812	7.938

Low comfortability scores

There were three participants how gave fairly low comfortability scores. From which one gave a ten on the discomfort scale in region E, F, but still a 5 on comfort. Two participants gave a 4 on comfort. One with a discomfort of 3 in region E, F and a 4 in region G, H. The other person gave a 4 in E, F and a 6 in G, H.

High comfortability scores

There were also three participants that gave very high scores. Even though anthropometric data from participants was not noted down. While not officially documented any antropometric data, two out of three participants that had the highest scores on comfortability and the lowest scores on discomfort were significantly shorter than average and had small hips. Their discomfort was maximum 1 and in the region E, F, O and P. This gives the idea that if the frame was increased, it might be comfortable for a bigger group. However, this has to be researched further.

Points of improvement

The last question of the questionnaire was too write down three strong and weak points of the seat. The weak point that has been named the most is an unpleasant feeling on the upper area of the backrest. Participants felt „as a chicken", their shoulders didn't fit in the frame. Others described this as the frame being to small or that the seat could be wider.

Another point that was discussed often is a lack of lumbar support. Some people even felt the metal bar of the seat construction through the seat. Some people felt that they fell too much through the seat. See appendix 8 for all feedback.

11.4 Conclusion

In conclusion, the prototyped seat scores slightly worse on discomfort than the reference seat. The problem areas are the width of the shoulders, region O & P and E & F. Furthermore lumbar support in the region G & H and sometimes also in E & F was missed by the participants. Although a few participants felt extreme discomfort, the mean value weren't that far apart.
Also on comfort, the prototype scored slightly worse. The power of these tests were too low to evidently conclude that the prototype is only significantly worse than the reference seat. Therefore, further research and more advanced prototypes should be tested.

CONCLUSION 12

In this master thesis, the research, ideation, conceptualization, and prototyping of a reclining car seat can be read. The goal was to create a working principle for a reclining car seat, based on the spinal movements. In the end, a working principle was created utilizing a prototype that was evaluated.

The project started with research about spinal curvature that showed a clear difference between upright sitting at a torso angle of 25 degrees and laying at a torso angle of 50 degrees. In general, the curvatures at 25 degrees were more straight than at 50 degrees. Where the curvatures of individuals at 25 do not differ much, they differ a lot at 50 degrees. Together with the literature research, it can be concluded that to design a comfortable reclining car seat, the seat should have an adjustable feature in the lumbar vertebrae (lumbar adjuster) and an adjustable feature around the shoulder area (shoulder adjuster). From the study, it became clear that the latter should have a higher range of motion than currently used in shoulder adjusters. A limitation of this research would be that the participants did not have a headrest. This can have an impact on the spinal curvature.
From the literature research, it became clear that to design a comfortable seat, freedom of movement and different posture possibilities are important.

In the ideation phase, the focus was on a mechanism that improved the freedom of the end user. The choice was made to create a very flexible mat, that could be tensioned in the upright position, giving the end user a more straight back. And released in the laying position, to have a more curved backrest.
This principle was then worked out in more detail, with material choices such as TPU, spacer fabric, and nonwoven foams.

A prototype was created to show the movement of the backrest when reclining. Although the final prototype was lo-fi, it was evaluated. From the evaluation, it showed that the seat was not wide enough for a lot of users.

In the graduation brief, the outcome was described as „delivering a first version or a part of a first version of a mechanism'. To conclude, this outcome is met with the creation of a prototype.

This project ended with an evaluation of the prototype. Eventhough it is not a full product yet, this concept has lots of potential in the comfortable automotive industry. The potential can be met by some recommendations, which can be read in the next chapter.

DISCUSSION

13

13.1 Recommendations

Frame

Width shoulder area

A problem that was already established before testing, is the width of the frame and the crossbeam around the shoulder area. First off, there is not enough room to ‚fall through' the frame. The width of the frame is made for sitting against it, not fitting in between. The second problem is felt against the shoulder blades. By creating a frame that goes through or includes the headrest, you could avoid this, see figure 90.
Ofcourse this is really dependent on safety features, but it could be worth looking into.

Topology optimization

To minimize the materials, environmental impact and costs a look could be taken at topology optimization of the frame made of recycled carbon fibers (organosheet). Since the material is very strong optimization could be an option.

Foam thickness

Some regions need more support and foam than other regions. This is a whole other study on it's own, but can definitely be utilized in the future, to minimize materials, environmental impact and costs.

Tensioning of suspension mat

The tensioning of the suspension mat is now regulated with the movement of the seat going up and down. In the prototype 4 strings in a vertical direction and 4 strings in a horizontal direction were used and all were tensioned and released at the same time. Dependent on how important comfortability is, these can be done per two or even individually. As a consequence the entire seat gets mechanically and electrically more complicated. Therefore, depending per OEM a trade-off between costs (complexity) and comfortability should be made.

Hip rotation point

A big part of discomfort in reclining car seats is that the hip rotation point is not aligned with the rotation point of the seat (Vink, 2023; Mobius, 2022; Sun Group Design, n.d.; Patrick Konkiel, personal communication, 3 May 2024). Often that results in a sort gap in the lower back where the seatpan and backrest are connected, figure 91.

The idea of the hammock can be extended to the seat pan, giving one flexible mat that goes from the popliteal all the way to the headrest. Since there is more pressure on the buttock than on the backrest, this should be investigated more. However, it will bring the movement of the SRP closer by the body, and hopefully reducing discomfort.

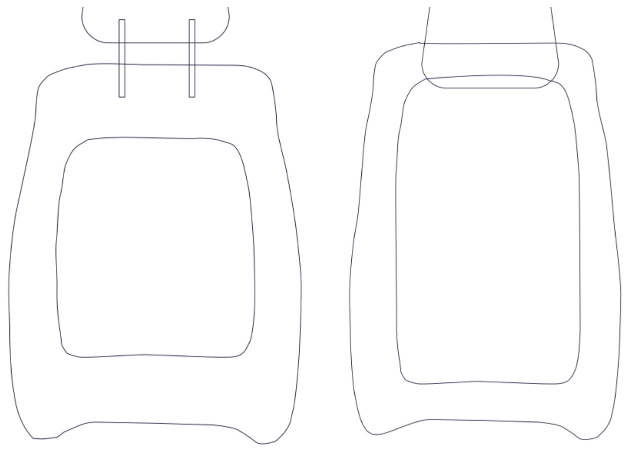


Figure 90: Sketch of envisioned frame

Figure 91: Gap when reclining seat

13.2 Reflection

Project evaluation
The project started off with a great research. The amount of information gathered, was really helpful in the ideation and conceptualisation phase. I might have took a bit too much time for the design, something that Brose normally keeps very simple. I went too much into detail with the target group and options for the car. It became almost two seperate projects; the mechanical part and the design part. I think if would redo this project, I would only focus on the mechanical part. The project quickly became more real after the help from Stefan with building a prototype. There the mechanism and the comfort could be checked and where needed things were adjusted.

