MODULAR SADDLE SYSTEM

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1. SUMMARY

Selecting the perfect cycling saddle can be a long and painful process trying and buying multiple saddles. Riding on the wrong type of saddle can cause various irritations and can even result in erectile dysfunction (Goldstein, 2007) and may in the end spoil the fun of cycling.

A direction in the design of female saddles was chosen because all of the female questionnaire respondents experienced discomfort while cycling (appendix 7). The project was done with saddle brand PRO, which doesn't have a female saddle shape yet in their product portfolio and most saddles on the market are based on male research. Male cyclists have various male based saddle shapes to choose from, females only a few.

Female cyclists have a larger sit bone angle and a greater sit bone width. They also prefer a different pressure division on the saddle compared to male cyclists. Next to these anatomical differences, chafing of the saddle nose, during the leg movement, is a problem that often occurs for females.

Increasing the lifespan of the saddle, being able to repair or upgrade the saddle and adjusting the comfort level are things respondents seek in a new saddle (appendix 6) and are in my opinion the best way to be more sustainable. With a modular saddle structure, the durable use of carbon fibre can be extended over a longer time frame and be standardized.

Additive manufacturing has the potential to be a manufacturing method for PRO saddles. Advantages are that forces can be locally absorbed by geometry and ductility can be modified. It is essential for PRO to get acquainted with the technique now to keep up with competitors. Next to that, this process allows customization and local production and could bring longevity by upgrades over the lifespan of the product. Being able to adjust the ductility and form is especially desirable for female cyclists, who have more sensitive pudendal nerves in their pelvises (Bicyclelab 2012).

The availability of new additive manufacturing methods and the clear focus of Shimano to produce saddles with low environmental impact, make room for this new approach. Therefore, the goal of this project is to design a solution that captures females' requirements and transform these into a road/gravel saddle. Women should be able to select the right saddle within the PRO collection.

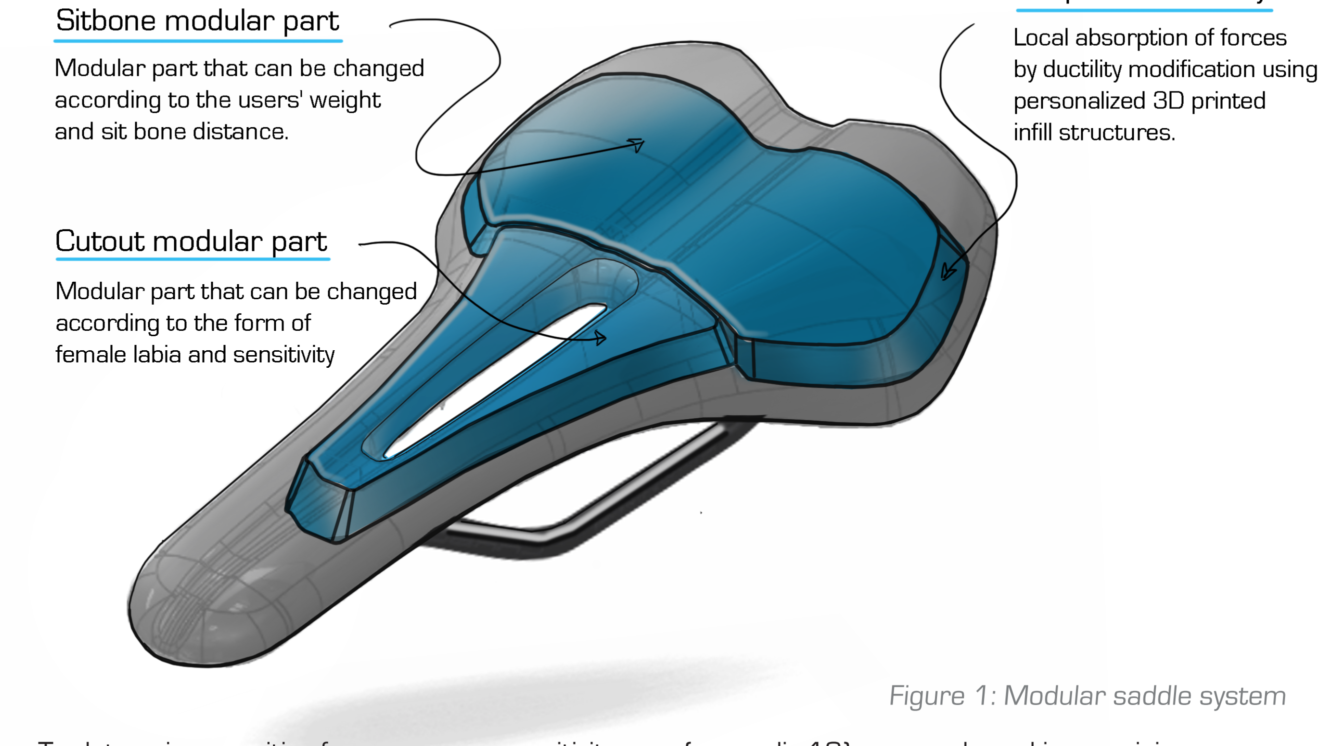

Figure 1: Modular saddle system

To determine sensitive focus areas, a sensitivity map (appendix 12) was made and is promising as a tool for future saddle design. This map adds in relieving sensitive zones and will increase the chance of designing a more comfortable saddle. This research showed that variation in female saddles is particularly needed in the current nose width, hardness and cutout position of the saddle.

Research shows (appendix 6) that users want to be able to adjust their saddle to achieve the highest personal comfort levels. This Modular Saddle System (MSS) could give users the possibility to adjust their saddle to their preferences. With a modular saddle structure, the durable use of carbon fibre could be extended over a longer time frame. Next to that, being able to repair or upgrade can increase the lifespan of their saddle.

To validate the concept of a modular saddle, models are made based on the most comfortable rewarded (appendix14) PRO saddle. A pressure map was used to prove or show what people feel when sitting on a saddle, together with a Likert comfort scale rating.

Having modular parts depending on parameters like weight and personal preferences will allow every rider to be able to find the correct saddle in the PRO product portfolio.

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3. INTRODUCTION

This report is the conclusion of my Master study Integrated Product Design (IPD) at the faculty of Industrial Design Engineering at TU Delft. The project was performed during a 100-day graduation internship at Shimano Europe (PRO sub-brand) with the result of a personalized bicycle saddle.

Selecting the perfect cycling saddle can be a long and painful process with still barely any room for personal adjustments. My fascination with this subject comes from the fact that I had a lot of saddle sores myself and I had trouble finding the perfect saddle for me. This resulted in me trying out a lot of different saddles and going to numerous bike fitters (adjusting the bike to fit you).

In this project various people and companies have contributed to the final result: First of all, I want to thank Mark Kikkert and Jos Koop for giving me the opportunity for this assignment within the PRO team. Next, I would like to thank all the experts and people working together with me in the pressure cooker sessions. Also, I want to thank Dr. Ir. Erik Tempelman and Ir. Maurits Willemen for their awesome guidance, support and ideas for this project. Lastly, I want to thank Rozemarijn Ammerlaan as a sparring partner and for her help during the sensitivity test.

I got in contact with PRO via my cycling association from the TU Delft and presented to them my vision on how personalisation can influence future road bicycle saddle development. This vision turned out to be one of the areas that PRO wanted to expand their expertise in; to be able to suit every rider with a PRO saddle. The current development of saddles is often done with male data or tests. With the upcoming popularity of female cycling (see Assignment) and the opportunities for new production techniques, this can provide space for new solutions, ideas and commercial opportunities.

Figure 2 shows an overview of the project planning and the structure of the project. It shows that the information analysis phase is split up into four pressure cookers (PC): A speed up process, wherein one week as much knowledge about a certain topic as possible is retrieved. After that several concepts were generated in a creative session and developed further. At the midterm, the choice for a modular saddle was made. With a sensitivity and pressure user test, the design attention points of female saddle design were determined. Finally, the mechanism for attaching the modular parts to the saddle and the interface between them were designed because they are essential for the proof of concept.

This report has the same setup as the end presentation. After this introduction, the analysis phase: the assignment, its context and the method, are explained. Secondly, the ideation phase: Main requirements of the design, ideation, conceptualisation and choice are argued. The synthesis choice for the embodiment of the modular saddle are explained. The last part of the report, the conclusion, is about the product presentation, validation, conclusions and recommendations. A further detailed explanation is done in the appendix on several topics.

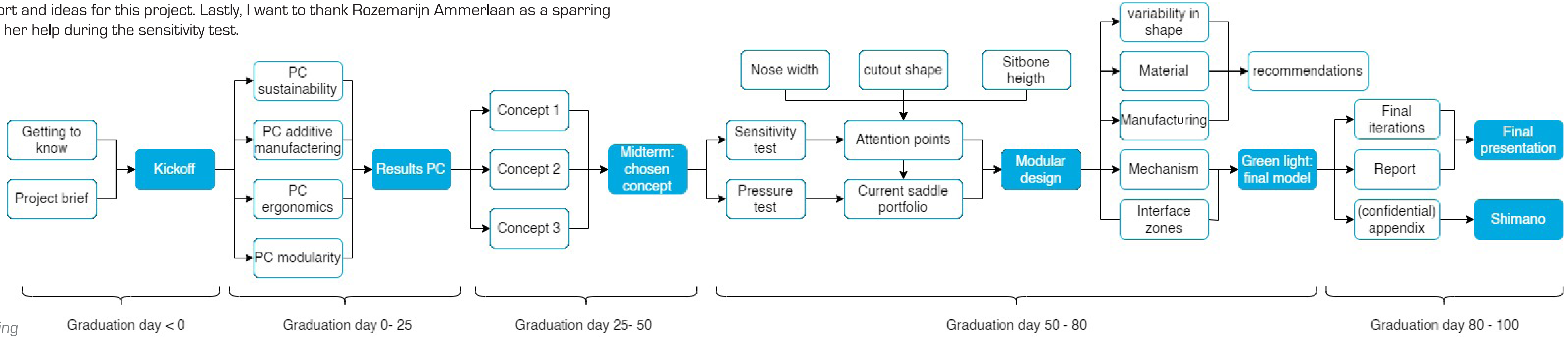


Figure 2: Project planning

SECTION 1

ANALYSIS

Figure 3: Bikefitting

4. ASSIGNMENT

In 1989 Shimano BeNeLux started PRO, to cover the complete product spectrum of the bike and give a full Shimano experience. PRO currently produces saddles, stems, handlebars and accessories. PRO saddles are the main revenue driver in the PRO product portfolio. PRO should help riders to get the most from their bike; achieving the perfect fit and selecting the most comfortable saddle.

PRO started introducing saddles in 1999 and since then saddles have become a core category for PRO and a still-growing revenue driver. PRO wants to stay ahead of competitors. The saddle research and development has grown along, resulting in PRO now having various saddle models suitable for many different types of riders. To gain more market share and suit every cyclist with a PRO saddle, PRO wants to expand their expertise on saddle research and development.

Most current saddles are based on research and tested with male subjects. However the female group of cyclists is growing: Strava shows that in 2020 109% more activities are recorded by females, compared to 2019 (Midred L., 2020). Up to 62 percent of competitive female cyclists reported feeling genital numbness, tingling, or pain within the past 30 days (Yeager S. 2021). Discomfort on a bike saddle can lead to injuries, swelling or perineal numbness and create an unpleasant cycling experience (Bakker T. 2015). So, this target group is increasing and it could be a good choice, both economical and ergonomic, to develop an ergonomically specific female saddle.

The target group consists of females between 15 and 50 that do road/gravel bike rides. They ride for fun but also have a competitive wish to stay healthy and fit. Endurance road and gravel cyclists spend longer periods cycling on their saddles. Cyclists in this category will mostly wear padded cycling clothes. This project aims to launch in the market in 2025.

"I am going to find a solution that captures females' personal requirements and transform that into a road/gravel saddle. In this way, I can help people to find the perfect saddle for them in a better way. Everybody should be able to find the right saddle in the PRO collection"

Taking into account the various range of shapes of the current saddle, a one size fits all solution for high-end road saddles is most probably not the way to go. Actually, it can be expected that the outcome will be a product (saddle) with a certain type of customisation. What level of customisation is possible, is something that is part of the investigation, taking ergonomic, economic, technical, sustainable and aesthetic requirements in mind. In this outcome I want to be able to adjust the saddle to the type of rider in a simple intuitive way, making selecting the perfect fit easier and supporting the user to have a pleasant cycling experience.

Figure 4: Shimano

5. CONTEXT

Competitive road bike saddles are the category I am graduating in since there is a lot of potential with new production methods, new market segments and personalized products.

New bought bikes often come with an entry-level saddle to save costs by the bike manufacturer. These saddles are not in all cases the perfect fit for users and are the first thing to upgrade on a bike. New saddles are bought either at a local bike shop or a webshop. Most brands offer test saddles or a test period. If the user still has problems, a bikefit can be done. Then a specialist looks at what saddle fits the user and sometimes checks how the pressure is divided on the saddle.

Nowadays PRO has a saddle selector, which is an online fitting tool (https://www.pro-bikegear.com/global/saddle-selector). Based on numerous factors like gender, flexibility and how competitive you are, 3 options for saddles are given. However, a real bike fit is not taken into consideration here. Important to mention is that most people (70% in my research) select their saddle without a bikefit (appendix 6).

PRO is part of the Shimano group, which is a larger organization also including bike fitting knowledge. This bike-fitting part uses pressure maps and other kinesiologic data that in reality is hardly used to produce a data-driven design for saddles. Competitors such as Gebiomized do use this feedback to base their design upon (appendix 3).

The current production method is focused on mass production. Here the artificial leather cover is glued onto foam mostly already in the mould. An injection moulded base supported with carbon fibre is then attached before the rails are assembled (figure 6).

What is also typical in this industry and especially for road/gravel racing, is a focus on the weight of the saddle, which is commercially used as a unique selling point (USP). Next to comfort, price, aesthetics, quality and durability, this is a specific factor for this industry. The importance of each of these factors can vary between the type of riders.

Nowadays PRO is making changes in (CAD)models and sending them to the vendor for production. The vendor then reproduces the CAD model in their own CAD software. After a check, PRO can request specific changes in the model and mould. Current shapes are all based on male tests and ergonomics.

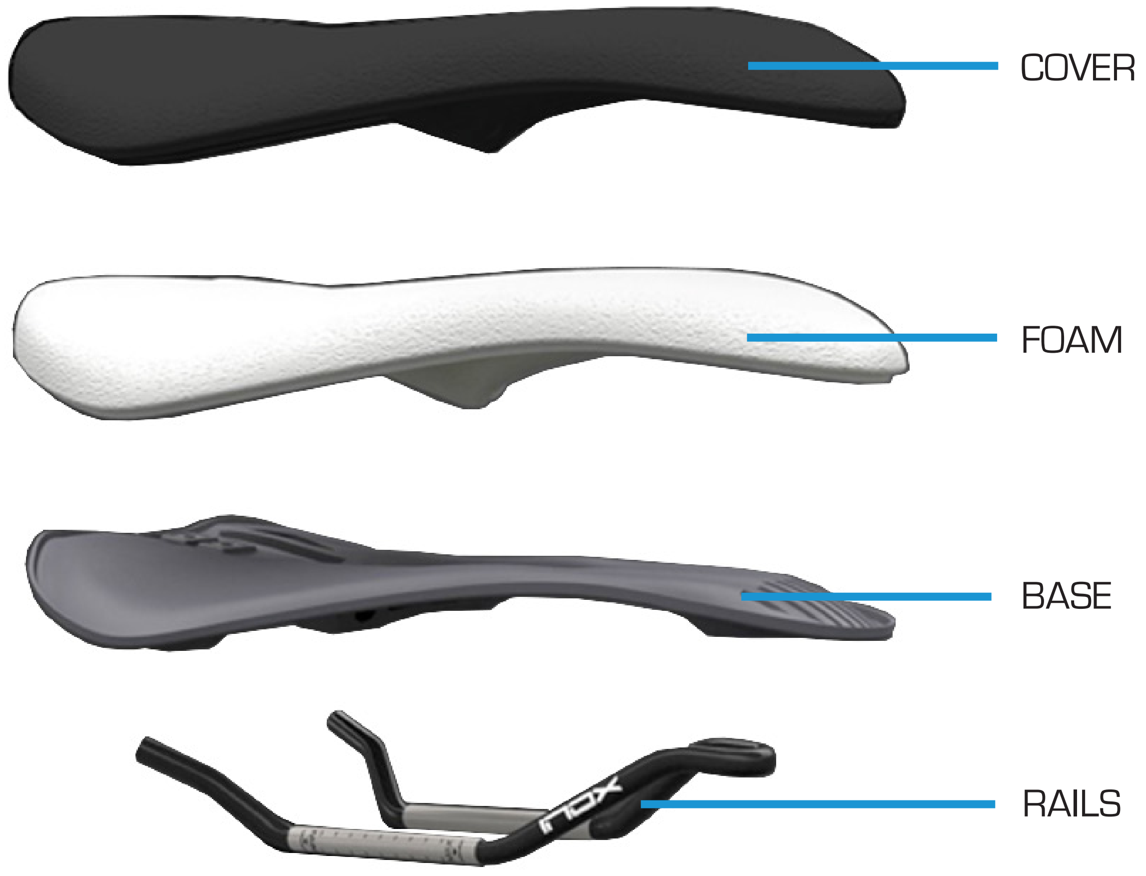


Figure 5: Exploded view saddle

6. METHOD

When first meeting the people of PRO, I told them about my vision on personalisation of saddles and they immediately were enthusiastic. Various directions were mentioned; 3D printing, modular design, ergonomics and sustainability were all possible directions.

Because of this wide variety of scope, a pressure cooker approach was chosen during brainstorming with my chair Erik Tempelman. This implies that each of the possible directions would be addressed separately during one week. This would help me and PRO to get a better understanding of which topics were most viable for my project. Before that, research on the company, competitors and assignment was done and concluded in the design brief.

For each of these pressure cookers research questions are made to investigate possible interesting directions within the scope together with PRO. To answer these questions, literature research, experiments and interviews were done. Next to that, an expert on each of these topics is asked for guidance that week.