Personal experience
Before moving to Germany I already had some contact with Jochen and Christian. This contact was all in English. I was therefore surprised to find that all team meetings in Bamberg were in German. I tried to understand as much as possible, but I realised that the accent was hard for me too understand.
In the beginning I was working a lot alone, because it was in my comfortzone and the industrial designer in the office was also on parental leave. After a while I tried to ask other people and therefore learned more.

I believe that the reason that this project was a success, is because of the great guidance I received from both the Peter Vink and Wolf Song of the TU Delft, but also from Jochen Hoffman and Christian Mergl from Brose. These together gave me a great group of knowledge I could always rely on.

Lastly, planningwise I surprised myself. I often make plannings and stop there. Now I was able to follow it through and got everything done in time. This was also because I got help with building the frame of the prototype that electrically moved up and down.

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APPENDICES

15

Appendix 1: Graduation brief

DESIGN FOR our future

TU Delft

IDE Master Graduation Project

Project team, procedural checks and Personal Project Brief

In this document the agreements made between student and supervisory team about the student's IDE Master Graduation Project are set out. This document may also include involvement of an external client, however does not cover any legal matters student and client (might) agree upon. Next to that, this document facilitates the required procedural checks:

- Student defines the team, what the student is going to do/deliver and how that will come about
- Chair of the supervisory team signs, to formally approve the project's setup / Project brief
- SSC E&SA (Shared Service Centre, Education & Student Affairs) report on the student's registration and study progress
- IDE's Board of Examiners confirms the proposed supervisory team on their eligibility, and whether the student is allowed to start the Graduation Project

STUDENT DATA & MASTER PROGRAMME
Complete all fields and indicate which master(s) you are in

Family name	Bokdam	IDE master(s)	IPD ✓ DfI ☐ SPD ☐
Initials	A.G.	2nd non-IDE master	
Given name	Anna	Individual programme (*date of approval*)	
Student number	5666619	Medisign	☐
		HPM	☐

SUPERVISORY TEAM
Fill in he required information of supervisory team members. If applicable, company mentor is added as 2nd mentor

Chair	Peter Vink	dept./section	Materials Manufacturing
mentor	Wolf Song	dept./section	Mechatronic Design
2nd mentor	Jochen Hoffman		
client:	Brose		
city:	Coburg / Bamberg	country:	Germany
optional comments	I choose Peter Vink for knowledge about ergonomics, vehicle seat design, and the curvature of the back. I choose Wolf Song because he can help me with gathering the data in software (Python/Rhino) and translating this to a mechanical principle.		

! Ensure a heterogeneous team. In case you wish to include team members from the same section, explain why.

! Chair should request the IDE Board of Examiners for approval when a non-IDE mentor is proposed. Include CV and motivation letter.

! 2nd mentor only applies when a client is involved.

APPROVAL OF CHAIR on PROJECT PROPOSAL / PROJECT BRIEF -> to be filled in **by the Chair** of the supervisory team

Sign for approval (Chair)

Name Peter Vink   Date jan 8th 2024   Signature

CHECK ON STUDY PROGRESS

To be filled in **by SSC E&SA** (Shared Service Centre, Education & Student Affairs), after approval of the project brief by the chair.
The study progress will be checked for a 2nd time just before the green light meeting.

Master electives no. of EC accumulated in total 30 EC

Of which, taking conditional requirements into account, can be part of the exam programme EC

★	**YES**	all 1st year master courses passed
	NO	missing 1st year courses

Comments:

Sign for approval (SSC E&SA)

Name Date Signature

APPROVAL OF BOARD OF EXAMINERS IDE on SUPERVISORY TEAM -> to be checked and filled in by IDE's Board of Examiners

Does the composition of the Supervisory Team comply with regulations?

YES		Supervisory Team approved
NO		Supervisory Team not approved

Comments:

Based on study progress, students is ...

	ALLOWED to start the graduation project
	NOT allowed to start the graduation project

Comments:

Sign for approval (BoEx)

Name Date Signature

DESIGN FOR our future

TU Delft

Personal Project Brief – IDE Master Graduation Project

Name student Anna Bokdam **Student number** 5,666,619

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT

Complete all fields, keep information clear, specific and concise

Project title The design of a reclining car seat following the spine movement

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)

The reclining of a car seat usually is arranged in one joint between the seat pan and the back rest. That means that the entire backrest is straight. However, when reclining, the spine has a lordose sitting upright, which changes into a kyphose while reclining. To optimize comfort, it would be ideal to have the seat followthis movement of the human body. The focus of this graduation project will be to optimize a reclining car seat. The project will be conducted at Brose, the fourth-largest family-owned automotive supplier (Brose Fahrzeugteile SE & Co. KG, n.d.) and TU Delft. The project will start at TU Delft with an ergonomic research in which the back rest curve will be recorded in different back rest angles (see last page for set-up). It will continue at Brose with the actual conceptualizing of a seat based on the recorded data. Since Brose is already a leading company in the industry, this project will be one of many. With the idea of making a new reclining mechanism, I could help with a starting point for future innovation. A big opportunity for me is that Brose is already a leading company and has the resources to do these projects. Limitations I foresee are that I might not have enough technical skills. Other limitations can be the language; I don´t speak very well German, so I hope most contact will go in English. Lastly, I want a lot of things in short amount of time. This requires a high work pace, but also a good planning.

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introduction (continued): space for images

image / figure 1

image / figure 2

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)

I want to create a working principle for a reclining car seat that follows the curvature of the spine in different back rest angles. Therefore I first need to understand how the curvature of the spine actually moves. The working principle should be created with a minimum of material to reduce weight and with a minimum of mechanisms to maintain durability, while also taking into account car safety regulations. This means that the problem is challenging and this project would probably deliver a first version or part of a first version of a mechanism.

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:

Creating a prototype to validate the working principle of a reclining car seat for p5 to p95 car seat users.

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)

I will start with collecting data, by an ergonomic researc that will be conducted at the TU Delft. With this data, that will show the curvature of the spine, concepts will be created. After the creation of different concepts, I will be using a Harris profile or weighted objectives method to make a final decision. After the final prototype is created,
the working principle is evaluated (together with Brose employees if possible).

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 8 Jan 2024

Mid-term evaluation 11 Mar 2024

Green light meeting 29 Apr 2024

Graduation ceremony 31 May 2024

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	

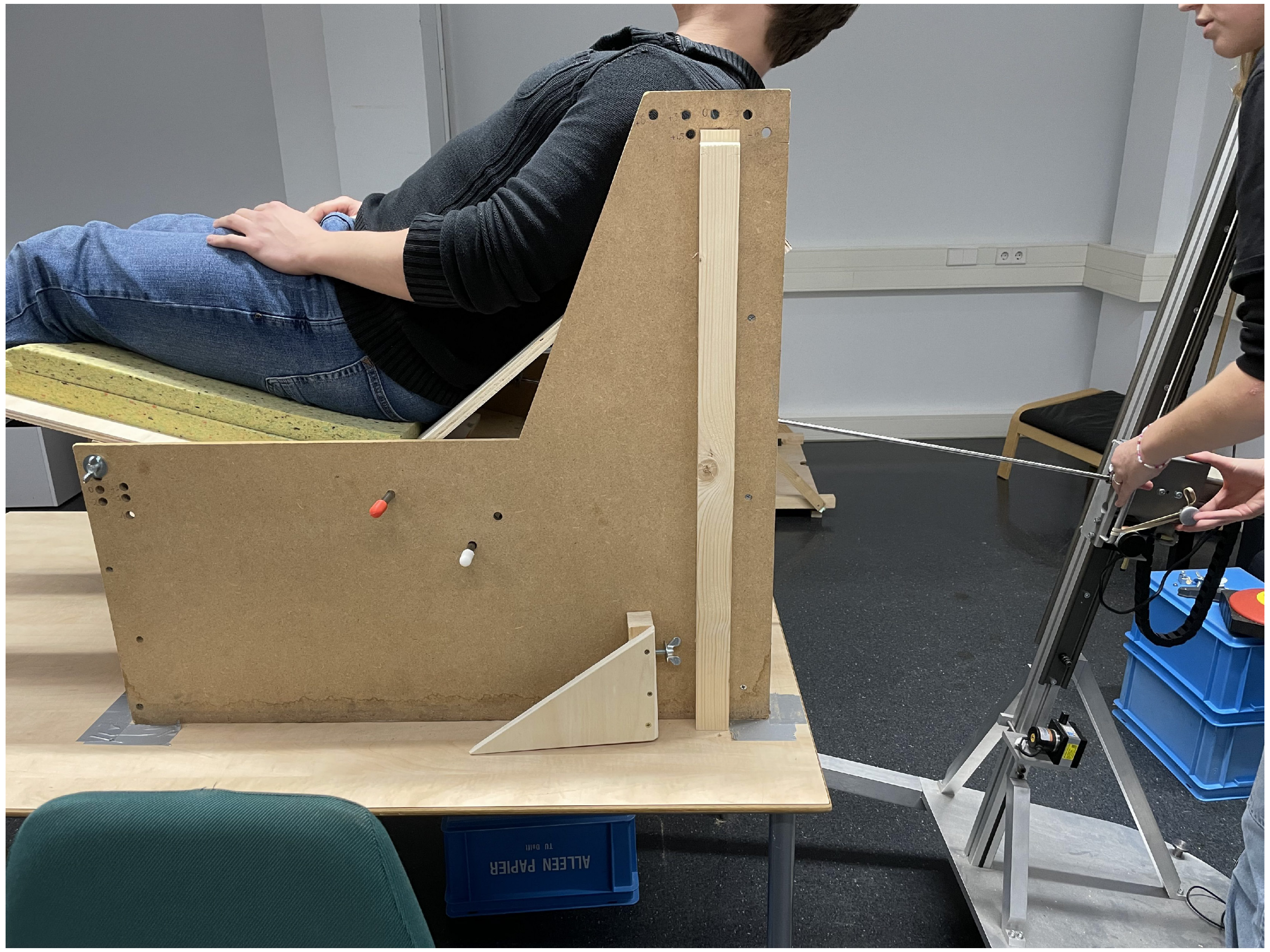
Comments:

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).

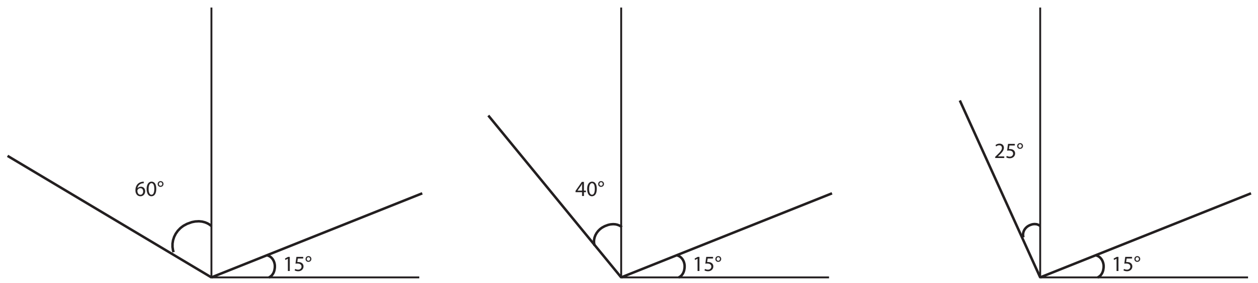
Optionally, describe whether you have some personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or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

During my masters I realised that I am most interested in embodiment design and redesigning products. This also includes creating prototypes. I realised that I prefer to create things, feel it, touch it, instead of only thinking about it. Furthermore, I am interested in mechanical engineering. I am mostly interested in industrial design, but to combine it with a bit more mechanical engineering is for me a perfect outcome. Therefore I followed two courses from the mechanical engineering faculty during my exchange. To conclude, I think I can use my knowledge in embodiment design and interest in mechanical engineering to successfully complete this project.