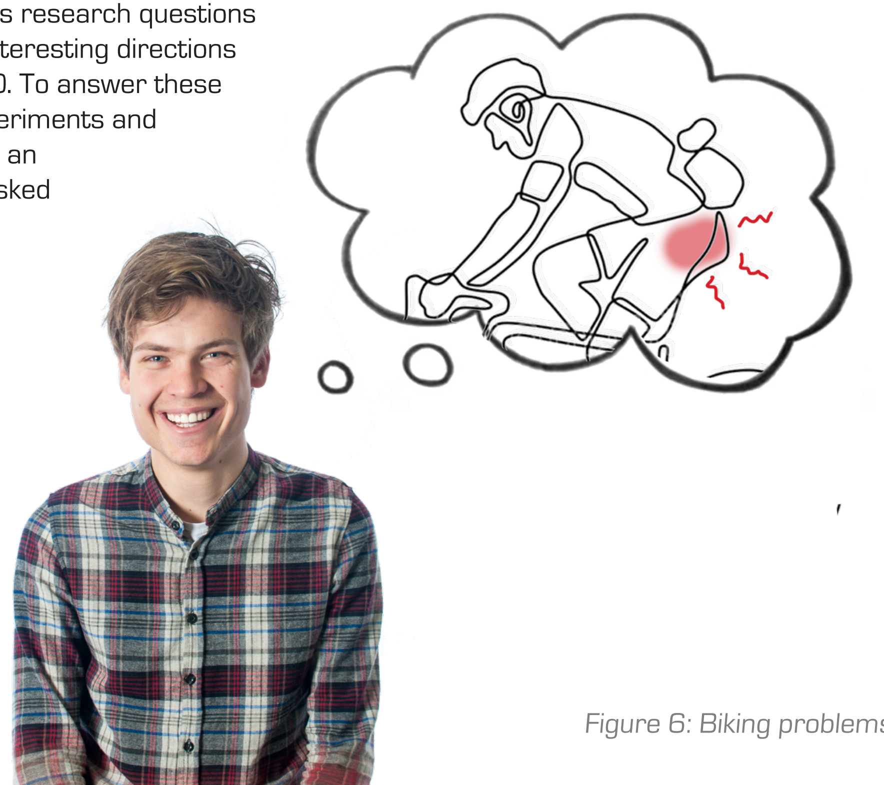


Figure 6: Biking problems

The research questions were the following:

ERGONOMICS PRESSURE COOKER
- Where does discomfort often occur while cycling?
- Which human parameters are important for designing a saddle for males and females, and is there a difference between them?

SUSTAINABILITY PRESSURE COOKER
- How is a current saddle manufactured?
- What steps in the manufacturing process have the most environmental impact?
- What happens with an unused saddle?

ADDITIVE MANUFACTURING PRESSURE COOKER
- Could 3D printing be a suitable way of producing saddles?
- Which type of printing would be most suitable?

MODULARITY PRESSURE COOKER
- Is it viable to have a completely personalized saddle?
- How much do the current PRO products vary in shape?

The conclusions of each pressure cooker were presented to the client and coaches in a creative session and possible design directions were generated. Out of these directions, the three most promising ideas were developed further. These ideas were evaluated with a program of requirements, after which a choice was made.

With the choice for modular inserts made, the attention points of the female saddle design were determined with a sensitivity and pressure user test. With that information, a subdivision and prototypes were made to iterate and explore different mechanisms to keep the modular parts in position while riding on the saddle.

After that, validation was done with 6 female users to test if the changes made and the modular system could contribute to the perceived comfort level of the saddle. The conclusions of this test, project conclusions, recommendations for further research and a reflection can be found at the end of this report. Further elaboration about this research is done in the appendix, including, for example, prototypes, calculations and interviews.

7. TRENDS

PRO currently owns 10 percent of the market share and focuses on providing as many people as possible with a saddle (appendix 7). They produce four different types of road/gravel saddles with mostly three variable widths in three different width versions. Their main competitors in the saddle branche are Specialized, Bontrager, Fizik and Selle Italia (appendix 7). All produce various types of saddles at various prices. A competitor analysis of these four brands in pricing and weight of female saddles can be found in appendix 21.

In recent years the cycling industry is paying more attention to developing more sustainable products. While cycling is a relatively 'green' way of transporting, currently loads of carbon fibre is used in bicycle products. However, brands are trying to change this slowly, Selle Italia already claims to have made a sustainable saddle with eco-friendly materials and production methods. They also have a model that has repairable parts. Therefore a sustainability pressure cooker of the PRO saddles was performed.

Saddles used to be covered by a Polyurethane cover that was attached with screws on the bottom. Nowadays that is done by moulding processes and they can't be separated anymore, for weight and aesthetic reasons. Lately, however, two big competitors have introduced DLS printed saddles. Details about this printing process can be found in appendix 11. 3D printed saddles now don't have personalized features (figure 7), but the technology now allows these brands to actively handle general pressure zones. Because of this potential, this production method is researched in the additive manufacturing pressure cooker.

Nowadays the trend is that saddles are decreasing in length. There are more and more short nose designs on the market. A shorter nose should allow the pelvis to tilt in a more aerodynamic position without perceiving more discomfort (Spender J, 2020). It also stimulates the user to sit on the back of the saddle and therefore get more pressure on the sit bones. Detailed saddle ergonomics are investigated in the ergonomics pressure cooker.

Saddle shapes used to be completely solid. First, a hollow strip was implemented to relieve pressure on the perineum mainly for male riders. This developed further into a cutout (hole) that differs per design. The variation in shape and cutout between models is further explored in the pressure cooker modularity.

The side profile of the saddle has also changed over the years. While it used to be completely flat, currently it is a complex 3d shape. Together with the short fit models, more tail up models was developed to stimulate the pelvis to move forwards and relieve the spline.

Figure 7: Printed saddles

8. PRESSURE COOKERS

All the research in the topics ergonomics, sustainability, additive manufacturing and modularity, gained in the pressure cookers are explained in this chapter.

Figure 8: Contact points

8.1 ERGONOMICS

8.1.1 INTRODUCTION

In this chapter the contact points with the bike, the influence of bike position, common problems on the bike and finally the core differences between male and female bike ergonomics are investigated. These are essential to know before designing a bicycle saddle. Both literature and user interviews were conducted for these topics.

Designing a more personalized saddle should have added value compared to standard saddles to make customers willing to purchase it. It is important that the perceived comfort level is higher than a standard production saddle. In literature however, studies regarding bicycle comfort are often measured in the perceived discomfort. Comfort is a highly subjective term and most literature concludes that there is no one clear definition about what comfort is. Moes et al. concluded that comfort can only be experienced if no discomfort is experienced and therefore uses discomfort as a measuring scale; when no discomfort is experienced, comfort is experienced (see appendix 7 for factors that influence comfort) (Moes et al., 2006).

8.1.2 CONTACT POINTS

Cyclists have three main contact points with the bike: The saddle, handlebars and pedals (figure 8). These three are the main factors that determine bicycle comfort (Ayachi, F. S., Dorey, J., & Guastavino, C. (2015), pp. 124–136). The saddle design, the frame geometry (position of the contact points) and the handlebar position influence these contact points and are the factors that can influence the rider's feeling of (dis)comfort. With finding the correct position, frame geometry and handlebar position can be modified.

Finding the perfect cycling geometry on the bike has a great influence on the perceived level of (dis)comfort on the bike (Priego Quesada, J. I. et al., R. M. (2017), PP. 1459–1465). According to Priego Quesada et al. the bike geometry, for example, the saddle height and reach of the handlebar, is the most important factor in the perception of (dis)comfort.

Therefore we can conclude that saddle design does play a role in the (dis)comfort experienced on the bike, but it starts with finding the correct position on the bike. The current procedure of bike fitting can be found in appendix 5 where I experienced a bike fitting session. However, most cyclists do not perform a bikefit when buying a bike (about 16% performs a bikefit according to the research in appendix 6) and PRO mostly sells to these customers nowadays.

8.1.3 BICYCLE POSITION

For determining the best bicycle position a bike fit can be done. Important measurements for a bikefit are the trunk flexion (1) (the angle the upper body makes with the horizontal), the knee flexion (2) (the angle between the knee and upper leg) and the reaction of the pelvis (see figure 9).
The trunk flexion and especially the degree of knee flexion strongly affects the perception of fatigue, pain and comfort (Priego Quesada, J. I. et al., R. M. (2017), PP. 1459–1465). This can be modified by changing the saddle height and moving the saddle in the horizontal direction. The orientation of the pelvis can be modified by changing the type of saddle and rotating the saddle angle with the horizontal.

8.1.4 COMMON PROBLEMS

Cyclists experience various injuries and problems (van Hoof, W. et al, 2012). These problems can feel like small problems or irritations and are mostly mild. However, these injuries can become chronic and result in requiring dynamic therapy with a specialist (Clarsen et al., 2010). Most problems found in studies are related to a bikefit position: neck pain is experienced by 34% of the respondents, back pain by 41%, hand/wrist pain by 41%, buttock/perineum pain by 41%, hip pain by 7%, knee pain by 33% and foot/ankle pain by 24%. (van der Walt, A, 2014). Problems like tailbone pain are left out of scope because they only occur at more upright cycling positions (Bakker T, 2015).

Genitalia pain

The most common problems in cycling are urogenital problems for both females and males. This often results in genital numbness for male and genitalia discomfort for females, mostly caused by pinching the blood vessels underneath the pelvis. It is experienced in 50-91% of cyclists (Leibovitch, I et al, 2005). The saddle design can affect the blood flow in the perineal region (Jeong SJ, 2002) and result in erectile dysfunction (Goldstein, 2007).

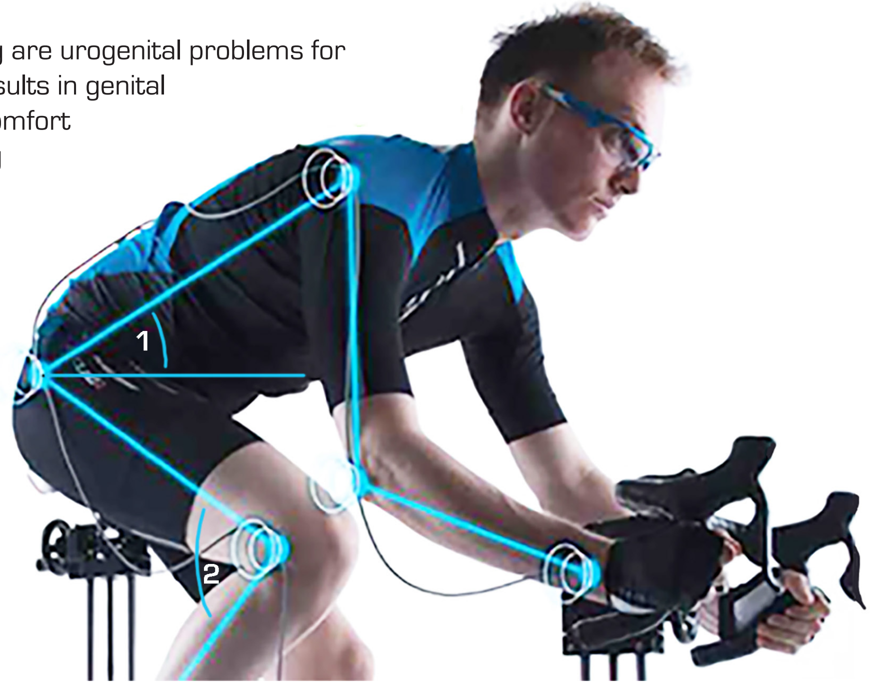


Figure 9: Geometry angles

Sitting bone pain

The ischial tuberosity is pain around the sit bones. The sit bones can handle the most pressure on the seating area but can be not symmetrical, causing one sit bone to have more force applied. Also around the sit bones, the genitalia, blood vessels and nerves are placed so that they can handle less pressure. For beginning cyclists, this pressure on the sit bones can also result in discomfort. However, this often disappears when cycling regularly according to bike fitter Niels Boon (appendix 5) and gynaecologist Frederieke Siemens (appendix 15).

Low back pain

The pelvis of a cyclist is not static during cycling but it rotates around all three axes (Potter, 2008). Also, the pelvis has to tilt to get into an aerodynamic position on the bike (figure 10). When having low pelvic tilt ability, the rider has to compensate with the lumbar flexibility. Having a lot of rotation in the pelvis and too little pelvic tilt can cause lower back pain. The ability to tilt the pelvis is strongly dependent on the saddle design. Research has shown that a cutout (8% more tilt) and short nose saddles (16 % more tilt) allow more pelvic tilt (Bressel, 2003).

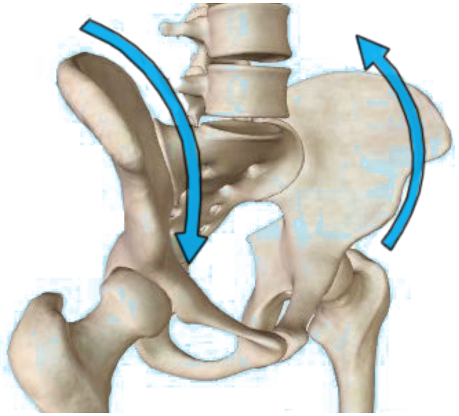


Figure 10: Pelvis rotation

Irritated skin on the sitting area

Irritation in the sitting area is often experienced by cyclists. Common problems can be swelling or pimples caused by ingrown hair. The warm foggy temperature in the padded pants makes the skin extremely sensitive to these problems. They often occur when going for longer rides in the summer. For females, swelling is experienced for 70% of the cyclists (Fröbose, 2003).

Irritated skin inside leg

This problem occurs when moving up and down while pedalling on the bike. It is mostly caused by irritation of the clothing or a too wide saddle nose. Especially for female cyclists, this is a big problem. In a more aerodynamic position (e.g. in the drops) their labia can be compressed and take part in this chafing movement. To see how these problems relate to each other and to get quantity on this data a questionnaire was performed with 85 respondents of my cycling clubs. The questionnaire therefore, had more younger respondents; 51 were male and 34 female (for full questionnaire see appendix 7).

What is striking to see is that females experience relatively more problems. All of the female respondents experience discomfort. Also, they have fewer problems with the perineum and more discomfort in the reproductive organ while cycling.

8.1.5 MALE AND FEMALE DIFFERENCES

Female and male bodies are not the same and that counts especially for designing a saddle. It is important for both genders that the pressure is distributed in a good way and the shape of the saddle supports this pressure division on the saddle.

In literature, saddles are often studied for two parts separately. The front side is called anterior and the backside posterior. The posterior part is meant for equal pressure division of the ischial tuberosity (sit bones). The anterior part is mainly for steering in corners and to keep balance whilst riding. The cut between these parts is made at the 80mm point, a reference point that most people begin to apply most sitting bone force (see also pressure maps in appendix 14).

However, the distribution of pressure differs per gender (Potter, J, 2008). These gender-related differences in saddle loading are important to take into account when designing saddles. The differences are increasing when riders are riding in an aerodynamic position and more weight is distributed over the anterior pelvic position. Males are likely to have the most pressure on their perineum, while for females that is the position where the genitalia are placed.

The difference between male and female ischial tuberosity (sit bone) width is a minor difference: The width of males is around 9% smaller than for females. However the standard deviation among males are higher (Chen, Y. L., 2021).

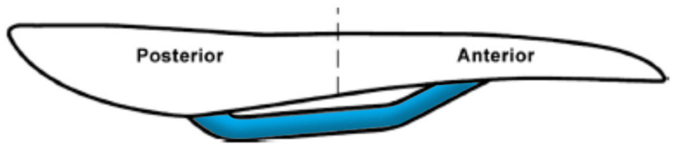


Figure 11: Anterior posterior

The real difference in the male and female pelvis is that the inferior pubic angle for females is a larger angle than that of males. This is because it allows the pelvis for childbirth. A wider pubic angle can allow the saddle to press more into the soft tissues of a rider. That is a concern since on the inside of the pubic rami bone a series of nerves and blood vessels run. For males, these nerves and blood vessels run through the genitalia, but for females, they stop at the genitalia. These nerve-ends can be extremely sensitive and compressing these can lead to discomfort or pain and long term dysfunction of the genitals (Bicyclelab 2012).

The pelvis is more flexible for females than for males (Sauer et. al, 2007). This anterior pelvic tilt differs 3 degrees on average and is next to gender depending on the ischial tuberosity width and hamstring flexibility. This difference results in more pressure in the genitalia for females. This is the reason why most female-specific saddles have a higher posterior part. Ischial tuberosity width (sit bone) becomes narrower the more the pelvis is tilted. So the location where maximum pressure is applied differs between females and males (figure 12).

8.1.6 CONCLUSION

As found in the literature and the questionnaire, many people still struggle with specific problems during cycling. Not having the right position on the bike is a large part of this perceived (dis)comfort. However, the questionnaire shows that there are still many riders experiencing saddle related discomfort.

Male and female bodies are not the same, especially for a performance sport a one size fits all solution does not fulfil individual needs. Irritation on the inside of the leg, the difference in sit bone angle and width and pressure division between the anterior and posterior parts, are three main differences between genders that need special attention when designing a female saddle.

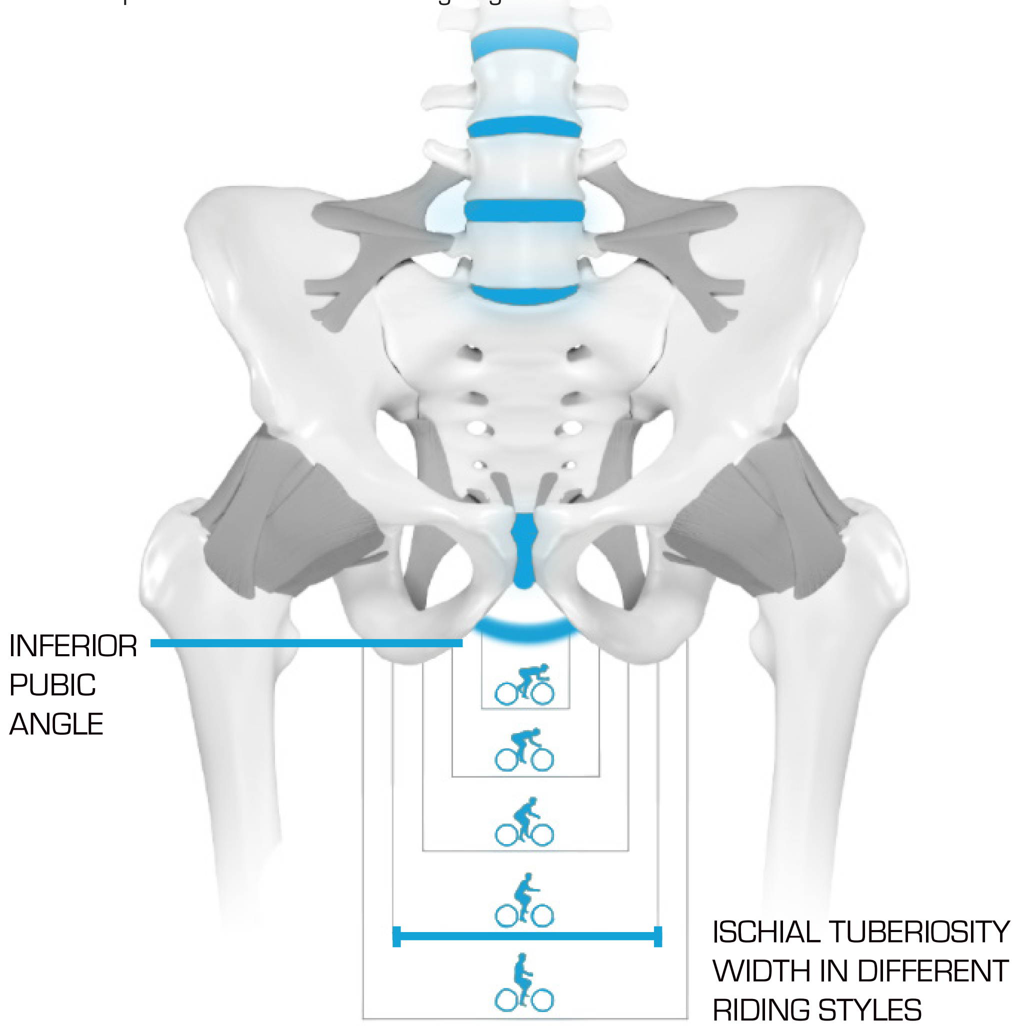


Figure 12: Different riding styles

8.2 SUSTAINABILITY

8.2.1 INTRODUCTION

PRO and competitors in the saddle branche are looking for more eco-friendly ways to produce their goods. Different sustainable strategies were investigated using life cycle assessments, user-interviews.

In sustainable product design, a sustainable strategy is often determined. In my research, the 7R-model was used (Morseletto, P. (2020)), figure 13. With this model, companies can easily see which options in sustainable product design could fit their products. In appendix 16 some sustainable examples are given within the cycling industry and PRO's sustainable statement is explained (appendix 16).

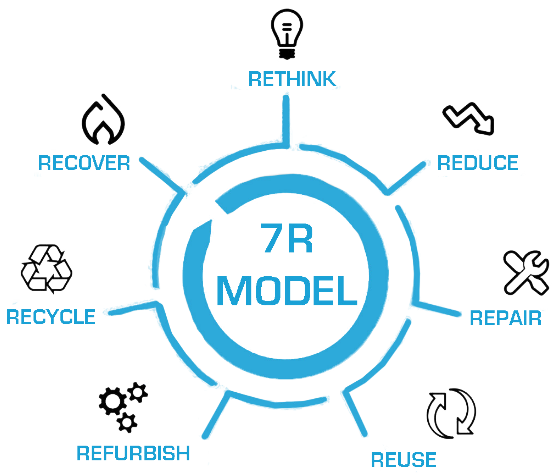


Figure 13: 7R model

8.2.2 LIFE CYCLE ASSESSMENT

To determine which of these 7R's could have the most impact, a life cycle assessment (LCA) has been done on the current lineup of saddles, using the Ecolizer database. There was a distinction made between the base, the rails and the padding of the saddle. Next to that, a questionnaire among 259 cyclists was done to get insights into bicycle saddle behaviour around buying and disposal of them.

The outcomes of the LCA can be seen in figure 14. Comparing the three parts;

- The saddle base has the most impact, followed by the saddle rails and the padding.
- Carbon fibre reinforced nylon is now used in the lightest saddles but has the most impact as a base material. The hand lay-up carbon fibre rail even has worse impact values but has a relatively low weight. Although the impact of the use of carbon fibre is larger, a reinforced base can cause a longer lifespan.
- For the padding, EVA has less impact than PU. Adding gel material has a positive impact on the production impact but makes it harder to separate and therefore worse for end of life.
- In this research, only one model was analyzed. So, the weight per saddle may differ from model to model. But generally speaking, this is also representative of other models.

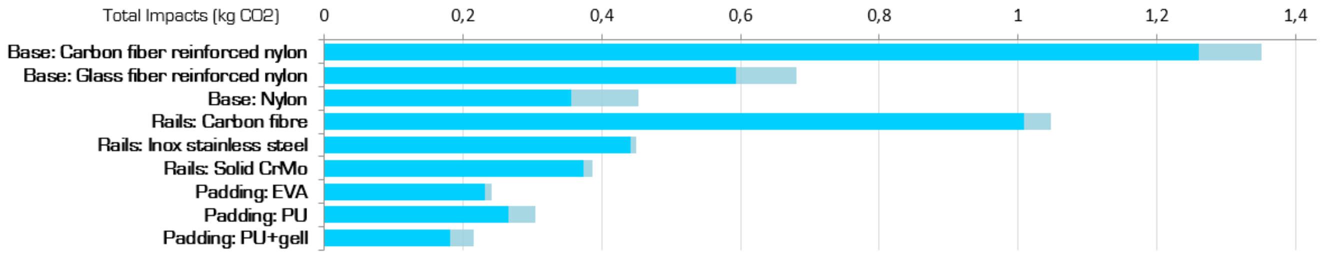


Figure 14: LCA, blue= calculated impact, grey= uncertainty

8.2.3 QUESTIONAIRE

To make assumptions regarding end of life and values for the LCA, a questionnaire is performed among 259 participants, the main conclusions when analysing the LCA are:

- The average lifespan of a saddle is 3.6 years.
- After use 12.8 % of the saddles are thrown away and incinerated, 32.1% is not currently used and 49.5% is given a second life already
- Regarding why they buy a new saddle, 22% says because the old one broke down, 33% because they want a new saddle with better comfort and only 6% of the participants claims to buy a new saddle because of new looks or trends

PRO now offers a 30-day money back to try out different saddles. These saddles can't be sold afterwards and are now thrown away or ridden by staff/test bikes. For the last three years, there have been around 1300 saddles brought back, which is not even 1% of the total sales for three years and therefore does not have a significant environmental impact.

8.2.4 CONCLUSION

- To conclude, four possible directions were found in the pressure cooker:
  Rethink, redesign, recycle: using less carbon fibre reinforced material in the base and only providing it where it is needed for strength. Looking at PRO's sustainability goals (appendix 16) for a 2025 time scope, finding an alternative for carbon fibre reinforced plastic is the main challenge, This material produces 50% more kg CO2 than a non-reinforced nylon saddle and is, therefore, the most effective way of reducing impact.
- Reduce: getting rid of carbon fibre is the most efficient way to reduce impact, also reducing glue usage and recycling at end of life are possibilities that drastically improve the impact on the environment.
- Repair, refurbish and reuse: increasing the lifespan of the saddle, being able to repair or upgrade the saddle and adjusting the comfort level are things respondents seek in a new saddle (see research in appendix 6). Looking at a 2030 timeframe of PRO's sustainable goals, having an adjustable modular product is the focus of PRO. Gaining knowledge and doing research in modular products is essential for making a modular product work.
- Recycle: Using only one virgin material in the saddle base and being able to disassemble the product as a user will enable users to recycle every component.

8.3 ADDITIVE MANUFACTURING

8.3.1 INTRODUCTION

Foams are used in saddles to create comfort. However new additive manufacturing methods have high potential because of their tunable deflection. Different methods and infills are explored in this chapter.

8.3.2 FOAM

The current foam is now either made from EVA, PU or Gel. Foam gets its specification by trapping air in pockets inside the material (D. Weaire, 1999). The foam now is sealed from the environment to prevent dirt and water from sticking in. Competitors (appendix 21) already produce additive manufactured saddles. Current foams used are lightweight, flexible and have a good performance against wear. Foams currently used in saddles are generally made from crosslinking thermosets with chemical bonds between polymer chains. Crosslinks assure that foam expansion is stabilized and produces favourable properties for this application (Chen, N, 2012).

8.3.3 INFILL STRUCTURE

FDM printing method was selected as a prototyping tool to make quick and low costs prototypes. For this production method, a study was performed to research the ductility of different infill structures. Infill structure is the structure and shape of the material inside of a part. Together with expert Tim Kuipers, three different infill structures were selected that have high potential to mimic the ductility properties of the currently used foam.

Figure 15: Prototype 10% Crossfill infill

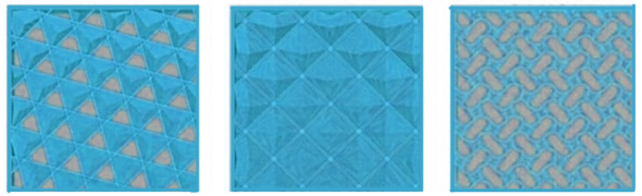


Figure 16: Infill structures

When applying force on foam (e.g. while riding), it has three regimes. First, it transforms linearly, so the saddle foam will compress the saddle. As the load increases, foam cells begin to collapse (yielding). The strain has a roughly constant value. This can be felt when pushing on a saddle to the point that the foam does not deform anymore. When opposing walls of cells meet and touch, the third phase causes the stress to increase rapidly. This can't be felt with human hands on a saddle but can only be seen when applying extreme forces (Elliott, J. A. et. al, 2002)

To mimic this behaviour three different infill structures were generated using the Ultimaker software: Gyroid, Cubicle subdivision and Crossfill 3D. Both were printed with a 10% and 20% infill and tested in a compression test to analyze how different infill structures influence stiffness (appendix 8 and figure 15). Modifying these structures can implement personal preferences regarding foam hardness or ductility. Five different additive manufacturing methods were analyzed and scored on seven properties (full process and research in appendix 11). These were selected together with 3D print expert Tessa Essers because of their availability and potential in the bicycle saddle industry. FDM printing at the company Colorfabb was selected as the option with the most potential, because of material and printing speed optimization.

8.3.4 CONCLUSION

So, additive manufacturing has the potential to be a manufacturing method for PRO saddles. Forces can be locally absorbed by geometry and ductility can be modified. On top of that, this process allows customization and local production. FDM printing at Colorfabb allows mass production of customized products with lower production time. Nevertheless, having a production time of about an hour per saddle is more time consuming than conventional methods with more room for errors in the process.

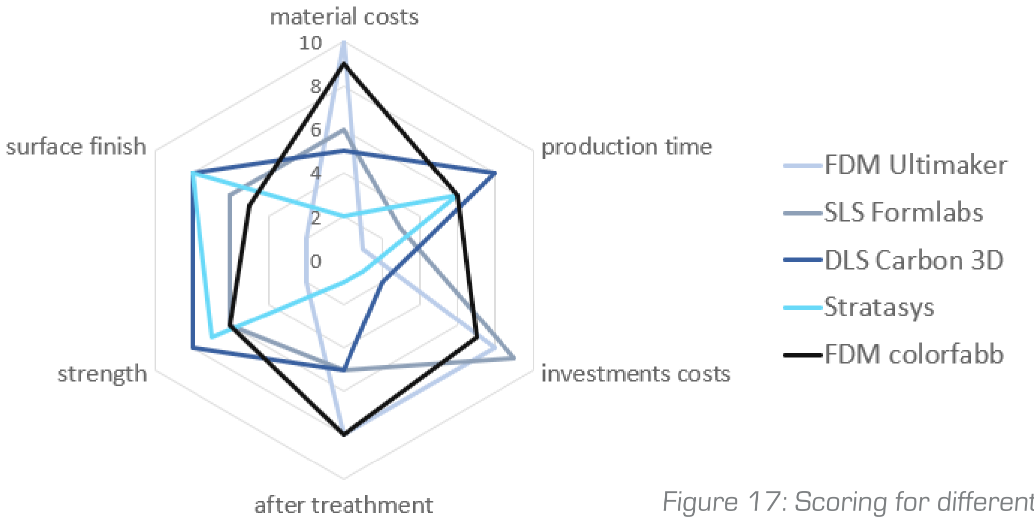


Figure 17: Scoring for different additive manufacturing methods

8.4 MODULAR DESIGN

8.4.1 INTRODUCTION
PRO currently has a lineup of five different shapes of saddles: Falcon, Turnix, Griffon, Stealth and the later released Stealth Curved (figure 19). Most of the saddles are made in three variable widths. They differentiate in side-profile and rear-profile, stimulating different types of riders. Having a modular system for all the different types can decrease costs, decrease environmental impact and enable users to customize.

8.4.2 DIFFERENT PROFILES
A weaved side profile is often used for less flexible riders, to stimulate the pelvis rotation or to relieve certain pressure points. The more round the side profile is the more it enables the pelvis to tilt when cycling. The riders sitting still on their saddle will therefore use a flat saddle.

To analyze the current lineup and see whether the designs differ, the complete range was measured and cut into 3 parts. These parts were analyzed and combined to see whether combinations were possible.

Figure 18: Modular prototype

Pro and Bikefitting.com both use the 80 mm point as a reference point to keep the same position when changing saddles. This point is also the spot where most people start applying sit bone pressure (Boon N. 2021). For this modularity research therefore the saddle was divided into three parts: from front till 80mm point, from 80 mm to the maximum width and from maximum width to the end.

All PRO products can be sorted into two categories: Short or long nose. Both Stealth models have a short nose, the other models have a long nose. The padding shape of most long nose saddles is similar. It can be seen in figure 18 that the padding thickness differs per model, depending on the material and the use of gel inserts. Depending on the intended riding position, the position of the cutout on the saddle changes per saddle.

8.4.3 CONCLUSION
- So, modularity would be possible within the current product range with differentiation between short and long nose saddles and a variable cutout position.
- Transforming these foams to a universal bed would add weight to fill in shape differentiation among models. However, it would offer numerous possibilities and shapes to make a modular system. Also, it would offer PRO to implement changes in design more quickly.
- The thickness of foam differs per saddle. The thickness and flexibility depend on personal preferences but also body weight. Nowadays every rider gets the same foam but not every rider has the same weight.

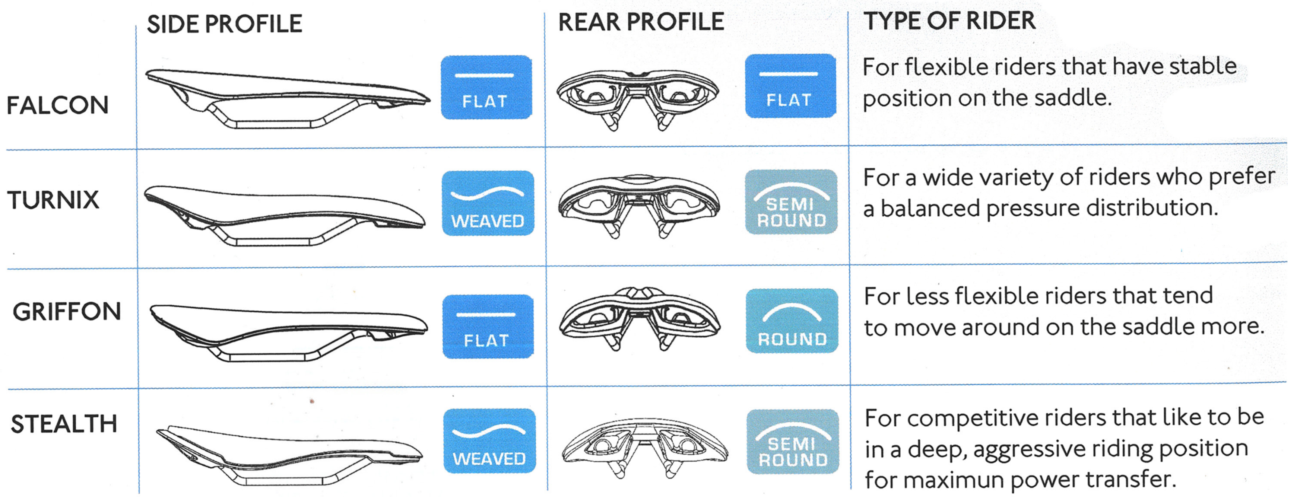


Figure 19: PRO product portfolio

8.5 MAIN CONCLUSIONS PRESSURE COOKERS

For the ideation phase the following results of the PC were presented:

- Not having the optimum position on the bike is a large part of the perceived (dis)comfort. However, the questionnaire shows there are still many riders experiencing saddle related discomfort. Irritation on the inside of the leg, the difference in sit bone angle and width and pressure division between anterior/posterior parts, are three main differences between male and female saddle designs.
- The saddle base accounts for around 50% of the total CO2 emissions (appendix 6); using less composite material or increasing the lifespan of this part will drastically improve these numbers.
- Varioshore is a type of TPU that expands after ejection and therefore becomes more ductile. It is already widely used in the insole industry and could be a suitable manufacturing method for producing saddles because of its low investment costs and local tunable ductility.
- Modular designed saddles would offer numerous possibilities and shapes, enabling users to customize their saddle (e.g. foam thickness). Also, it would offer PRO to implement changes in design more quickly. It would be possible within the current product range with differentiation between short/long nose saddles and a variable cutout position.

Figure 20: PRO Stealth saddle

SECTION 2

IDEATION

Figure 21: PRO custom saddle

9. PROJECT SCOPE AND IDEATION

An ideation workshop was done with the team (coaches and colleagues) to come up with several pre-concepts and to align on possible directions to take. First, the results of the pressure cookers were presented, secondly, the scope of the project was discussed. This scope was the starting point of the ideation. Next to that a complete programme of requirements was made and can be found in appendix 9.

Because none of the female respondents experienced no discomfort while cycling (appendix 7), the fact that PRO doesn't have a female saddle shape yet in their product portfolio and the fact that most saddles are designed from a males perspective, the direction in developing a cycling saddle for females was taken:

O **The product should have specific functions/designs based upon western female road/gravel riders between 15 and 50 years old, that cycle more than 5 hours per week.**

Due to the coronavirus, factories can not produce as much and the cycling market has exploded. Because of this extreme rising demand it's hard to find extra production capacity. Because of that:

O **The product should be produced by manufacturing processes with low lead-time**

Designing for a new target group and with possible new vendors requires more development time. Nevertheless PRO does not want to fall behind in the increasing target group of female riders.

O **The product should be able to launch in 2025**

A personalized saddle is only desirable if the users can feel less discomfort while riding.

O **Users should experience the difference in comfort between the current PRO lineup and personalized saddles**

In the workshop, five pre-concepts were generated together with the team. An overview of the workshop mural can be seen in figure 22. The five pre-concepts are briefly explained below:

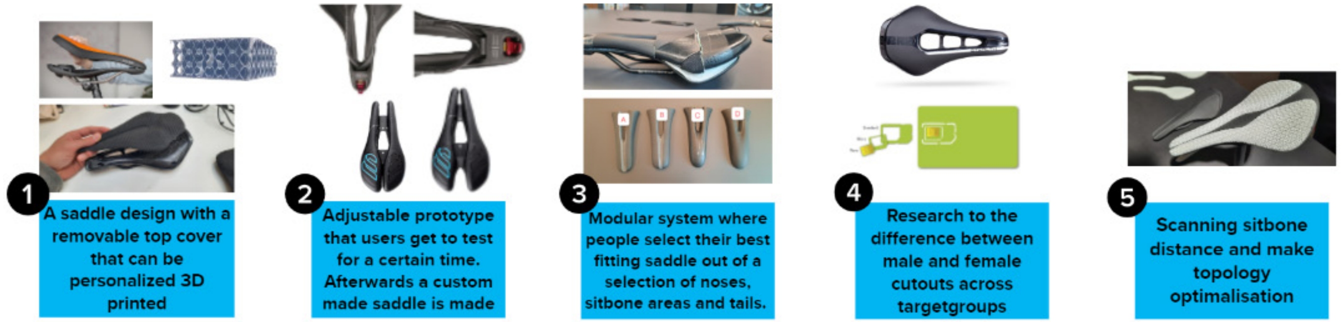


Figure 22: Idea generation

1. A complete printed saddle cover that can be customized to someone's extent. Personal preferences can be taken into account and parts with higher environmental impact can be kept for longer.
2. An adjustable prototype that users get to test to find their optimal shape. This shape is then fully 3D printed afterwards to make a perfect ergonomic, unique and superlight personal saddle.
3. A modular saddle where certain zones can be chosen according to the preferences of users. It enables PRO to integrate shape iterations quickly in the market with smaller investment costs
4. Research in the perfect cutout shape. Making a saddle with a step by step removal of the cutout and doing research on the shape would help PRO design the best cutout for females.
5. This idea was inspired by the model PRO/CESS of Tim Schütze who made a personalized printed saddle with the help of 3D scanning. Doing research in the best topology and structure of 3D printing would be suitable for making the best choice for a new saddle manufacturing method.