Appendix 2: Suggested research angles

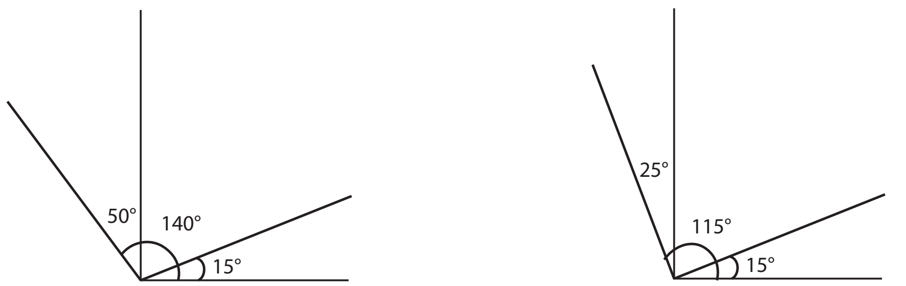
Requested angles of Brose



Maximum angle

Standard upright driving angle

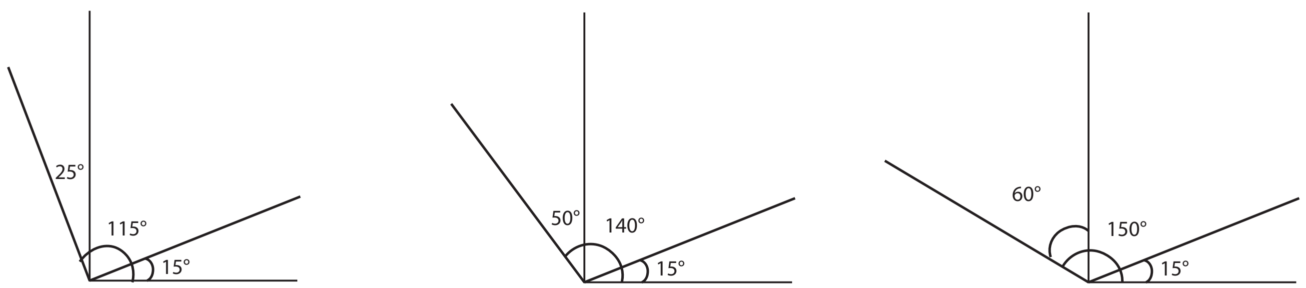
Suggested angles research



Highest sleep comfort

Standard upright driving angle

Proposed measuring angles



Only if time allows (should be determined during try-out)

Appendix 3: Consent form

Participant number: ________

Spine curvature measurements for reclining car seats

This research is conducted as part of the MSc study Integrated Product Design at TU Delft.

Student: Anna Bokdam
Contact info: [redacted]

Informed consent participant

I participate in this research voluntarily.

I acknowledge that I received sufficient information and explanation about the research and that all my questions have been answered satisfactorily. I was given sufficient time to consent my participation. I can ask questions for further clarification at any moment during the research.

I am aware that this research consists of the following activities:

1. Spine measurement at a torso angle of 25 degrees
2. Spine measurement at a torso angle of 50 degrees
3. Anthropometric data, such as height and weight

I am aware that data will be collected during the research, such as notes, photos, video and/or audio recordings. I give permission for collecting this data and for making photos, audio and/or video recordings during the research. The data will only be accessible to the researcher, TU Delft supervisors and Brose Fahrzeugteile SE & Co.

The photos, video and/or audio recordings will be used to support analysis of the collected data. The video recordings and photos can also be used to illustrate research findings in publications and presentations about the project.

I give permission for using photos and/or video recordings of my participation:
(select what applies for you)

- ☐ in which I am recognisable in publications and presentations about the project.
- ☐ in which I am not recognisable in publications and presentations about the project.
- ☐ for data analysis only and not for publications and presentations about the project.

I give permission to store the data for a maximum of 5 years after completion of this research and using it for educational and research purposes.

I acknowledge that no financial compensation will be provided for my participation in this research.

With my signature I acknowledge that I have read the provided information about the research and understand the nature of my participation. I understand that I am free to withdraw and stop participation in the research at any given time. I understand that I am not obliged to answer questions which I prefer not to answer and I can indicate this to the research team.

I will receive a copy of this consent form.

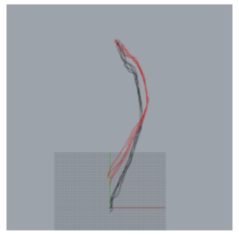
________________________	________________________
Last name	First name
___ / ___ /___	________________________
Date (dd/mm/yyyy)	Signature

Appendix 4: Anthropometric data

lo.	M/F	Age	Nationality	Ethnic origin	Secondary ethnic origin	Stature	Popliteal height	Buttock-knee height	Sitting height	Weight	Hip width
1	M	20	Dutch	Western Europe		182	51.2	50.7	91.4	77	38
2	M	29	Dutch	Western Europe		182	50.8	52.6	92	75	36.5
3	F	19	Dutch	Western Europe		176.2	47.5	49.2	91.9	67	40.5
4	F	23	Dutch	Western Europe		170.8	45	50.3	86.5	53	33.9
5	M	27	Indian	South and Southeast Asia		163.5	44.8	49.1	83.2	65	37.1
6	M	26	Dutch	Western Europe		178.5	49.5	50.6	90.4	83	40.2
7	F	25	Dutch	Western Europe		158.6	42.6	48.1	83.7	69	44.5
8	M	25	Dutch	Western Europe		176.1	46.5	49.2	93.8	65	34.9
9	F	22	Dutch	South and Southeast Asia		158.1	42.5	45.8	81.9	51	33.4
10	M	66	Dutch	Western Europe		173	47	52	88	90-95	42
11	M	23	Dutch	Western Europe		185	51	54	91	74	35
12	F	19	Dutch	Western Europe		174.5	49	48.9	89.5	75	36.5
13	M	24	Dutch	Western Europe		176.5	46.5	48	92	90	48
14	M	32	Dutch	Western Europe		189.5	52	55	93.5	91	43
15	M	26	Dutch	Western Europe		170.3	44	46	90	83	38
16	M	66	Dutch	Western Europe		191	52.5	55	96	93	40.5
17	F	30	Dutch	Western Europe		165.5	43.5	48	88	79	43
18	M	22	Dutch	Western Europe		182.5	52	54	89	77	36
19	F	26	Dutch	Western Europe		174.5	46.5	51	89	70	38
20	M	24	Dutch	Western Europe		187.1	50	53.5	97.5	92	39.5
21	F	32	Chinese	East and Central Asia		168.4	44.3	48.3	88	54	34.3
22	M	24	Russian	Eastern Europe		180.6	49	49	90.5	64	33.4
23	F	22	Dutch	Western Europe	South and Southeast Asia	169	47.5	49.5	83	53	35
24	F	27	Dutch	Western Europe		169.9	45.8	50.7	87.6	83	44.1
25	F	23	Dutch	Western Europe		172.4	45.2	49.3	88.8	58	37.1
26	F	23	Indian	South and Southeast Asia		162.1	44.5	48.5	80.7	48	36.8
27	F	22	Dutch	Western Europe		175.2	45.5	48.5	92.5	53	36.7
28	F	23	Dutch	Western Europe		179.4	46.8	49.6	95.2	64	37.2
29	M	22	Dutch	Western Europe		181.9	49.5	51.7	93.8	98	41.3
30	F	23	Dutch	Western Europe		167.6	43.1	50	89.6	66-67	38.2
31	O	22	Dutch	Western Europe		172.1	44.5	49.4	89.8	76	39.2
32	F	24	Dutch	Western Europe		183	51	52.5	93.6	69	38.3
33	M	19	Dutch; Brittish	Western Europe		185.2	53	48.4	95.9	72	36.2
34	F	23	Dutch	North Africa		159.5	41.6	49.1	83.8	62	41.4
35	M	24	Dutch	Western Europe		179	49.8	52.3	89.9	75	40.2
36	F	23	Dutch	Western Europe		167	44	46.5	86.5	56	XXXXXXX
37	M	30	Chinese	East and Central Asia		167.8	42	44	90.5	56-57	36.1
38	F	21	Dutch	Western Europe		171.7	45.5	49	90	63	38.5
			Dutch	32							
	19		Western Europe	31		174.39	47.02631579	49.92894737	89.684211	70.77	38.4459
	18		South and South	3		191	53	55	97.5	98	48
	1		East and Central	2		158.1	41.6	44	80.7	48	33.4
	38		Eastern Europe	1							
			North Africa	1							
		26									