After the brainstorm, the five directions were summarized and we concluded that pre-concepts 2 and 4 can be integrated into one model that has various adjustable parts to find one best female shape. Pre-concept numbers 1 and 5 were also combined since topology optimization and scanning technique could be a way of determining the perfect shape within idea 1.

The outcome of this session was three directions (see concepts). These ideas were further developed, sketches of partial problems and quick prototypes were made to solve research questions in these three directions and investigate possible show stoppers.

10. CONCEPT 1

PERSONALIZED PRINTED TOP COVER

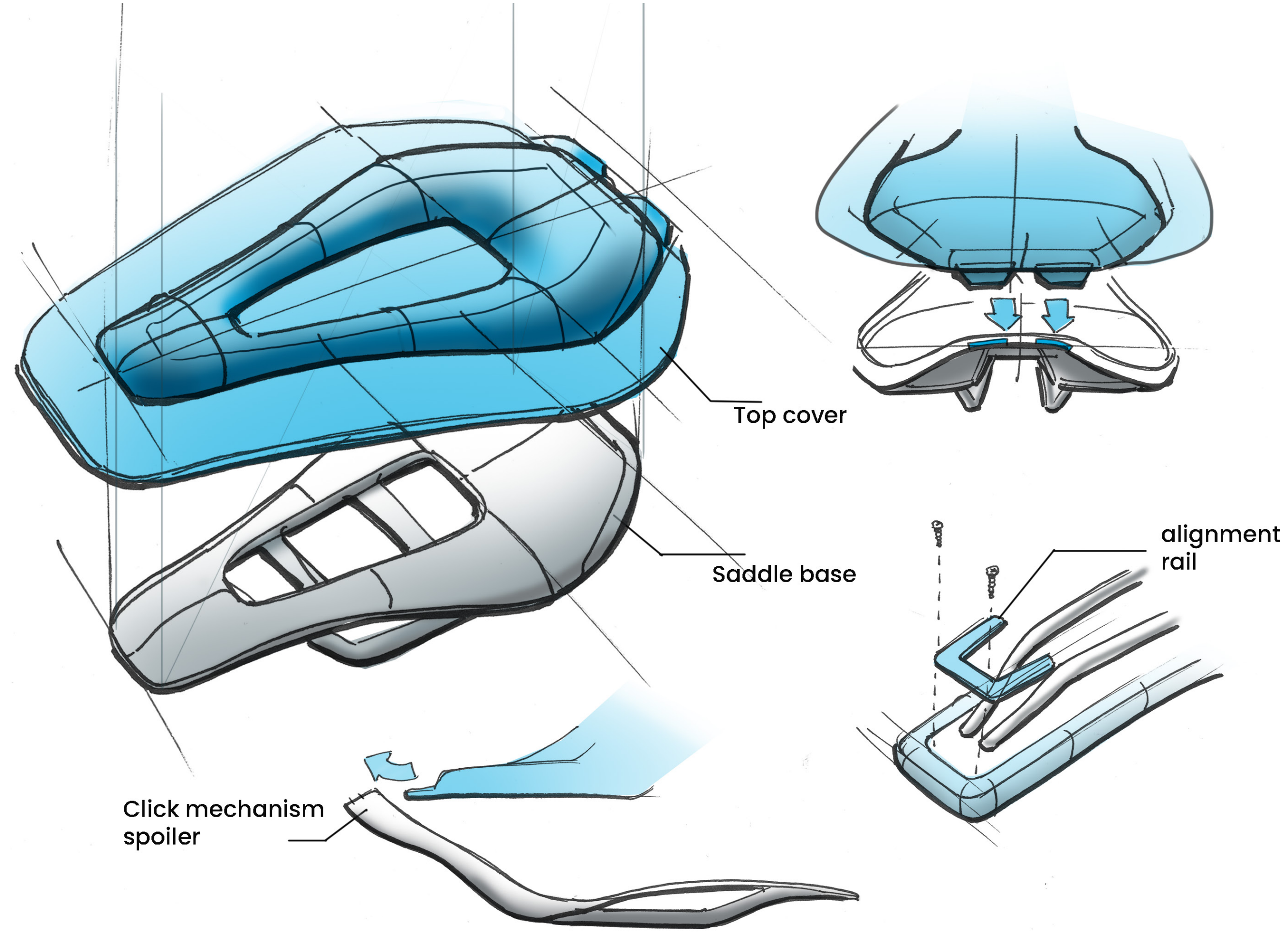


Figure 23: Personalized printed top cover

10.1 WORKING

Concept 1 makes use of a printed TPU cover that can be customized to a certain extent by a bike fitter. A bike fitter has to go through a selection menu and software will automatically make shape modifications (like they do with insoles). A custom saddle cover will be printed during the bikefit in around an hour and assembled on the carbon fibre base and rails that customers keep over a longer period.
The saddle base and rails are the parts with the most environmental impact. A 3D printed cover will be sold separately and be personalized to their needs. This cover is likely to wear earlier and can be replaced, in case of a crash or for comfort adjustments. Wear of the top cover or adjusting comfort is the main reason to replace a saddle (Appendix 6).

10.2 MANUFACTURING

Colorfabb developed a special Podoprinter that is also able to print saddle covers. The ductility of their material can be modified using expansion additives and smart infill structures. The cover is printed bigger, allowing the extra edges to be fixed with an alignment rail, keeping the top cover in place (see appendix 10). The spoiler is used to align the top cover. This way these unique design elements of the spoiler and the aesthetic advantages of 3D printing make for a unique design. The cover can be FDM printed with TPU material because of its tuneable ductility (see PC additive manufacturing). Varioshore, the type of TPU Colorfabb developed, can be fully recycled and turned into 3D printed material again. Making new saddle covers out of this recycled material is not possible since the foaming expansion additives lose their function.

10.3 TPU MATERIAL

This material is now already used in insoles and has an average lifespan of around 2/3 years, depending on the weight and the usage of the user (see appendix 4). A load of a shoe sole is not comparable with the load while cycling; pressure is distributed over a longer time with a more constant load. The effect of pressure on TPU is tested during a compression test with different infill structures (see appendix 8). Currently, different infill structures support the rider's body in different ways. To say more about the wear of the top cover, the product should be tested over a longer period.

10.4 BENEFITS

- As earlier concluded in the ergonomics pressure cooker three main adjustments to the current saddle lineup should be possible.
- Custom adjustment in ischial tuberosity width and shape
- Adjustment of nose width and shape to relieve genitals pressure
- Adjustment of height of posterior part of saddle to relieve pubic area pressure
- Storage of real user data regarding that could be a starting point for further saddle development

11. CONCEPT 2

PERSONALIZED INSERTS

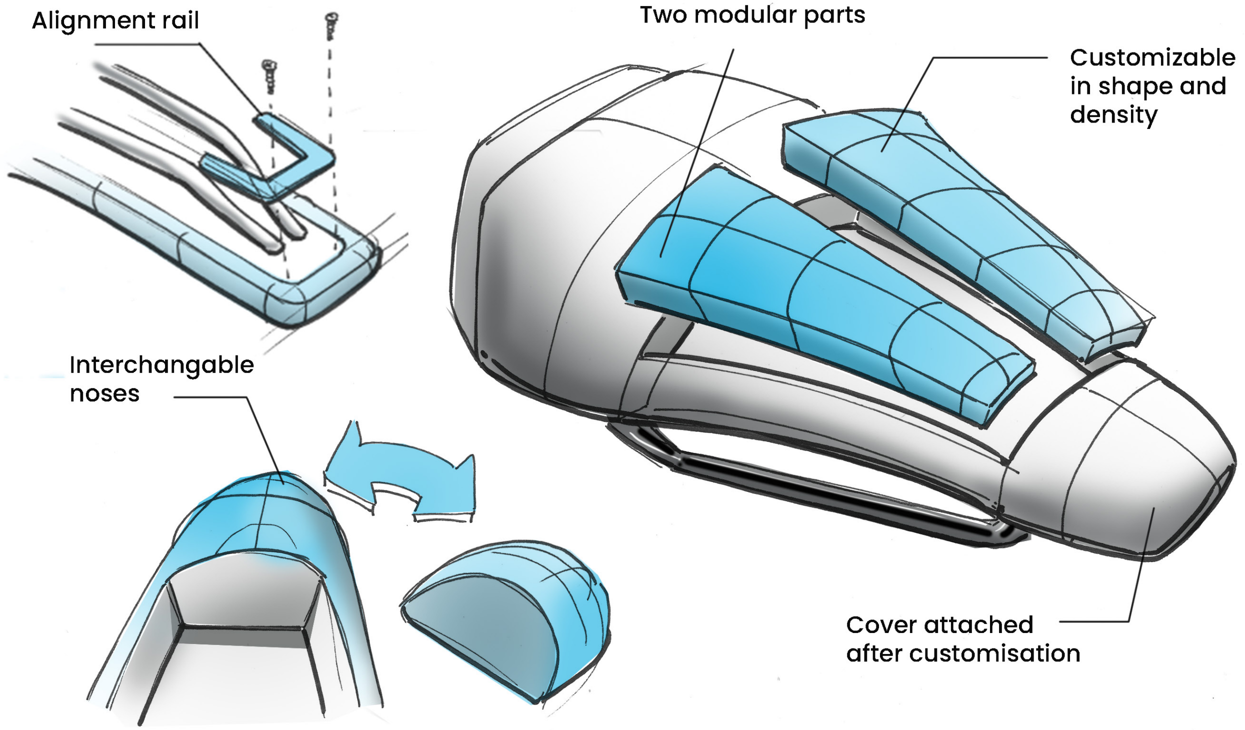


Figure 24: Personalized inserts

11.1 WORKING

This concept is a modular concept where different sections can be exchanged to find the optimal configuration. In the ergonomic research, it can be seen that compression of the labia, pressure division and sit bone width are the three main problems that females now feel discomfort with.

This concept has two modular parts. Firstly, the nose has certain shapes that can stimulate pressure relief of the genitalia. The shape influences chafing on the inner leg and compression of the labia. Secondly, the thickness of the foam of the sit bone area is important to have pressure relief. Depending on the placement of the bones and the weight of the rider this can differ. In current saddles, no matter the weight of a person, the same amount of foam is put on the saddle. Heavy people will have no dampening when sitting, while the foam is barely deformed for light people.

11.2 PLACEMENT

Keeping the sit bone parts in place is essential. Therefore a framework around the outer edges of the saddle was made (see figure 25). Various inserts then can be added that can be customized in thickness, form and cut out dimensions. The nose shape is kept in place by the cover to customize width and height.

Figure 25: Framework

To keep these modular parts aligned and in place, a similar alignment brainstorm with the information in appendix 10 was done. Covering these parts with a (traditional) PU cover was selected as the best option to keep the parts aligned, avoid moisture in the connection parts and increase the rigidity of the design. The cover is attached with a rail, making users able to disassemble it for adjustments themselves or by their bike fitter.

11.3 BENEFITS

The saddle can be adjusted with different parts that can be changed by the rider or bike fitter. Being able to modify and replace parts gives the user control of building their own, personalized and best-fitting, saddle

As said earlier (see modular PC) the 80mm is the point where most people start sitting and therefore start applying most pressure (Boon N, 2021). The modular section therefore should be around this area; underneath the ischial tuberosity. The exact position of the sit bones on a saddle differs per person and saddle design. Investigating the exact length position of these sections is therefore something that should be investigated with a pressure mat.

12. CONCEPT 3

TEST SADDLE FOR R&D PURPOSE

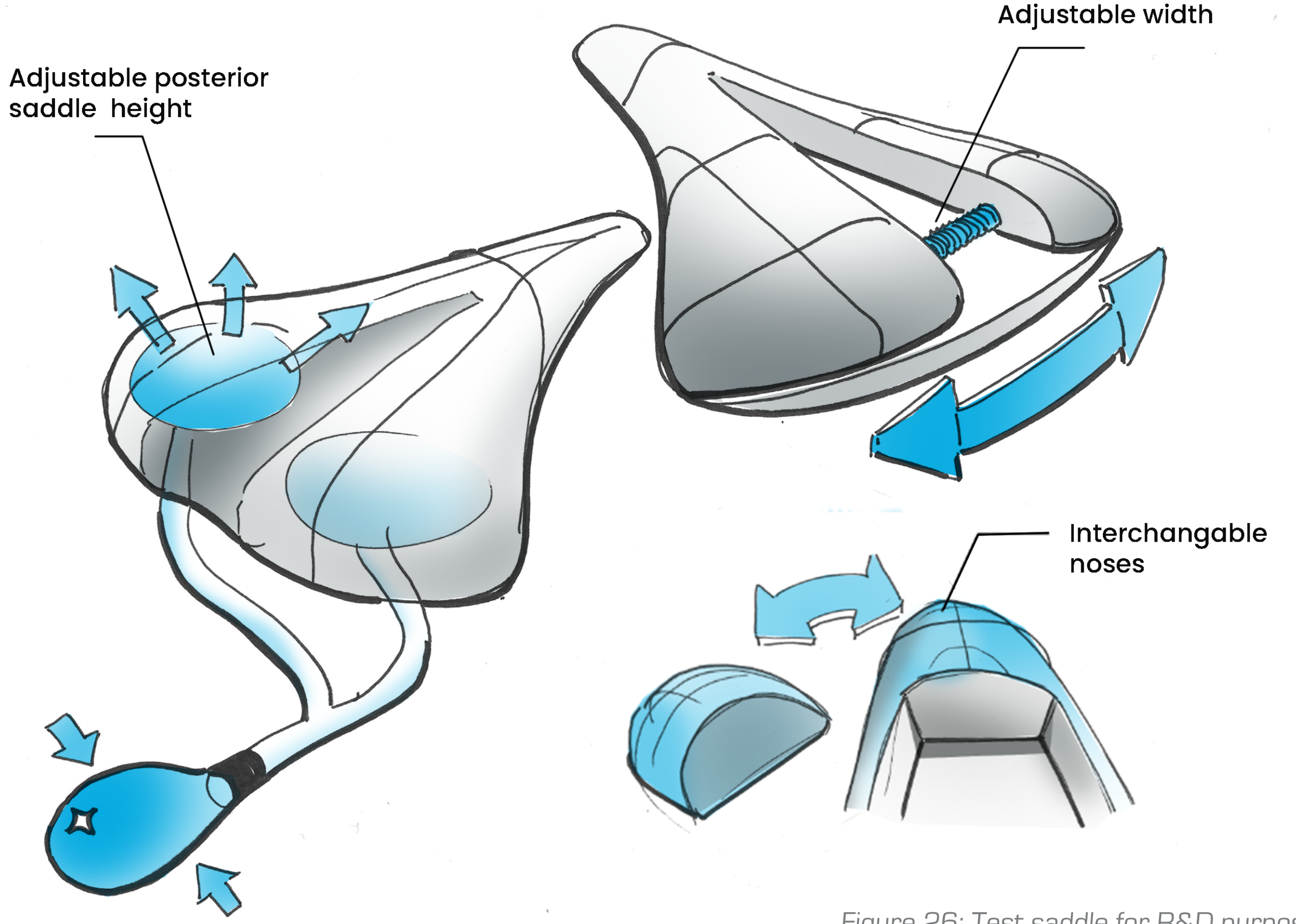


Figure 26: Test saddle for R&D purpose

11.1 WORKING

The last concept is meant for research and development purposes to produce a saddle with the current production facilities. Currently PRO has been investigating female-specific saddles but because of the shape complexity and the variable parameters, the optimal shape is not yet found.

11.2 TEST PARAMETERS

The concept can adjust different parameters to find and test shapes with users. Multiple different parameters therefore should be able to be integrated into one model to test the shape. Because not all different ergonomics parameters can be integrated into one part, the following parameters were selected:

- The saddle width to support the Ischial tuberosity (sit bone)
- Height of the support area underneath pelvis, to relieve the pubic area
- The width of the saddle nose to prevent chafing on the inner leg
- The form of the nose (height and ductility) to relieve pressure points

Figure 27: Screw (top) and puming (bottom) prototype

A quick prototype was made with a two-sided screw thread (figure 27 top). In this way, both sides of the saddle move from the middle. A rope was attached for this prototype to show the possibility of the mechanism. The mechanism can be used for width differentiations in the nose and sit bone width of the saddle.

To vary the height of the pelvis a prototype with a pump was made (figure 27 bottom). With adding more air, pressure can be relieved from the pubic bone and put onto the sit bones. In reality, the pumping wedge volume should be smaller to make little difference. With pump wedges on both sides, the test model can also suit not symmetrical pelvises.

11.3 BENEFITS

Varying the ductility of the nose is hard to integrate into one model; attaching multiple (yet existing) noses can be an option to see which one participants prefer. However, testing male noses might not be ideal for investigating a female shape.

Combining all these variables in one model can be challenging: for example, pumping the pump wedges can also influence the width of the saddle. Furthermore, being able to read the different settings from the model is important. Therefore each adjustment should be measurable.

13. CONCEPT CHOICE

To choose between the three concepts a programme of requirements and wishes was made (Appendix 9). The most important wishes were selected together with the PRO team:

- The product should add as much comfort as possible
- The product should be as durable as possible
- The user should be able to repair as many components of the saddle as possible at home or the local bike shop
- The materials of the product should be as recyclable as possible
- The product should empower the user to be attached to the product and increase the lifespan of the saddle as much as possible
- The product should be as light as possible
- The product should have a lead time as low as possible
- The product should be locally produced for as much as possible

For comparing the three concepts efficiently and honestly, the third concept was assessed as a tool to produce a better female shape within the current production facilities.

The choice for the concept then was made with the weighted objectives method. Each of the previously explained criteria is given a score from 1 to 10 for each of the concepts. That is then multiplied by the weight of importance each of the criteria has. The total weight should be 100 points in total. The weight of each of these factors was defined in cooperation with the PRO project team.

CRITERIA	WEIGHT	1. TOP COVER	2. INSERT	3. TEST MODEL
Added comfort	25	9	8	6
Durability	15	5	8	9
Attaching	15	8	7	3
Repairability	10	6	8	2
Recyclability	10	7	5	1
Weight	10	8	6	2
Production time	10	8	6	2
Local production	5	7	6	4
Total	100	725	715	480

Figure 28: Weighted objectives

In this calculation, concepts 1 and 2 score higher than concept 3 mainly because of the less innovative character and because of the lack of sustainable features. The difference in scores between concepts 1 and 2 is minor and was discussed in the midterm meeting.

There, concept 2 was chosen because of:

- Easy implementation within the current production facilities.
- It can be developed with the current (also existing) product shapes
- It tackles female problems effectively.
- It allows PRO to gain knowledge directly and get familiar with 3D printing within this 2025 timeframe and options to implement in future full customization. With smaller investment costs and thus with lower risks

SECTION 3

USER TESTING

14. PRESSURE ANALYSIS

14.1 INTRODUCTION

For the chosen concept 2, two essential research questions are: how many modular zones are needed and where are they positioned? Together with coaches and team, I was determined to give these questions priority in my research as well as the concept of the connection of the padding to the base.

14.2 LIKERT SCALE

To answer those two questions a pressure map analysis was done with the current product portfolio of PRO saddles. With these maps, basic shape variations were tested and the best fitting saddle was selected as a design starting point. Five saddles were tested among ten female participants: their saddle, PRO Stealth Curved, Griffon, Turnix and Falcon. To be able to see how curvature and shape resulted in perceived discomfort and pressure, both theoretical pleasant and unpleasant saddles were tested.

The respondents were asked to cycle for 2 minutes on their bike on a home trainer. A Gebiomized pressure mat was put over their saddle. Next, a pressure map was made while cycling with a resistance of 100 watts to simulate a endurance ride. Afterwards, respondents were asked to give comments about the saddle shape and to give a 1 to 10 score per saddle area (figure 29). The complete method can be found in appendix 13.

1&3	7,0
2	7,7
4&5	6,6
7&8	6,7
6&9	7,2
10	x

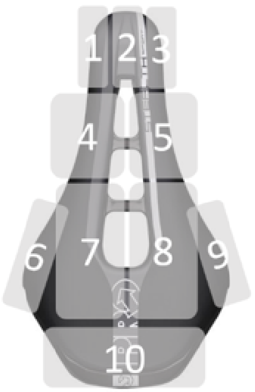


Figure 29: Saddle comfort score

PRESSURE VALUES

	PUBIC BONE	SITBONE LEFT	SITBONE RIGHT
Maximum pressure (mbar)	Low	Low	Low
Mean pressure (mbar)	Low	High	High
Loaded area (mm2)	Low	High	High
Abs. Maximum force (N)	Low		
Mean of total force (N)	Low		
Centre of Pressure (mm)	High		

Figure 30: Pressure values analysis

14.3 PRESSURE VALUES

The pressure maps almost always supported the (dis)comfort scores. The maximum, minimum and mean pressure, loaded area and the centre of pressure per saddle were analyzed (appendix 14).

In general, respondents often gave feedback that PRO saddles were a lot harder than their saddles, resulting in pressure points. For some respondents the width of the nose of some of the PRO saddles was too wide, resulting in chafing against the inner leg.

14.4 CONCLUSION

When comparing the pressure values results from these four saddles (appendix 14), the PRO Griffon scores the best. This saddle has for 9/10 participants symmetrical distribution both left-right and anterior-posterior. This saddle has low maximum pressures, low mean pressures on the pubic area and the lowest mean of the total force in the results of the pressure map. The analysis of these values was discussed with pressure map expert Jan Neuheus (appendix 3).

On top of that, the PRO griffon was for 9/10 participants the most comfortable rated saddle. Mostly because: the nose of the Griffon is smaller, the cutout is longer, the cutout has a better shape and the sit bone area is softer compared to other PRO saddles according to the participants (Appendix 14). Because of this Likert scale comfort rating and the pressure values, the Griffon is taken as a design starting point.

15. SENSITIVITY ANALYSIS

15.1 INTRODUCTION

To determine shape variations of the modular saddle research was done to determine the sensitivity of females' sitting area. With this information, a design can be made with pressure relief at sensitive zones and pressure addition at non-sensitive zones. Relieving those areas leads to less discomfort (D. Lips, 2017).

15.2 USER TEST

A test with the same 10 participants from the previous pressure analysis was done to determine this sensitivity. A saddle with a multitude of holes in different locations was assembled on the bike (figure 31). A female assistant applied a slow increase in pressure in one of these holes and measured the force magnitude at which respondents felt discomfort. Doing this at multiple holes, resulting in a sensitivity map of the bicycle saddle sitting area of females.

Figure 31: Sensitivity prototype

Safely performing this research in an environment where participants feel at ease was super important for this research. Therefore an official ethical application at the HREC committee of the TU Delft was done with the help of expert Maxim Smulders. The consent form made for this application can be found in appendix 13.

The holes on the saddle were placed because of anatomical reasons, bone structures and muscles of the female body. Also, the structure of the rails and the seat post were taken into account for being able to reach these spots. More limitations of this research are discussed in appendix 12.

		x		
	6,78		7,35	
		10,23		
		10,38		
	20,03		22,37	
		8,65		
	14,72		18,05	
	14,76	8,51	14,92	
15,38	13,31		11,84	16,29
	13,13		12,46	
20-25	15-20	10-15	05-10	0-5

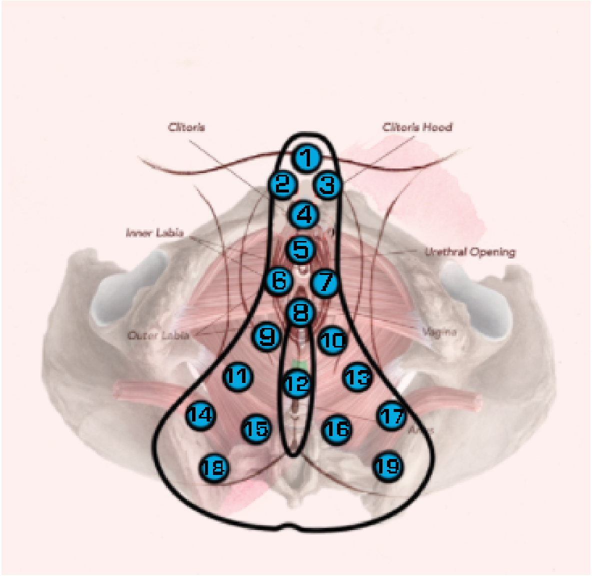


Figure 32: Sensitivitity map

15.3 CONCLUSION

The outcome of the research was a map with the values of the force in Newton where participants felt discomfort (figure 32). In general counts: The lower the discomfort values, the more sensitive the spot.

- Points 2, 3, 8 and 12 are considered most sensitive. These spots are placed in the soft tissues of the female body and correspond with the reproductive organ and the anus.
- Points 9, 10, 11, 13, 14, and 17 are considered to be the least sensitive and can be declared by the V shape of the pelvis bone.
- Around the pelvis bone, the standard deviation is also higher, probably because of the difference in weight and fat percentage.
- Gynaecologist Frederieke Siemens (appendix 15) was asked for validation: "Overall the map was quite exact, but labia points 6 and 7 of the test should be sensitive too. On these points, the model might have influenced the test results." This can be declared by the fact that the saddle stem stood in the way while measuring.

That also corresponds with the pressure map, where the better-experienced saddles also showed a upside down V shape (figure 33). This sensitivity map could provide designers and engineers with a theoretical base for adapting the softness, contact area and shape of a competitive bicycle saddle model.

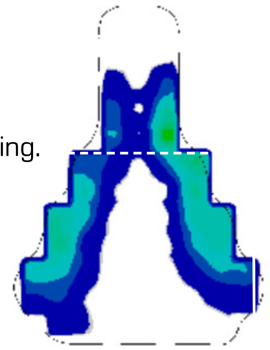


Figure 33: V shape

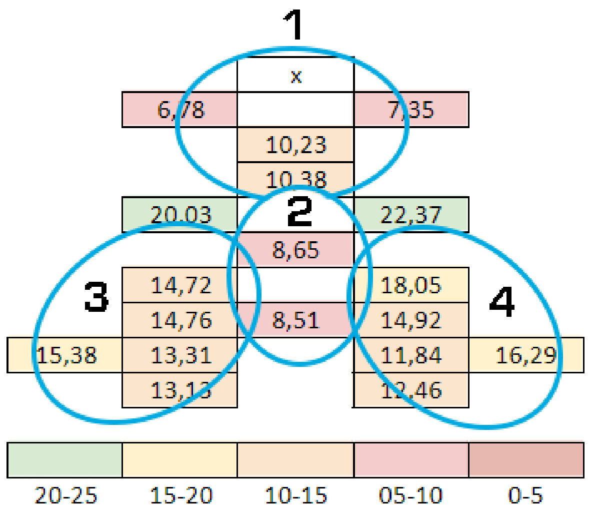
SECTION 4

EMBODIMENT

Figure 34: Prototype overview

16.1 NUMBER OF ZONES

Based on the sensitivity test four zones can be identified (figure 35):
zone 1: Sensitive saddle nose width
Zone 2: Sensitive soft issue cutout form
Zone 3 and 4: Less sensitive pubic bone support



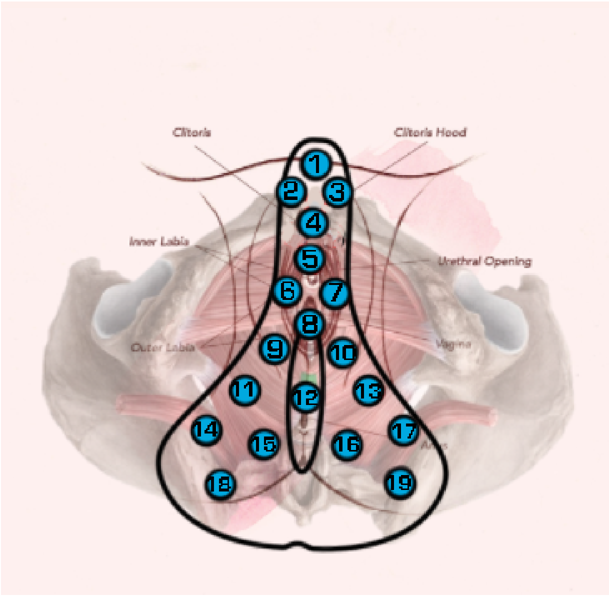


Figure 35: Definition zones

Combining the outcomes of the sensitivity research and the comments on saddle design during the pressure, ergonomic and kinesiologic research, the following modular parts configuration can be identified:

1. The nose width: this parameter can cause chafing on the inner leg. In the pressure mapping test, 6/10 respondents struggled with the width of the nose, causing irritation, chafing and numbness.

2. The cutout area: the form of the cutout prevents the labia from chafing. The labia can have various shapes but are generally categorized in two categories: "innies" and" outies" according to gynaecologist Frederieke Siemens (appendix 15). Inner labia are more sensitive. The difference between those groups is therefore a parameter of the cutout shape of this modular concept.

3&4. The sit bone area: the saddle height of the posterior part relieves the pubic area. According to Gebiomized, this support of the pelvis gives a stable foundation to the bicycle position. Being able to change this will enable users to play with the balance on their saddle.

Not only pressure division is important to make a subdivision in the zones, also the variability of these zones are important (standard deviation): having modular zones in regions where the standard deviation is high, could result in a better fitting saddle.

In figure 36 it can be seen that zone 3 and 4 show a large standard deviation. This could be explained by the variation in weight and fat percentage across participants. Modular zones in those areas are therefore preferable. Zone numbers 1 and 2 don't show a large standard deviation but are mostly chosen for shape variation, zone 3 and 4 for ductility variation.

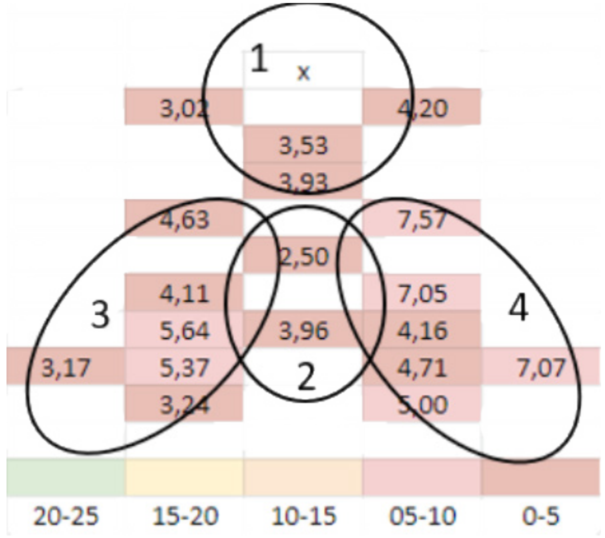


Figure 36: Standard deviation zones

Both the pressure and sensitivity tests were discussed with gynaecologist Frederieke Siemens (appendix 15). In this meeting, the placement of the parts was also discussed and validated based on her experience in the field and as a cyclist herself.

16.2 PLACEMENT OF ZONES

After the determination of the general position and geometry of the modular areas, the specific placement of these zones has been determined. The sensitivity test prototype was measured to estimate the geometry of different inserts.

To make a design configuration for the modular parts, the pressure maps of the PRO Griffon were analyzed. The pressure maps all have specific pressure hotspots for each of the three zones. The distance of the pressure hotspot to the front of the nose of the saddle was measured.

The scale of the map was adjusted according to the participants' mean pressure. So, if the pressure was more than the mean pressure, it was identified as a "hotspot" (figure 37). The complete measurements can be found in appendix 17.

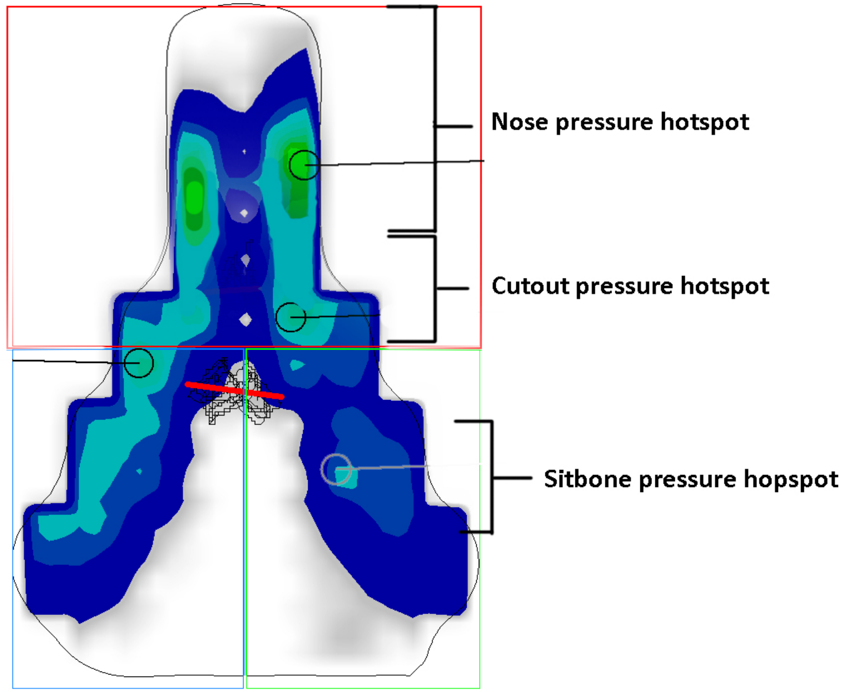


Figure 37: Pressure hotsports

Pressure maps of the 10 participants were analyzed and distances were measured. The overview of the different distances can be seen in figure 38:

1. Length of the nose (mm)
2. Beginning of the cutout (mm)
3. Begin width of the cutout (mm)
4. End of the cutout (mm)
5. End width of the cutout (mm)
6. Minimum pressure spots sit bones (mm)
7. Maximum pressure spots sit bones (mm)
8. End pressure saddle (mm)

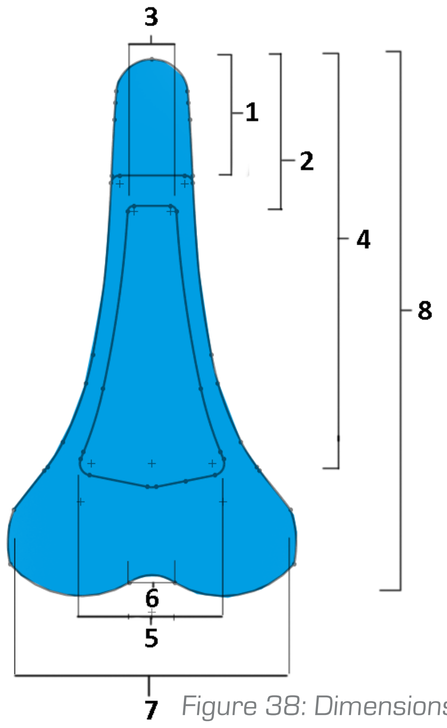


Figure 38: Dimensions

Figure 39 shows the results of the measurements. This was analyzed and minimum, maximum and average were calculated. These values were taken as a starting point for a CAD model. For some values, the maximum was taken, for example for the length of the nose and the end of the saddle. This is because under dimensioning these can create pressure hotspots on the saddle (J. Neuheus, 2021). The maximum sit bone width should still, be scaled by the saddle width and therefore an average is taken for a first prototype.

Because the pressure map depends on how the mat is placed on the saddle, the length calculations can vary with a new saddle shape design. Also, this test was only done with only 10 respondents and is not completely representative (see limitations appendix 12). These sizing guidelines were taken as a starting point for prototyping the modular system. Throughout the project, these have therefore been tested and validated in appendix 18.

	Average	Minimum	Maximum
1. Length of the nose (mm)	48.5	37.0	71.1
2. Beginning of the cutout (mm)	58.7	45.6	81.2
3. Begin width of the cutout (mm)	11.5	10.0	13.0
4. End of the cutout (mm)	119.4	107.2	148.1
5. End width of the cutout (mm)	26.5	21.5	35.9
6. Minimum pressure spots sitbones (mm)	51.3	39.6	72.6
7. Maximum pressure spots sitbones (mm)	132.9	115.7	147.9
8. End pressure saddle (mm)	198.4	177.2	212.2

Figure 39: Length calculations

16.3 CONNECTION PARTS

Next to the number of zones and the location of these parts the focus was how to assemble these parts to a base. The modular parts should:

- Be connected to other modular parts: the modular parts are aligned next to each other and should not be able to get loose while cycling.
- Be connected to the rest of the saddle (base): the modular parts should not get loose from the saddle base.