Appendix 5: All participants' curvature

Participant 1

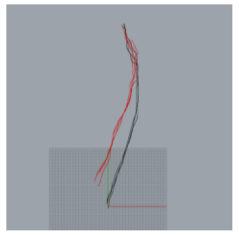


Male, 20

Sitting height	91.4
Popliteal height	51.2
Western Europe	Dutch

1

Participant 2

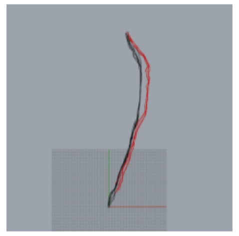


Male, 29

Sitting height	92
Popliteal height	50.8
Western Europe	Dutch

2

Participant 3

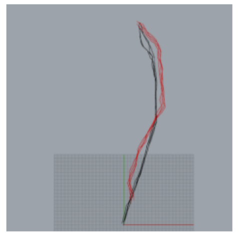


Female, 19

Sitting height	91.9
Popliteal height	47.5
Western Europe	Dutch

3

Participant 4

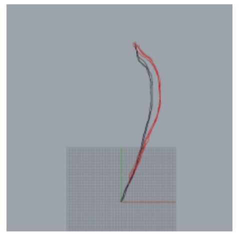


Female, 23

Sitting height	86.5
Popliteal height	45
Western Europe	Dutch

4

Participant 6



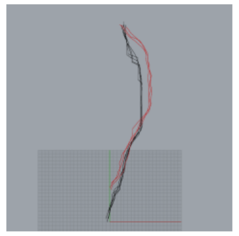
Male, 26

Sitting height	90.4
Popliteal height	49.5
Western Europe	Dutch

5

Participant 7

P5

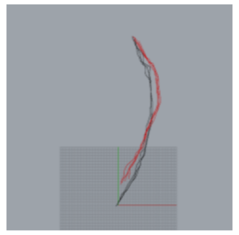


Female, 25

Sitting height	83.7
Popliteal height	42.6
Western Europe	Dutch

6

Participant 8



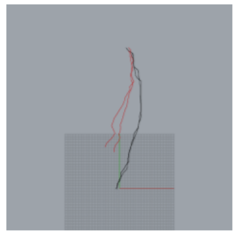
Male, 25

Sitting height	93.8
Popliteal height	46.5
Western Europe	Dutch

7

Participant 9

P5

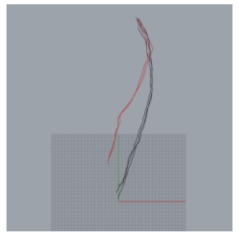


Female, 22

Sitting height	81.9
Popliteal height	42.5
South and Southeast Asia	Dutch

8

Participant 10

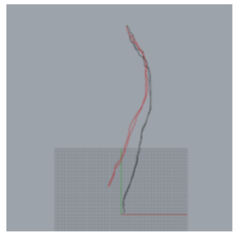


Male, 66

Sitting height	88
Popliteal height	47
Western Europe	Dutch

9

Participant 11

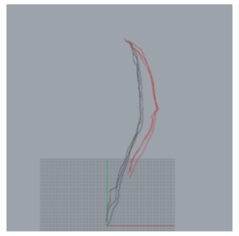


Male, 23

Sitting height	91
Popliteal height	51
Western Europe	Dutch

10

Participant 12

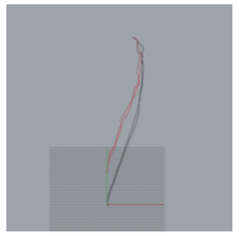


Female, 19

Sitting height	89.5
Popliteal height	49
Western Europe	Dutch

11

Participant 13

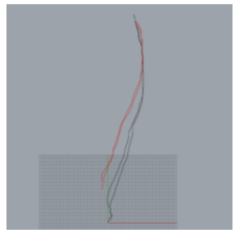


Male, 24

Sitting height	92
Popliteal height	46.5
Western Europe	Dutch

12

Participant 14

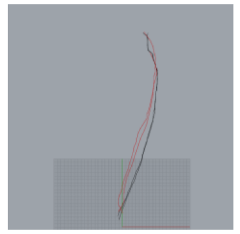


Male, 32

Sitting height	93.5
Popliteal height	52
Western Europe	Dutch

13

Participant 15



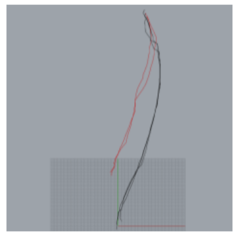
Male, 26

Sitting height	90
Popliteal height	44
Western Europe	Dutch

14

Participant 16

P95

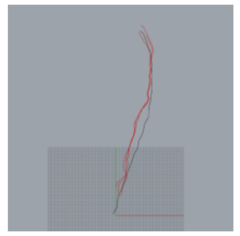


Male, 66

Sitting height	96
Popliteal height	52.5
Western Europe	Dutch

15

Participant 17

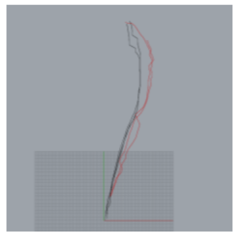


Female, 30

Sitting height	88
Popliteal height	43.5
Western Europe	Dutch

16

Participant 18

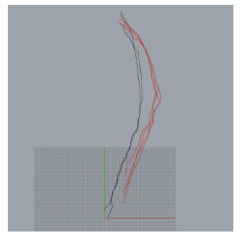


Male, 22

Sitting height	89
Popliteal height	52
Western Europe	Dutch

17

Participant 19



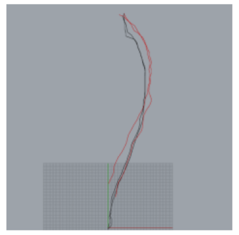
Female, 26

Sitting height	89
Popliteal height	46.5
Western Europe	Dutch

18

Participant 20

P95



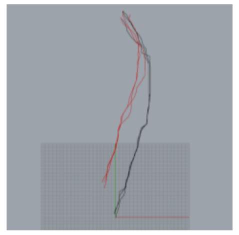
Male, 24

Sitting height	97.5
Popliteal height	50
Western Europe	Dutch

19

Participant 23

P5

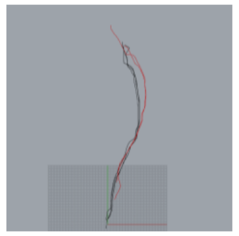


Female, 22

Sitting height	83
Popliteal height	47.5
Western Europe / South and Southeast Asia	Dutch