For both connection possibilities, brainstorm sessions with the coach and the PRO team were done and four different connections to fix different modular parts to each other were identified:

1. Clamping the modular zones in each other because of their form
2. Puzzle mechanism to attach two parts
3. To keep the nose standard and have a draft that prevents the parts from releasing
4. A profile strip that locks the modular parts in place

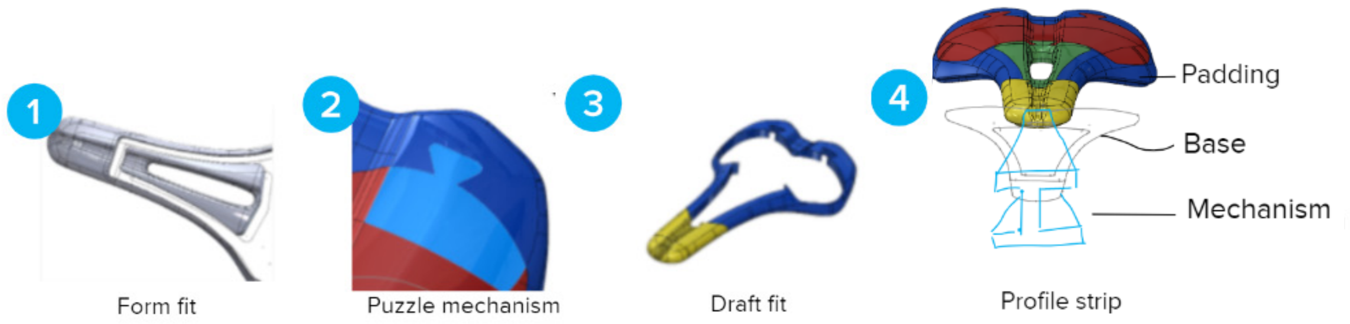


Figure 40: Attaching modular parts

Next to this, mechanisms for attaching the padding and base were:

1. Velcro is attached to both parts. Velcro can also be injection moulded in the saddle base.
2. Using a conventional cover that can be re-opened by a zipper or other clamping mechanisms.
3. Use glue to attach the base to the foam. This foam should come loose when heating the saddle to be able to change modular parts.
4. An injection-moulded profile strip is placed in the cutout area so it can't be felt when sitting on the saddle.

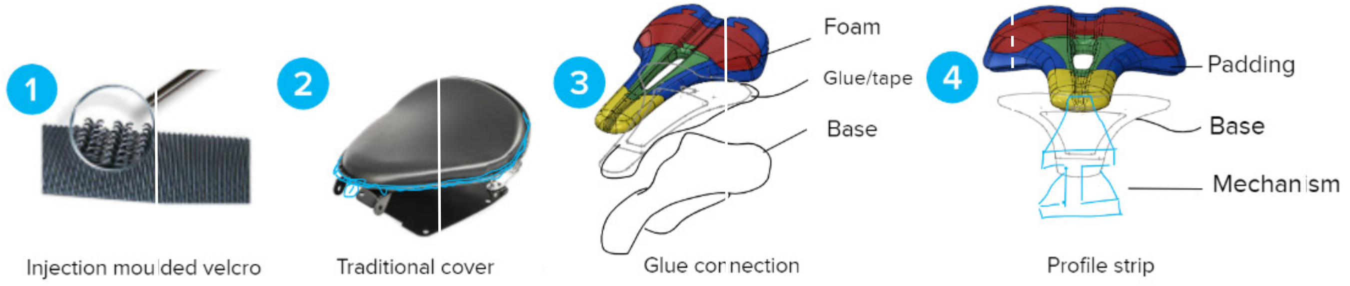


Figure 41: Attaching to the base

In appendix 20 an overview is made with prototype iterations. Here the different prototypes (also to test these connections) are explained. During the prototype tests (appendix 20) it was found that an oversized nose compared to the base can cause extra friction, movement in the nose and irritation. This is essential to work to keep a standardized small base with additional nose width.
The PRO saddles currently have a quite large width (42mm) compared to other female-specific saddles (Specialized Power, 30 mm). A replaceable zone for the nose width of the saddle is not a preferred modular section because of this irritation effect (appendix 20). However, research should be done for a sleeker optimal nose width for females.

Figure 42: Different prototype iterations

16.4 CONNECTION CHOICE

A part of my modular idea is to enable users to change their parts themselves. I want to make users feel like they can make their own semi-customized saddle by changing modular parts. Giving users the power of adjusting or repairing their saddle, gives them a feeling of control over their own customized product.

User-friendly modular parts have important requirements to take into consideration for this connection:

- Interchanging modular parts should be plug-and-play, without instructions to change modular parts
- The modular parts should be able to be simply changeable without tools
- The modular parts should remain in position while cycling
- The modular connection and system should preferably have a low environmental impact

Criteria	weight	1. Formfit	2. Puzzlefit	3. Draftfit	4.Profile strip
Plug and play	30	7	8	8	4
Changing time	20	7	8	9	4
Movement of modular parts	30	2	5	8	7
Environmental impact	20	6	8	6	6
Total	100	530	710	780	530

Figure 43: Scoring part connection

The same was done with the mechanism of how to attach the padding to the base. The same requirements were ranked:

Criteria	weight	1. Formfit	2. Puzzlefit	3. Draftfit	4. Profile strip
Plug and play	30	7	8	8	4
Changing time	20	7	8	9	4
Movement of modular parts	30	2	5	8	7
Environmental impact	20	6	8	6	6
Total	100	530	710	780	530

Figure 44: Scoring base connection

Using an outer ring as an assembly mechanism and using velcro as a connection mechanism are selected, mainly because of the ease of use of these mechanisms. It has fewer edges than other concepts that could cause irritation. Velcro (Aplix.com) can optionally be injection moulded onto a surface nowadays, which avoids the use of glue (figure 43). The edges are explored further in the next chapter.

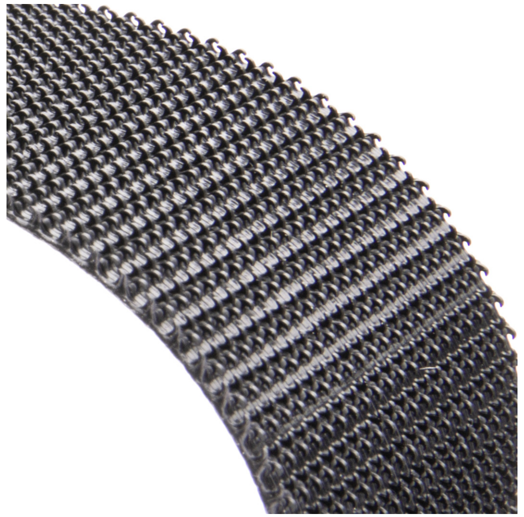


Figure 45: Applix

16.5 INTERFACE PARTS

To determine the connection between different modular parts, a study about the optimal angle between these parts was done. Five different small prints were made to validate the optimum angle.

The angle alpha was tested with angles of 65, 70 75, 80 and 85 degrees. The angle was limited to a maximum angle of 65 degrees due to the saddle geometry. In total five combinations were tested. For one test two blocks were printed with different infills. Both blocks were printed with the Gyroid Ultimaker infill (the most appropriate infill according to Colorfabb); one with a 20% infill and one with a 50% infill.

Figure 46: Angle analysis

These boundaries were chosen because this is the most extreme situation possible in a bicycle saddle. The area of this prototype is as big as the area that the pressure sensors in the cover of the pressure mat used in the pressure test.

Out of the 10 participants participating in the pressure test, the maximum force exerted on one of the sensors of the saddle was 220 N and the minimum force was 30 N. Different infill percentages were printed to optimal match the minimum and maximum forces exerted on the saddle for a saddle (in steps of 5%) (figure 48). This resulted in a final test prototype with a 20% (equal to 30 N resistance) and 50% infill (equal to 220 N resistance).

For determining the optimal angle 10 participants were asked to give a score from 1 to 10 to each of the blocks with different angles (see results in appendix 19) (figure 49).

The result of this test is that the higher the angle is, the smoother the transition is perceived between two materials. However, the scores from 75 degrees and larger don't differ that much.

Angle	Average score (0-10)
65 degrees	8.6
70 degrees	8.1
75 degrees	8.3
80 degrees	6.2
85 degrees	4.1

Figure 47: Angle comfort score

Because of this small difference in scores between the 75, 70 and 65-degree angles a prototype with the 75-degree angle was made (see prototype overview in appendix 20). This was chosen to avoid fragile edges in the connection with the base.

In appendix 20 can be seen how prototyping with this edge creates a self-locking system, preventing the modular parts from falling out

Figure 48: Maximum resistance in Newton

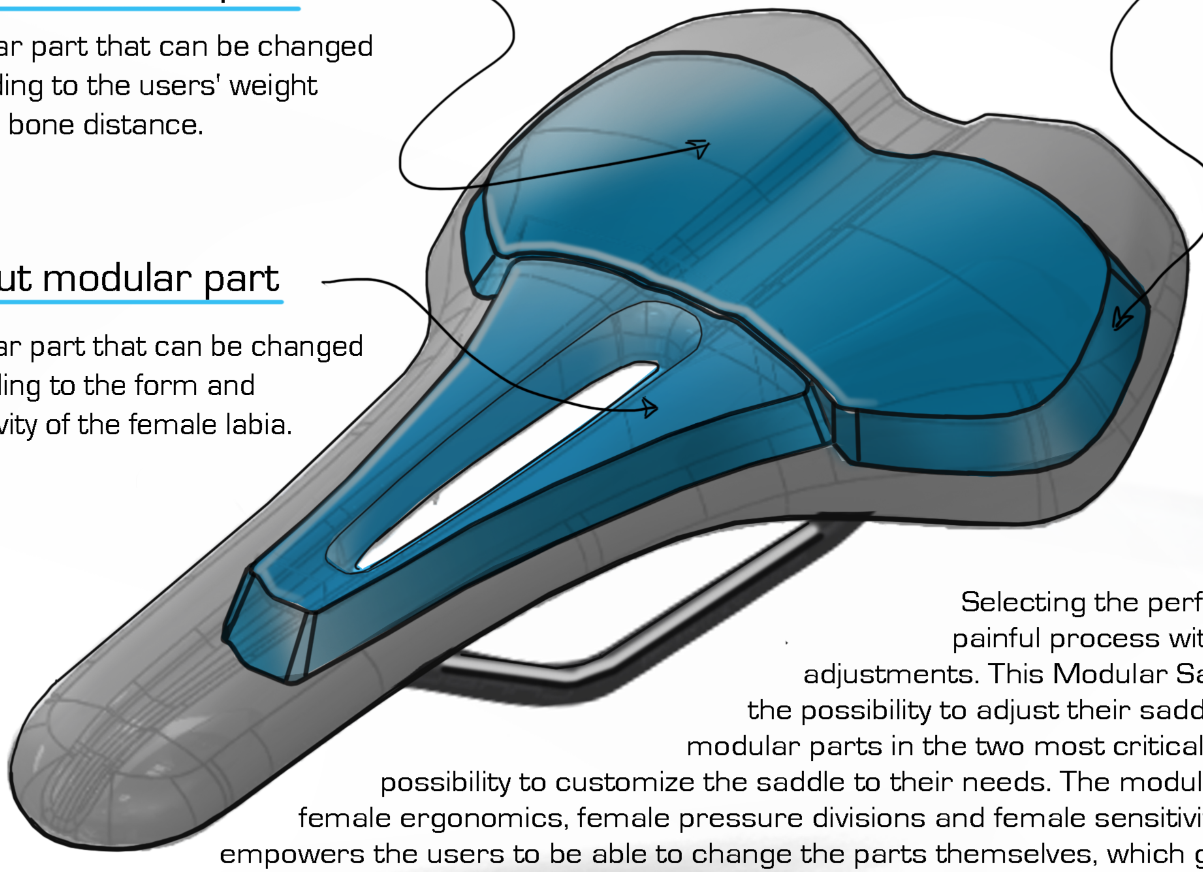
Figure 49: User test

SECTION 5

CONCLUSION

17. PRODUCT PRESENTATION

MODULAR SADDLE SYSTEM (MSS)



Sitbone modular part

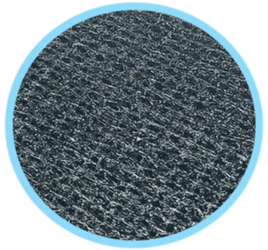
Modular part that can be changed according to the users' weight and sit bone distance.

Cutout modular part

Modular part that can be changed according to the form and sensitivity of the female labia.

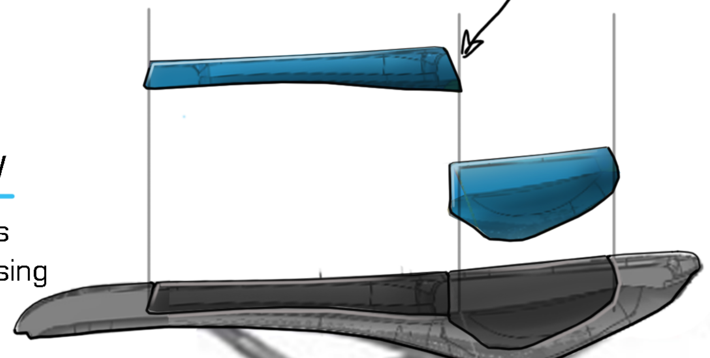
3D printed ductility

Local absorption of forces by ductility modification using personalized 3D printed infill structures.



Draft angle

75-degree angle for better transition between different ductilities



Selecting the perfect cycling saddle can be a long and painful process with still barely room for personal adjustments. This Modular Saddle System (MSS) could give users the possibility to adjust their saddle to their preferences. Having two modular parts in the two most critical pressure zones gives users the possibility to customize the saddle to their needs. The modular saddle structure is based on female ergonomics, female pressure divisions and female sensitivity measurements. This concept empowers the users to be able to change the parts themselves, which gives them control and personal attachment to their saddle comfort. In this way, the durable use of carbon fibre in the saddle base could be extended over a longer time frame. Next to that, being able to repair or upgrade the saddle can increase the lifespan of this saddle.

Figure 50: product presentation

18. VALIDATION

A validation test with 6 test people was done. These people also performed the pressure test and therefore their data can be compared to that test. The bike was put in the same position as the previous test (see procedure appendix 12), to prevent small measuring and positioning differences from having a result on the pressure map.

The modular saddle system prototype (figure 51) was assembled on the bike in the same position as the original saddle. Users were again asked to cycle on a home trainer with 100W resistance. Both pressure maps and a comfort scale rating were asked to the participants.

Figure 51: Testing model

With this validation test, the optimal personal configuration of the ductility of the modular zones was determined. To ask more details about the experience the users were asked to rate the perceived (discomfort) on a 1 to 10 Likert scale (figure 52). This information was compared to the results of the original PRO Griffon saddle.

It can be seen in appendix 18 that different participants prefer different modular parts. For this test with these 6 participants, it seems like parameters such as weight could lead to the preference for a more ductile saddle. Next to that, almost all participants prefer a softer cutout part compared to the sit bone part. Also, pressure maps of the different participants and configurations were compared with each other and with the original PRO Griffon saddle (appendix 18). Next to that, all participants were able to change parts within 5 seconds without tools, fulfilling the plug and play requirements of chapter 16.4.

Of course, the prototype should be tested among more participants in variable age groups but based on this test we can conclude:

- For 5/6 participants, looking only at the pressure values, a more optimal saddle than the original PRO Griffon can be assembled.
- Participants have different modular configurations that give the best results in the score and on the pressure maps.
- It seems that body weight can influence the preferred ductility.
- For the nose element (of geometry) all participants preferred the smallest possibility (32mm).

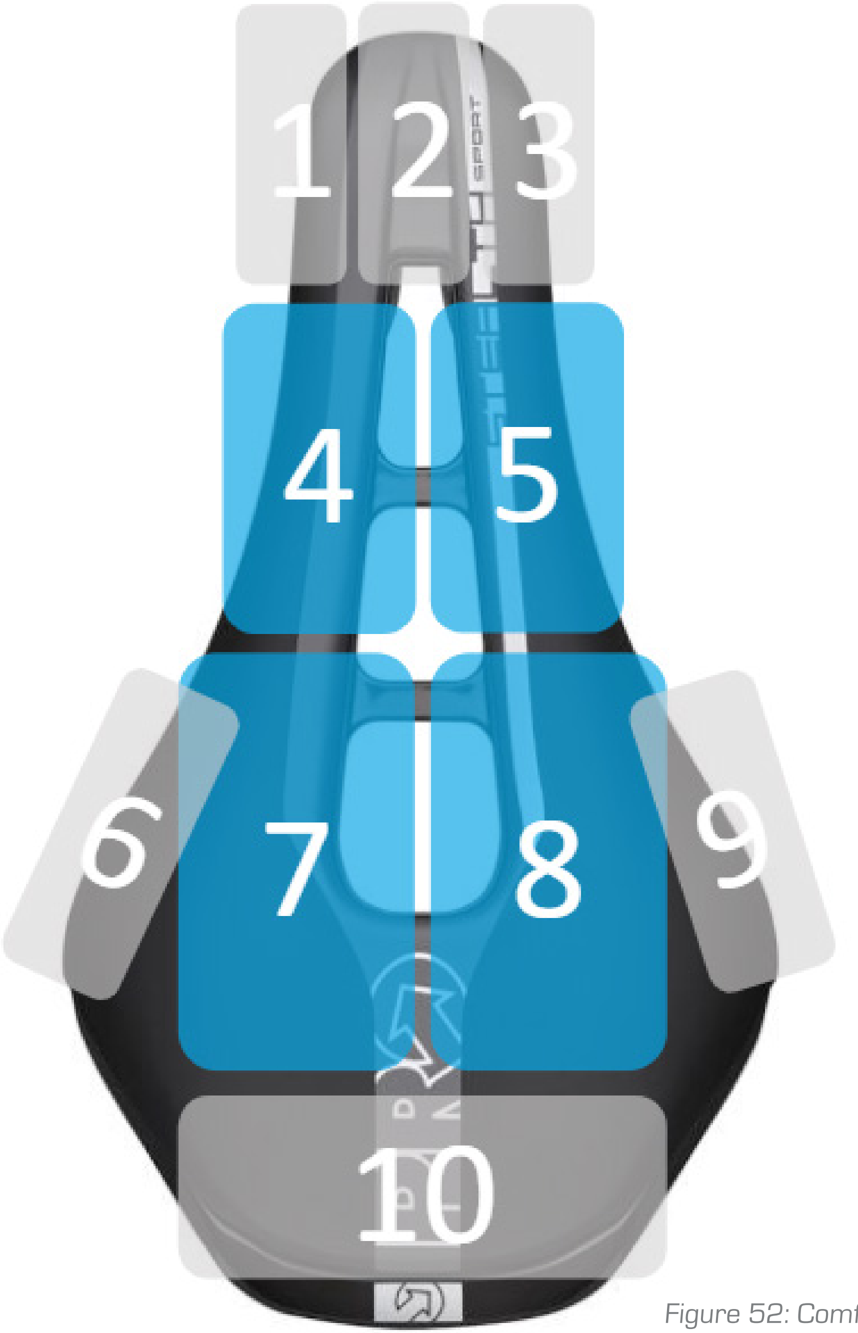


Figure 52: Comfort score placement

19. CONCLUSION

Male and female bodies are not the same, especially for a performance sport a one-size-fits-all solution is not the preferred solution. Irritation on the inside of the leg, the difference in sit bone angle and width and pressure division between anterior and posterior parts, are three main differences between genders that need special attention when designing a female saddle.

Increasing the lifespan of the saddle, being able to repair or upgrade the saddle and adjusting the comfort level are things respondents seek in a new saddle (appendix 6) and is in my opinion the best way to be more sustainable. With a modular saddle structure, the durable use of carbon fibre can be extended over a longer time frame.