20

Participant 24

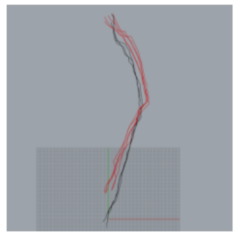


Female, 27

Sitting height	87.6
Popliteal height	45.8
Western Europe	Dutch

21

Participant 25

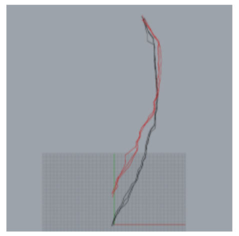


Female, 23

Sitting height	88.8
Popliteal height	45.2
Western Europe	Dutch

22

Participant 27



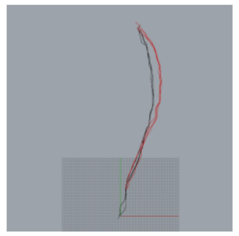
Female, 22

Sitting height	92.5
Popliteal height	45.5
Western Europe	Dutch

23

Participant 28

P95

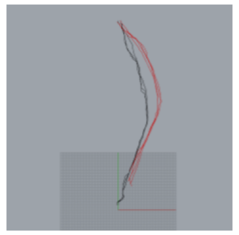


Female, 23

Sitting height	95.2
Popliteal height	46.8
Western Europe	Dutch

24

Participant 29

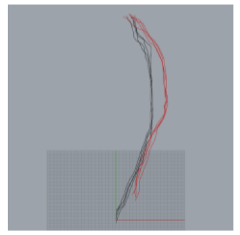


Male, 22

Sitting height	93.8
Popliteal height	49.5
Western Europe	Dutch

25

Participant 30

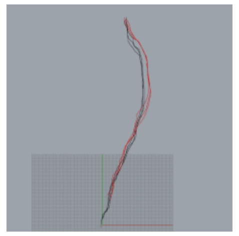


Female, 23

Sitting height	89.6
Popliteal height	43.1
Western Europe	Dutch

26

Participant 31

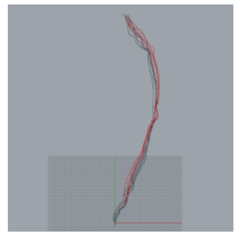


Other, 22

Sitting height	89.8
Popliteal height	44.5
Western Europe	Dutch

27

Participant 32



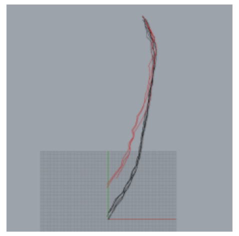
Female, 24

Sitting height	93.6
Popliteal height	51
Western Europe	Dutch

28

Participant 33

P95



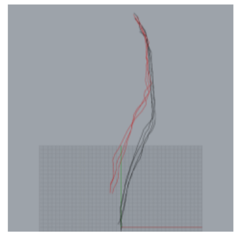
Male, 19

Sitting height	95.9
Popliteal height	53
Western Europe	Dutch

29

Participant 34

P5

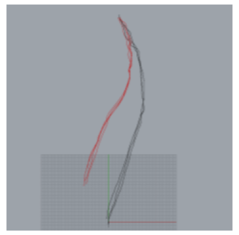


Female, 23

Sitting height	83.8
Popliteal height	41.6
North Africa	Dutch

30

Participant 35

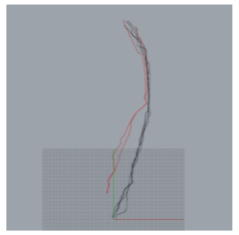


Male, 24

Sitting height	89.9
Popliteal height	49.8
Western Europe	Dutch

31

Participant 36

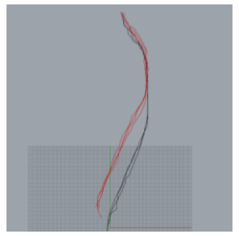


Female, 23

Sitting height	86.5
Popliteal height	44
Western Europe	Dutch

32

Participant 5

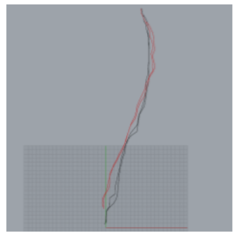


Male, 27

Sitting height	83.2
Popliteal height	44.8
South and Southeast Asia	Indian

33

Participant 21

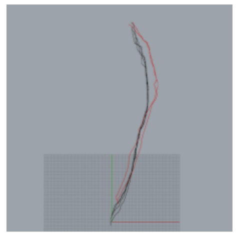


Female, 32

Sitting height	88
Popliteal height	44.3
East and Central Asia	Chinese

34

Participant 22

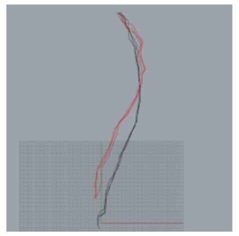


Male, 24

Sitting height	90.5
Popliteal height	49
Eastern Europe	Russian

35

Participant 26

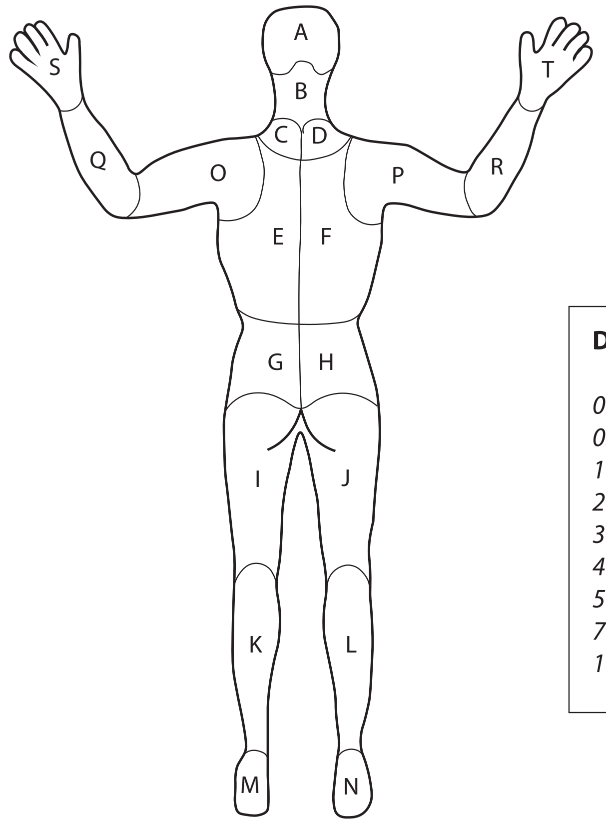


Female, 23

Sitting height	80.7
Popliteal height	44.5
South and Southeast Asia	Indian

36

Appendix 6: Evaluation test



Participant number:
Seat:

Discomfort scale

0	No discomfort at all
0.5	Extremely little discomfort (hardly noticable)
1	Very litle discomfort
2	Little discomfort
3	Average discomfort
4	Raised discomfort
5 - 6	High discomfort
7 - 9	Very high discomfort
10	Extremely high discomfort

Question 1
Please give each region a score based on the discomfort you feel.
The discomfort scale is explained on the right side.

A = ____________________
B = ____________________
C = ____________________
D = ____________________
E = ____________________
F = ____________________
G = ____________________
H = ____________________
I = ____________________
J = ____________________
K = ____________________
L = ____________________
M = ____________________
N = ____________________
O = ____________________
P = ____________________
Q = ____________________
R = ____________________
S = ____________________
T = ____________________

Question 2
After you gave all regions a score from 0 to 10, look at the regions you stated 5 or more, please explain on the front side of this paper (behind the discomfort score) why you feel discomfort.

Question 3
Please give the overall comfort of this seat a score from 0 to 10. Where 0 is not comfortable at all and 10 extremely high comfort.

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Question 4
Please state 3 strong points and 3 weak points of this seat.

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Appendix 7: Results evaluation test

The table above shows the discomfort results of participants 1 to 19, who all sat in the prototyped seat. U stands for upright position and L stands for laying position. The table on the right shows the discomfort results of participants 20 till 28, who were all part of the control group.

CONTROL	U20	L20	U21	L21	U22	L22	U23	L23	U24	L24	U25	L25	U26	L26	U27	L27	U28	L28	TOTAL	MEAN
A	0	0	0	0	2	0	0	0	0	0	0	0	0	1	0.5	0	0.5	0.5	4.5	0.25
B	0	0	0	0	5.5	0	0	0	0	2	0	0	0	2	1	0	0	2	12.5	0.694
C	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	2.5	2	2	9.5	0.528
D	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	2.5	2	0.5	8	0.444
E	0	4	0.5	0.5	1	0	0	0	0	0	0	0	0.5	4	1	1	4	0.5	17	0.944
F	0	4	0.5	0.5	1	0	0	0	0	0	0	0	0.5	4	1	1	4	1	17.5	0.972
G	4	0	1	1	1	2	0	0	0	0	1	0	0	0	1	4	4	1	20	1.111
H	4	0	1	1	1	2	0	0	0	0	1	0	0	0	1	4	4	0.5	19.5	1.083
I	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	4	0.5	7.5	0.417
J	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	4	0.5	7.5	0.417
K	0	0	0	0	0	0	0	0	0	0	0	0	0.5	1	0	0	0.5	0.5	2.5	0.139
L	0	0	0	0	0	0	0	0	0	0	0	0	0.5	1	0	0	0.5	0.5	2.5	0.139
M	0	0	0	1	0	0	0	0	0	0	0	0	0	0.5	0	0	0.5	0.5	2.5	0.139
N	0	0	0	1	0	0	0	0	0	0	0	0	0	0.5	0	0	0.5	0.5	2.5	0.139
O	2	0	0	0	0	0	0	0	0	0	0	0	2	1	0.5	2	0.5	0.5	8.5	0.472
P	2	0	0	0	0	0	0	0	0	0	0	0	2	1	0.5	2	0.5	0.5	8.5	0.472
Q	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0.5	0.5	3	0.167
R	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0.5	0.5	3	0.167
S	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.5	1	0.056
T	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.5	1	0.056
OVERALL	7	7	7	8	8.5	9.5	9	10	7	7	6.5	8.5	8.5	7.5	9	6	9	9.5	144.5	7.875