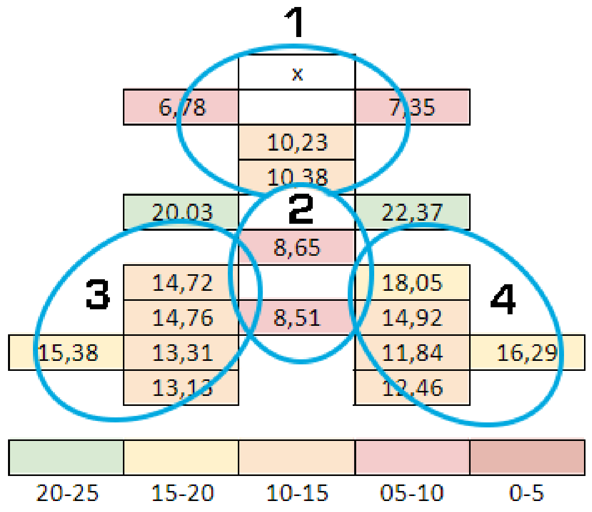
3D printing has many advantages and it is essential for PRO to now get acquainted with the technique to keep up with competitors. Additive manufacturing has the potential to be a manufacturing method for PRO saddles. Forces can be locally absorbed by geometry and ductility can be modified. On top of that, this process allows customization and local production.

This Modular Saddle System (MSS) could offer PRO possibilities to make more personalized saddle adjustments and implement them faster in the correct saddle shapes. This variation among females is particularly needed in the current nose width, hardness and cutout position of the saddle when measuring the current PRO product portfolio

FDM additive manufacturing is the best way to self-experiment and prototype with 3D printing. For making mass production inserts faster production with the Podoprinter or looking at SLS manufacturing methods are more rapid and have less chance of failure.

The pressure map is a perfect tool to prove or show what people feel when sitting on a saddle. In most cases the comfort perception of the test person correlated with the measurements in the pressure map. The sensitivity map of the sensitivity research in appendix 12 can be a tool for future saddle design. Relieving sensitive zones of this map will increase the chance to design a more comfortable saddle.

Making a saddle with two modular zones that can vary in ductility, allows users to make a personal configuration. The bigger the angle between these two modular zones, with different ductility, the smoother the perceived edge becomes. However the validation until now is only done with six participants, it seems like the modular saddle system can add comfort. Having modular parts depending on parameters like weight and personal preferences will allow every rider to be able to find the correct saddle in the PRO product portfolio.



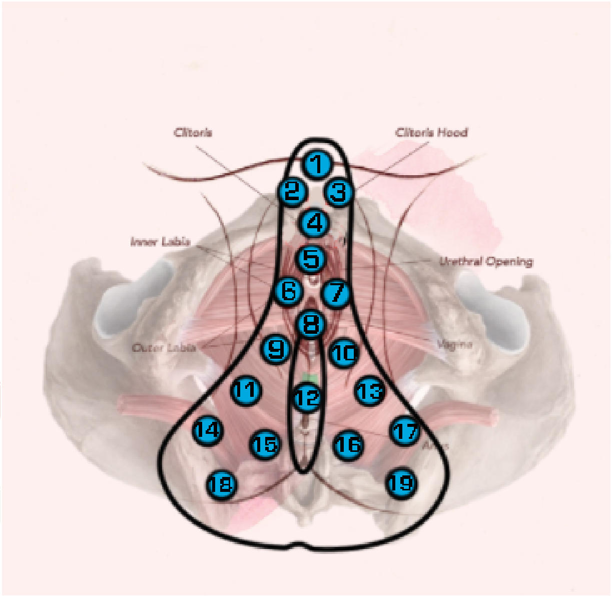


Figure 53: Conclusion modular zones

20. RECOMMEN-DATIONS

DESIRABILITY: WHAT YOUR CUSTOMER REALLY NEEDS:

- This concept of making modular inserts could be integrated into all saddles. I would advise PRO to first try this in the female category because females generally experience more problems (appendix 7). Additionally, the same approach can have benefits for male saddles.
- Research could be done on how users can select their perfect configuration. How do they know which modular parts they like the best? It could be integrated into the current online saddle selector tool or be combined with the bike fitters procedure.
- Further research could be done on how many shape variations are needed to suit the target group. In my experience, there should be at least two types of cutout forms for two types of female labia (appendix 15). For the sit bone area more variations in ductility can be possible.
- In the current modular subdivision, a possible asymmetry of the pelvis is not taken into account. However, in the pressure mapping experiment, this occurred in several cases. since my scope was on the ductility of the sit bone area and not on shape this is not taken into account. Professional ergonomic data would be required in this field of expertise.
- Research for an optimal saddle nose width for females is recommended. In the connection chapter, it was concluded that a modular nose resulted in construction integrity risks. In my opinion, an optimum width can be identified which is smaller than the current PRO Griffon nose.
- Prototypes are now based on the PRO Griffon, which is still a male based saddle. For optimal female ergonomics, a completely new female shape should be designed.

FEASIBILITY: BUILDING ON THE STRENGTHS OF YOUR CURRENT OPERATIONAL CAPABILITIES:

- I would advise PRO to consult their current saddle vendor to see what the possibilities are for manufacturing possibilities of only an outer edge by vacuum forming.
- Next to that, the team should also consider production possibilities with FDM printed inserts with Colorfabb. this technique is currently the best for a first printed product line because of its production time, costs and easy iterations:
  - For material selection and optimization of foaming and shore value ranges
  - For further research in infill structures optimisation
- Additionally PRO could also explore SLS printing options. This method is more precise and is better suitable for printing a complete saddle (in the long term)
- Further testing will be required to validate the long-term performance of the modular saddle system MSS; life cycle testing in all circumstances will be important to check if such a saddle will be comparable to the current PRO range performance.
- Development of saddles should be developed together with the development of Shimano bib shorts. 4 different bib shorts show big differences in the pressure division, as can be seen in appendix 22.

VIABILITY: PROFITABLE SOLUTION, WITH A SUSTAINABLE BUSINESS MODEL.

- To have a more sustainable concept, PRO can analyze the preferred production location of these modular parts. Producing the inserts close to where they are sold and assembling them locally would save transportation emissions (and cost).
- To mass-produce this saddle with additive manufacturing, a 3D printer should be rented or bought. The best possible option should be selected, having other production methods in mind, Return on investment calculation could be done on renting or buying such printers.
- For the complete saddle concept also an estimation in production and consumer cost price should be made to calculate the return on investment.

In the next chapter, a visual representation of the road to take for this project is presented. This is made to have a guideline for the continuation of this project.

21. PROJECT ROADMAP

This project will be continued after the end of my internship. For this, a project roadmap of the relevant steps was made. The goal of this roadmap is to give a visual guideline (figure 50) for the project for the team and me.

Most of the research was done with 6 to 10 participants, age varying from 18 to 23 and weight varying from 56 to 78 kg. For a more representative outcome, a bigger group with different ages, different fat percentages and different weights should be tested.

As explained in the recommendations, the variety of shapes must be determined for both the labia and sit bone modular parts. It is crucial to do this with users of a variety of ages to for example analyse if childbirth could lead to a different optimal shape.

Also, the production method of the saddle would require a more in-depth analysis. Producing inserts with additive manufacturing can have advantages for customisation and tuneable ductility. However, PRO should investigate the printing possibilities at their current vendor or connect with other vendors. Together with these vendors eventually, a work-like-real test model could be made, to iterate further on.

After having these steps determined and making iterations on the prototype; I would advise PRO to do a 20 piece pilot test with test users with a works-like-real prototype from the vendor. This test should be done together with Bikefitting.com, to have reliable results and exclude discomfort from not having the right position on the bike. I would advise doing this testing with dutch participants because of the female cyclists in the Netherlands and quick direct feedback, so changes can be implemented rapidly.

After having tested the prototype and determined the production method, PRO should have a look into the business case and consumer cost price. Positioning this saddle in a good market position is essential to make this a success. Going into mass production will require optimizations to the model, like tolerances, labels and marketing branding. After establishing this the product would be ready for mass production.

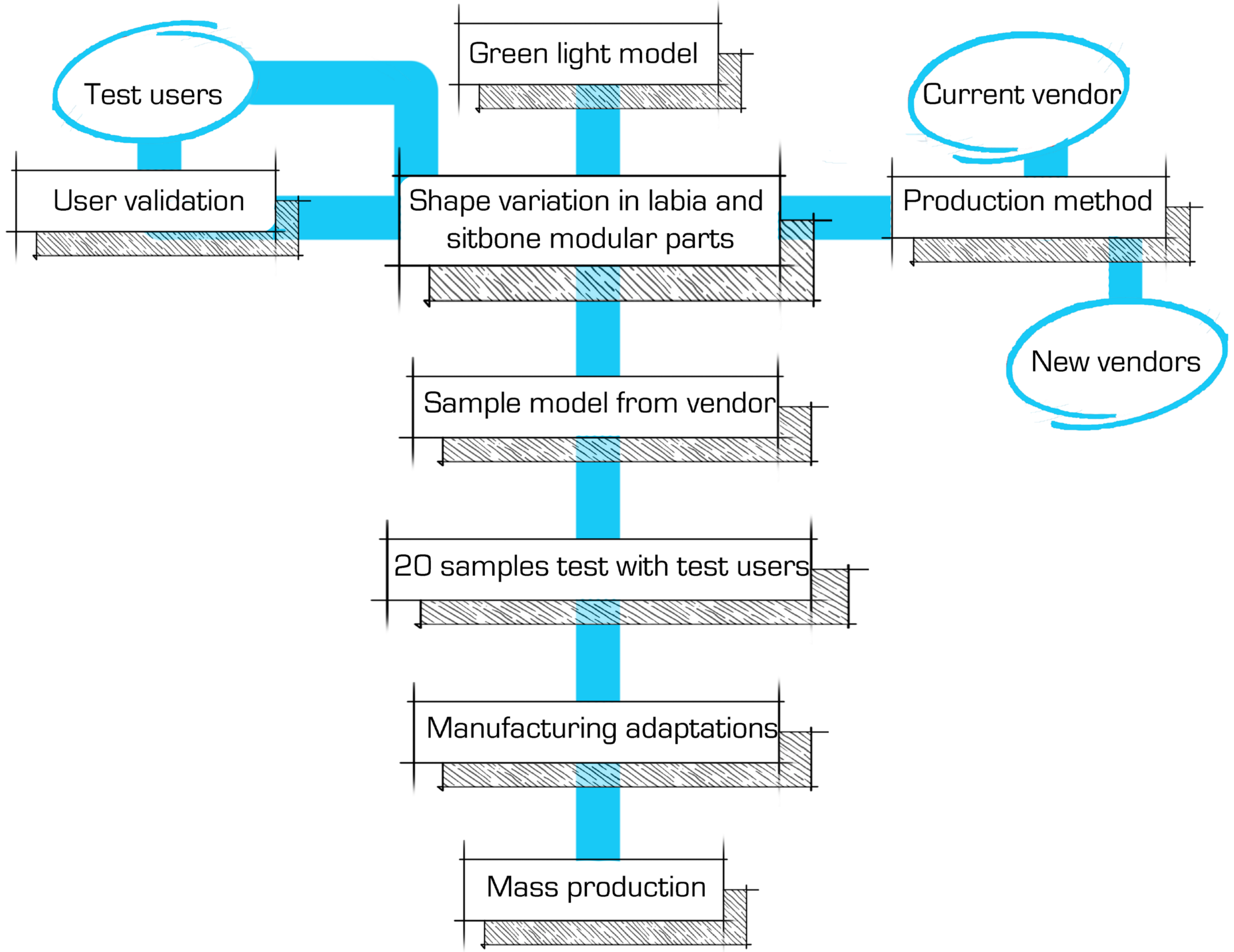


Figure 54: Design roadmap

22. REFLECTION

The choice of the project went smoothly, I had a clear wishlist with preferences for a project and wanted to investigate if a professional twist to my cycling hobby was something for me, and this turned out to be fantastic. Making products that I and my close friends care about is awesome. Being able to work in one of the market-leading companies still makes me feel like a small boy in a candy store. Integrating my vision on more sustainable cycling goods is something that in my opinion should be done rapidly. I can see the added value of my input and sustainable beliefs here.

The beginning of the project was quite fuzzy, many directions were possible and there was no clear focus. However, there was a lot of guidance from PRO to find innovative directions as an independent designer. Working with, for me, a new method of using a pressure cooker as an analysis tool, was exciting. It is a super way to shape a direction in a project like this and gain a lot of knowledge in a limited time frame. Having online brainstorming sessions in Mural is also a design tool that appeared to be super-efficient in limited graduation time.

During this project, I also learned to be a bit stubborn and stand my ground with doing sensitivity research. When doing the application for the ethical committee and talking to experts on this topic, it became more complex and more time consuming than expected. However, because I was convinced that this research could add detailed guidelines in designing saddles for the whole saddle branch, I invested more time in it and adjusted my planning accordingly. Instead of making assumptions on sensitivity, this is now supported with an academic approach, data and may result in a scientific paper publication!

My project was one with many stakeholders: users, bike fitters, vendors of saddles, Shimano, PRO, pressure mappers and ergonomic experts. Since there is limited scientific research and not one way to design a bicycle saddle, most of these stakeholders had different experiences, ideas and opinions. Dealing with many different opinions and ways of research was challenging. However, visiting many companies helped me in picking the parts of each stakeholder that were interesting for my project (e.g. pressure mat, Varioshore printing material and sensitivity ergonomic research). Also for combining these different approaches the creative sessions on Mural turned out to be a useful tool.

My planning for this project was quite elaborate and that definitely helped me in making this project come to a good end. I worked with a project planning that was transformed for each week, into to do's. Of course, I constantly adapted this planning; when for example finding something interesting, like the sensitivity research, more time than expected was needed. Doing the right planning adaptations and focusing on what is important as a result for PRO helped me a lot in the last part of my graduation project. For example, focus on the mechanism of the modular concept and testing that with prototypes, instead of working out the complete embodiment. Especially since some parts need more detailed research, that could be the next graduation project in itself. (e.g. shape research for the modular parts).

Writing and making the layout for the report is something that took me a bit longer than expected. Making all the visuals match in colour and style is something that I haven't done that much in my industrial design student career. Nevertheless is it a nice skill to boost!

Taking initiative in the approach of the project helped me a lot. Actively calling suppliers and experts on topics is something I used more than in previous university projects and is a super useful way of getting information instantly. Sometimes having a bigger perspective on the project is also required. In the beginning of the project I constantly felt that I should be actively designing stuff, maybe because of this high tempo pressure cooker start. However, the best ideas for me came during the weekend while biking in my spare time!

Figure 55: Smiling after a working day

SECTION 6

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23. REFERENCES

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SECTION 7

APPENDIX

APPENDIX 1 CHANGE OF SCOPE

The scope of the original assignment was the following: "I am going to find a solution that captures personal requirements and that can transform that into a saddle. In this way, I can help people to find the perfect saddle for them in a better way. Everybody should be able to find the right saddle in the PRO collection"

Due to the ergonomic outcomes of female discomfort in appendix 7, adjustments have been made regarding the scope of the project. A focus to design from a female perspective was chosen and this group consists of females between 15 and 50 that do road/gravel bike rides. They ride for fun but also have a competitive wish to stay healthy and fit. Endurance road and gravel riders spend longer periods cycling on their saddle. The assignment of the project then changed in the following:

"I am going to find a solution that captures females' requirements and will transform that into a road/gravel saddle. In this way, I can help people to find the perfect saddle for them in a better way. Everybody should be able to find the right saddle in the PRO collection"

APPENDIX 2 PERCEIVED (DIS)COMFORT

Already in 1997 research on the difference between comfort and discomfort was done (Helander, M.G., Zhang, L., 1997, pp. 895-915). According to them, the absence of discomfort does not automatically result in comfort. The perceived comfort level is dependent on the expectations of a person. When somebody experiences more than expected, comfort will be felt. Discomfort is related to biomechanics and fatigue, whereas comfort relates to well-being and aesthetics.

Interaction with a product is dependent on three factors: the person, product and usage with the product (Vink, P., & Hallbeck, S. (2012) pp. 271-276). The human body reacts to this interaction with the human body effect, such as posture change when sitting on a bicycle saddle. This results in a perceived effect that is influenced by expectations. These feelings can be interpreted as comfortable, nothing/neutral or discomfort.

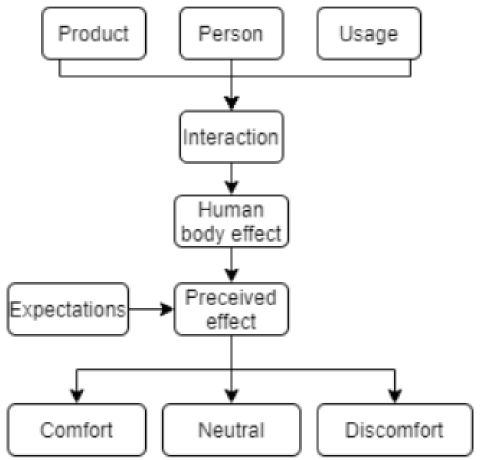


Figure 56: Perceived discomfort

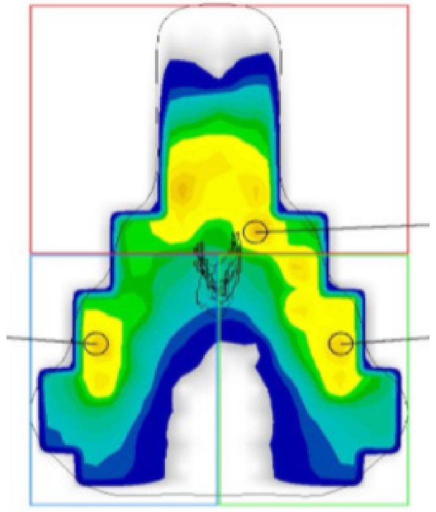


Figure 57: Pressuremap

APPENDIX 3 GEOBIOMIZED VISIT

05/10/2021/ @Muenster

GEBIOMIZED PRODUCES PRESSURE MAPPING PRODUCTS

Pressure mats for saddle, grip and foot. For saddles, they have 3 types (road, triathlon and city)
All saddle mats have 64 sensors (and are fragile) that each measure a pressure value. The software creates a pressure plot divided into 3 sections (pubic, left and right sit bone). In each zone, the maximum pressure is shown. The plot also shows the movement of the centre of pressure (black lines) and the left-right balance (red line).

GEBIOMIZED BIKEFITTING WORKING METHOD AND TIPS

Advice is to always combine the pressure mapping with a video recording (front-view and side-view). Record for 5 seconds only (otherwise people get bored soon and start looking around). The starting point is always a bikefit with pressure mapping done on the current subjects setup. This measurement is used as the reference to improve the position and/or pressure distribution on the bike/saddle. The software can export a bitmap to a pressure map in CAD.

Where some participants feel uncomfortable with a maximum pressure of 400 mbar, others feel it only at 2700 mbar, with an average of around 1000 mbar. A lot of force on the ischial tuberosity (sit bones) is not always bad, they can handle a lot of pressure. For perineal numbness, looking at the minimum pressure is interesting. Blood should be able to flow through so irregularities are not the main problem, constant pressure is. For analyzing, around 10% difference in pressure between left and right starts to get uncomfortable. The alignment of the mat is crucial to compare different measurements.