PROTOTYPE	U1	L1	U2	L2	U3	L3	U4	L4	U5	L5	U6	L6	U7	L7	U8	L8	U9	L9	U10	L10	U11	L11	U12	L12	U13	L13	U14	L14	U15	L15	U16	L16	U17	L17	U18	L18	U19	L19	TOTAL	MEAN
A	0	0	0	0	0	0	0	0	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.5	0	2	0	1	0	0	3	0	0	0	11	0.289
B	0	0	0	0	0	0	0	0	2	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0	0	2	2.5	1	0	0	0.5	0	0	1	12.5	0.329
C	0	0	0	0	0	0	0	0	0	4	0	0	0	4	0	0	0	2	0	0	0	1	0	0	1	0.5	0	0	0	2	0	0	0	0	0.5	0	0	0	15	0.395
D	0	0	0	0	0	0	0	0	0	4	0	0	0	4	0	0	0	2	0	0	0	1	0	0	1	0.5	0	0	0	2	0	0	0	0	0.5	0	0	0	15	0.395
E	3.5	0	0	0	0.5	1	0	4	4	5	0	0	0	0	0	0.5	2	3	1	0	3	4	0	0	2	2	2	0	3	1	0	1	4	0	10	5	3	3	67.5	1.776
F	3.5	0	0	0	0.5	1	0	4	4	5	0	0	0	0	0	0.5	2	3	1	0	4	4	0	0	2	2	2	0	3	1	0	1	4	3	10	5	3	3	71.5	1.882
G	0	0	4	3	0	0	0.5	0	6	6	1	0	0	0	1	1	2	2	0	0	0	0	0	0	0	0	1	6	4	0	0	1	0	3	4	0	0	0.5	46	1.211
H	0	0	4	3	0	0	0.5	0	6	6	1	0	0	0	1	1	2	2	0	0	0	0	0	0	0	0	1	6	4	0	0	1	0	0	4	0	0	0.5	43	1.132
I	0	0	0	0	0	0.5	0	0	1	0	0	0	0	0	0	0	0	1	0	0	2	3	0	0	0	0	2	1	0	0	0	0	0	0	1	0	0	0	11.5	0.303
J	0	0	0	0	0	0.5	0	0	1	0	0	0	0	0	0	0	0	1	0	0	2	3	0	0	0	0	2	1	0	0	0	0	0	0	1	0	0	0	11.5	0.303
K	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0	5	0	0	0	0	0	0	0	0	0	0	7.5	0.197
L	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0	5	0	0	0	0	0	0	0	0	0	0	7.5	0.197
M	0	0	0	0	0	0	0	0	2	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0	2	1	0	0	0	0	0	0	0	0	8.5	0.224
N	0	0	0	0	0	0	0	0	2	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0	2	1	0	0	0	0	0	0	0	0	8.5	0.224
O	0	3	0	3	0	0	0	0	2	2	0	1	0	4	0	0	0	2	0	1	2	3	1	0.5	1	1	4	4	6	2	0	0	6	9	1	1	1	1	61.5	1.618
P	0	3	0	3	0	0	0	0	2	2	0	1	0	4	0	0	0	2	0	1	2	3	1	0.5	1	1	4	4	6	2	0	0	6	9	1	1	1	1	61.5	1.618
Q	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	4	0.105
R	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	4	0.105
S	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.026
T	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.026
COMFORT	6.5	8	8	9	7	7	9	2	4	4	9	9.5	9	6	7	8	8	7	10	9	8	9	9	10	7	8	5	4	4	7	8	6	7	4.5	5	5	6	6	265.5	6.987

Based on the discomfort scores given in the last page, p-values were calculated. In the tables on the right the p-values per region and per posture are shown.

P-values per region	
A	0.843
B	0.216
C	0.646
D	0.861
E	0.144
F	0.112
G	0.844
H	0.924
I	0.645
J	0.645
K	0.782
L	0.782
M	0.607
N	0.607
O	0.027
P	0.027
Q	0.670
R	0.670
S	0.531
T	0.531

Region	Posture	P-value
A	U	0.980
	L	0.725
B	U	0.370
	L	0.413
C	U	0.412
	L	0.819
D	U	0.412
	L	0.934
E	U	0.174
	L	0.549
F	U	0.162
	L	0.458
G	U	0.894
	L	0.689
H	U	0.894
	L	0.791
I	U	0.734
	L	0.767
J	U	0.734
	L	0.767
K	U	0.033
	L	0.587
L	U	0.033
	L	0.587
M	U	0.409
	L	0.964
N	U	0.409
	L	0.964
O	U	0.314
	L	0.042
P	U	0.314
	L	0.042
Q	U	0.667
	L	0.973
R	U	0.667
	L	0.973
S	U	0.150
	L	0.973
T	U	0.150
	L	0.973

Appendix 8: Feedback evaluation test

	FEEDBACK		SCORE	
	POSITIVE	NEGATIVE	UPRIGHT	LAYING
1U		Unpleasant tight feeling in upper back area	6.5	8
		Very deep sitting or sliding in, especially in the lower back area		
1L	I felt very comfortable and was able to fall a sleep	Unfortunately the shoulders didn't fit inside the frame, feeling like a chicken		
	When the seat lowered and tilted backwards, you noticed how the seat changed and it felt more comfortable			
2	Seat angle is adjustable	Back support is too weak, too much weight at the shoulder area – I would like more lumbar support	8	9
		Seat length is too long		
3	Adjustability range	Narrow backrest	7	7
	Far adjustable	Hard foam		
4		the upper back sinks too deep into the seat and is severely constricted from the left and right	9	2
5	Tension of the foam is good	Too less support for the backrest	4	4
6	Upper back feeling was great	Weak: get up of the seat	9	9.5
7			9	6
8	High adjustment range for relax position	Shoulder area felt narrow	7	8
	Soft cushion of the seat pan	Lumbar area could be more adjustable		
		No 'luxury-seat' (functions, textile,...)		
9	Good position adjustment	It's a little bit tight at the back region	8	7
	Overall comfortable			
10	Nice position for the head	In the laying down position I felt a little pressure on the sides of my arms	10	9
	Nice position for the back			
11	Good posture/nice position overall	Pressure area in the area of the shoulders	8	9
	Soft initial comfort, warm material of backrest			
12	Backrest comfortability is high (relaxing)	Shoulder position should be adjustable	9	10
	Headrest comfortability is also nice	Legrest feature could be added for sleeping mode		
	Cushioning (foam) material is good (nice)			
13	Position change	Seat could be wider	7	8
	Very 'safe' posture	Head support could be more in the front		
	Overall comfortable			
14	Head rest	Metal bar of seat structure is noticed through cushion	5	4
	Lower back area while sitting upright	Ledge of seat is pressing against legs		
15	Shape is good for relaxing	Backrest too low	4	7
	Lower back is well supported	Upperend of the backrest is too hard		
	Good alignment with leg length	Headsupport is insufficient		
16	Comfortable overall	Could have more support in E, F, G, H	8	6
		Neck support could be improved		
17		Shoulders feel pressed, feeling is circular, would prefer a more trapezoid shape	7	4.5
		Arms feel a little pushed forward		
		Feels like seat is not fitting to my back – backrest on top too small and or not long enough		
18		Congested at E, F	5	5
19	Good torso, good back support (lower back)	Too small at the chest	6	6
		Shoulders too far pushed forward		