CUSTOM SADDLES

Gebiomized uses a base and rail with an oversized foam to create their custom foam shape. Based on the pressure mapping research a custom CAD file is created. This shape is milled into the custom foam. There is extra foam, so removing a layer of foam does not affect comfort, they claim. Finally, the saddle is wrapped by an external company. Costs are about 400 euro/saddle. They estimate that 5% of all people that enter Gebiomized need a custom saddle.
This process is also done to modify standard saddles in the Pro peloton.

Figure 58: Gebiomized custom saddle

STANDARD SADDLES

Their saddles can be seen at: https://secretsaddle.com. Gebiomized has a lineup of 3 saddles, Sleak (road, mountain bike), Area (road, mountain bike) and Stride (triathlon, track, time trial). These saddles are developed together with Syncros. The Sleak model is a flat saddle, developed with the male pelvis in mind. The area model is curved, developed with the female pelvis in mind (higher posterior part). Both Sleak and Area are available in 2 shapes. V-shaped for riders who mainly load the pubic area, T-shaped for riders mainly sitting on the ischial area. The saddles are available with a continuous pressure relief channel or cut out. Gebiomized saddles are only sold after consultation with a Gebiomized bike fitter. They specifically did not brand their saddles as a female and male version to also suit males with wider types of the saddle.

3D PRINT INSOLES AND PADS

Geobiomized has several 3D printers, mainly Cubix. They are using it for printing insoles and aeropads. They are researching the infill structures with the material TPU77D.

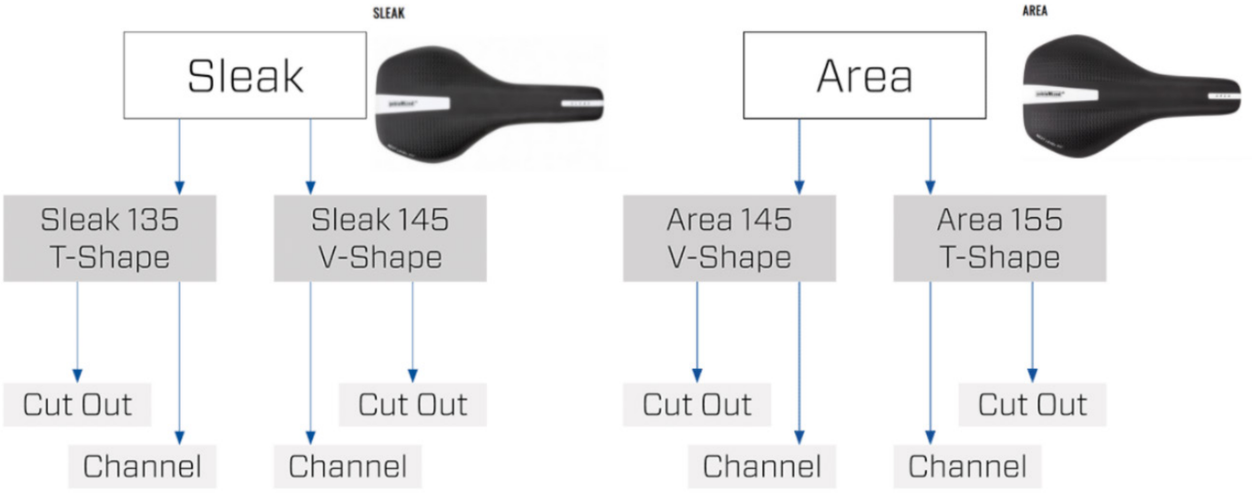


Figure 59: Gebiomized saddles

APPENDIX 4 COLORFABB VISIT

01/11/2021 @Belfeld
To get more insights into the printing process and development Colorfabb offers, a one day visit was done. Expert Ruud Rouleaux gave a tour and insights into the process. Colorfabb is part of Hylian Polymers and is one of three companies based in Belfeld. Colorfabb is developing 3D print material, Hylian Polymers is focussing on in/export of plastic granulate and the Podoprinter is a self-developed printer to make custom insoles. These three companies are integrated to cover the complete 3D printing experience.

The custom printer is called the Podoprinter and is now used for producing custom insoles. It is a belt FDM printing machine, which means it doesn't print on a static surface but the bed is moved along the printing process. This allows the process to be time-efficient because prints are scraped off automatically, without human support. This allows the printer to do a full 24/7 service.

This printer makes use of their self developed material Varioshore. This material is a TPU that foams after ejection because of the addition of additives. At temperatures between 200 and 250 degrees, the materials will start to expand to roughly 1.4-1.6 times their original volume. This means the material can be printed at low flow rates (60-70%), to compensate for the active foaming, which in return gives soft printed parts (Colorfabb.com, 2021). This all allows the material to have a shore value of A60 instead of the standard value of A95 which is standard for FDM TPU printing. Shore value is used for measuring the hardness of materials (Wikipedia, 2021). The higher values the harder the material is.

The printer is developed together with LutraCAD, a company specialized in making the transition between foot problems and making a CAD model out of that. They made certain presets in an online programme that podologic experts can select depending on the type of food they are making insoles for. When the podologic expert follows a couple of these steps a custom made insole is generated with the software.

The production price of insoles for material and manufacturing is lower compared to other additive manufacturing methods. Currently, they are rented out or bought by companies producing insoles. Depending on the machine development needed, size, material development and the amount of personalisation this can differ a bit for saddle covers.

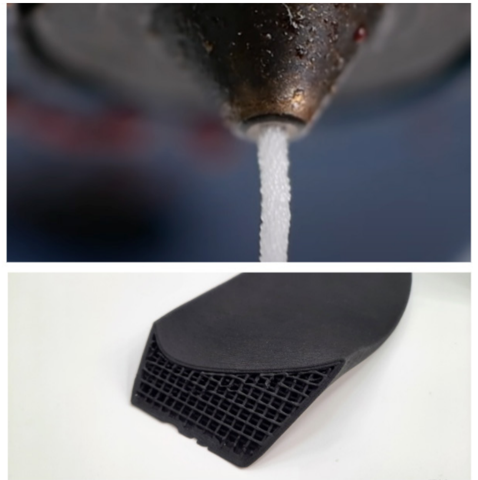


Figure 60: TPU printing

APPENDIX 5 BIKEFITTING VISIT

03/11/2021/ @Valkenburg
To get insights into the procedure of bike fitting and tools and struggles they have, I followed a day during a bikefit training at the Shimano Experience Center in Valkenburg. Niels Boon was instructing the workshop bike fitting and went through the adjustment process with me as the test driver. The bike fitters were following a 3 days training including anatomy and dynamics lectures to better understand the human body. The procedure that they currently follow for fitting people on the bike was practised with me as a testing person.

PROCEDURE OF BIKEFIT:

Normally first an intake is performed. Questions about complaints, type of riding, hours spent on the bike are asked and put into an online bikefit programme. Secondly, the client is asked to lay down on a physiotherapeutic bench and several ergonomic and flexibility factors are measured: e.g. leg length difference, flexibility and foot arch size.

Then a static bikefit is performed to measure the human body such as; leg and arm length. Those measurements are put into the Bikefitting.com calculator and a first setup is created on the test bike. From that point, the dynamic bikefit starts to take place: several sensors are placed on the human body and captured by a side camera. This camera measures the angles the human body makes on the bike and tells how to correct them.

The three main angles taken into account are the tunk angle, knee angle and arm angle. The flexibility and personal specifications of the body are always taken into account here. Finding the optimal position then comes down to trying out changes and seeing how the rider is responding to that. For selecting the right saddle a sit bone measuring device is used, but selecting the correct saddle is only done when the rider experiences discomfort. Bikefitters are stimulated to actively ask for these complaints. Lastly, a pedalling analysis is performed to see the forces on the pedals and the efficiency. The setup is then copied from the test bike to the normal road bike.

It is remarkable that for the tiniest deviation regarding the position, expensive sensors detect the difference, but regarding the fit of a saddle, it is still dependent on the user's perceived (dis)comfort level. Only sit bone width is measured with data currently.

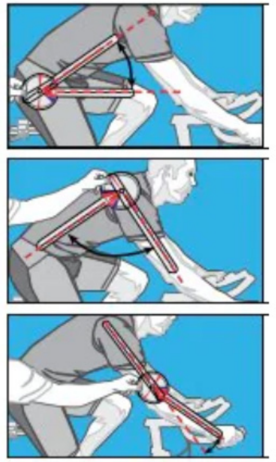


Figure 61: Measuring angles

APPENDIX 6 RESEARCH SUSTAINABILITY

LIFE CYCLE ASSESMENT

Three models of the current PRO lineup were compared using the Ecolizer LCA template. The three saddles were:

- Team (carbon rails with carbon-reinforced base and EVA padding)
- Performance (Inox rails with carbon glass fibre reinforced bed and PU padding)
- Sport (Chromoly rails with nylon base and PU padding)

As can be seen in figure 57 the Team saddle has the most impact. The carbon rails have a big impact on such a small part. Also, the Carbon reinforced plastic bed (CFRP) and the glue used for the base and padding has a significant impact. The production methods have a relatively small impact. Also, the impact of the end of life is quite small since around 49% of the saddles are already given a second life too.

For the Performance, the Inox rails also had a lot of environmental impact, but a little less compared to the carbon fibre one. The glass fibre reinforced also had less impact, than the team version. The weight of the saddle is higher, so the production method has a little more impact. Also, the end life of PU is worse compared with EVA foam.

For the Sport version, we see that stainless steel rails have more or less the same impact as the Inox rails. The nylon base has, compared to carbon and glass fibre reinforced plastic, a lower impact. In reality, the material of the base might influence the product lifespan, but for this analysis, this is kept the same. For the Sport version, the end of life of PU foam combined with the gel inserts has more impact than regular PU foam in the end of life but less in production.

Team

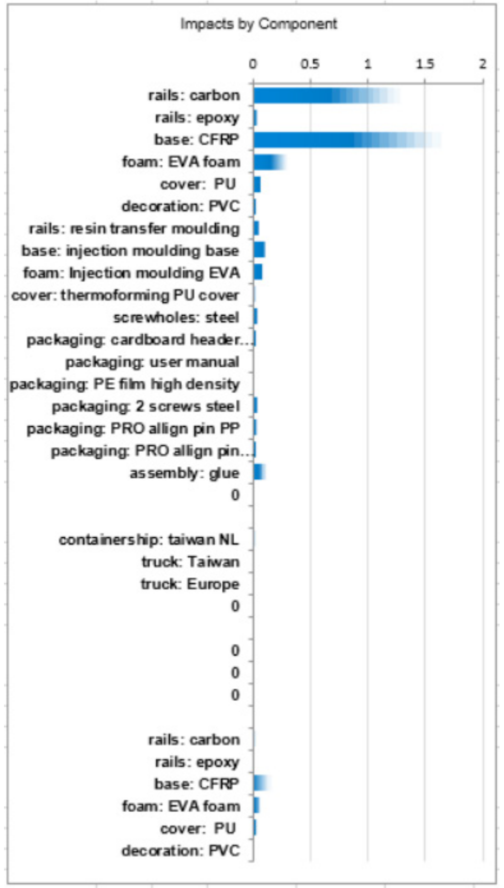


Figure 62: Team; carbon rails carbon bed

Performance

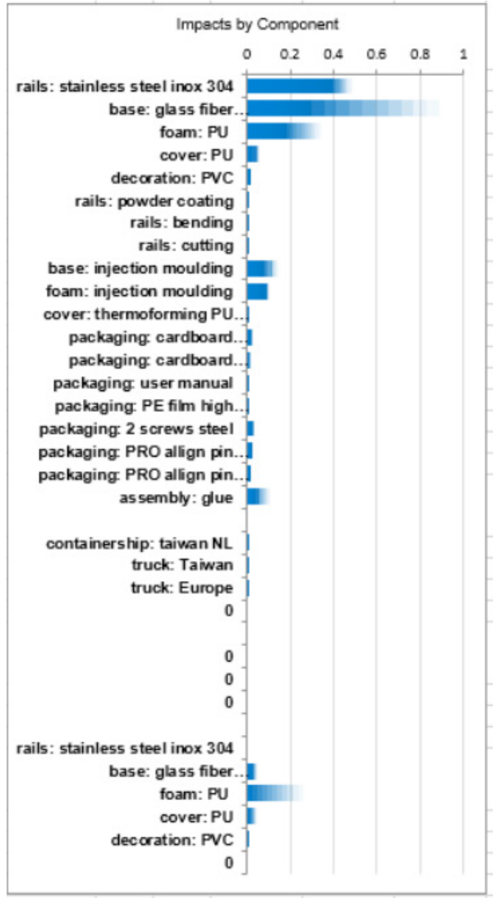


Figure 63: Performance ;inox rails glass bed

Sport

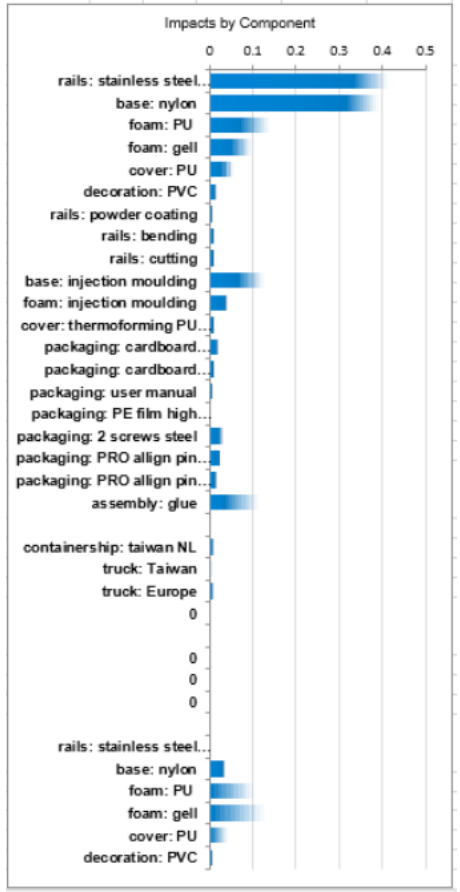


Figure 64: Sport; steel rails nylon bed

QUESTIONNAIRE

A questionnaire was performed to get insights regarding the sustainable behaviour of customers and to make estimations in the LCA regarding end of life. This was research with my cycling network, further research has not yet been done regarding pressure cooker time restraint. This research is not representative of the complete user group. Having a large group of fellow students influences the results. There were 238 participants in this research.

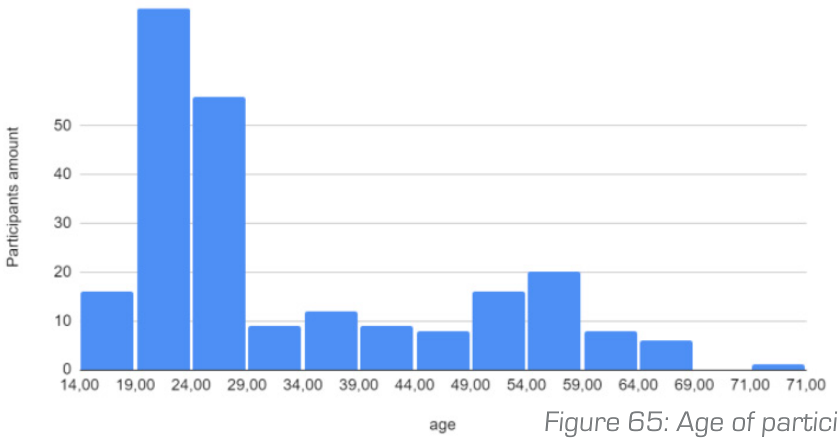


Figure 65: Age of participants

Also having more males than females might not be representative, especially not for my target group. However, this questionnaire was filled in by more males(72%) than females (28%).

PRO has now 10% of the saddle market, according to the questionnaire. Non-OEM Saddle brand competitors own around 55% of the saddles of this research. OEM saddle brands (bought standard on a new bike, so a sub-brand of a bicycle manufacturer) owns around 35% of the saddles of this research. So taking this research: around 65% of the people change their saddle after buying the bike.

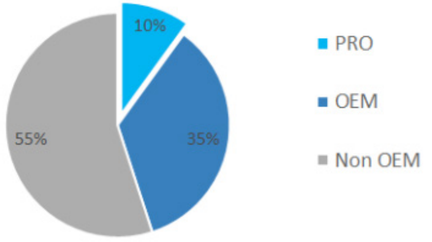


Figure 66: PRO marketshare

When asking participants what they do with used saddles 13% responded that their saddles are thrown away and incinerated. Nevertheless, 49% are given a second life already, which is quite an amount. Especially since 32% is left in the closet and they can also be used second hand. They could later be thrown away or sold. It is quite remarkable that such a high amount of saddles are kept in the closet, waiting for another user.

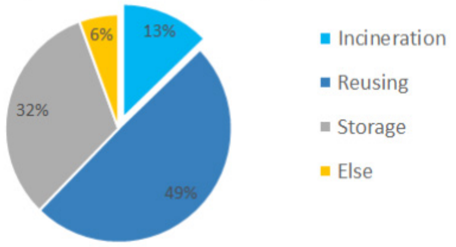


Figure 67: Disposal of saddles

The average lifespan of a saddle is 3.6 years of use, But there is a lot of difference between participants. Most people buy a new saddle because of the failure of the current saddle. Of that failure, 74% was caused by wear of the top cover.

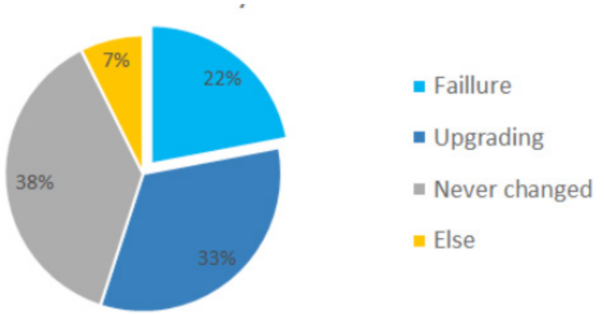


Figure 68: Reason to buy a new saddle

For purchasing a new saddle, sustainability is not one of the main factors. Comfort, quality and price are the main criteria when choosing a new saddle among participants.

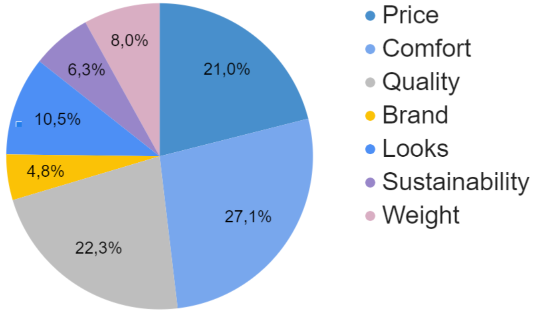


Figure 69: Criteria for buying a new saddle

For selecting saddles; most of the saddles are on the bike when buying (38%), however, bike fitting popularity is increasing (31%). However trial on error (20%) is still a significant part (possibly because online sellers offer a free-testing period). 16% of the respondents selected their saddle with a bikefit.

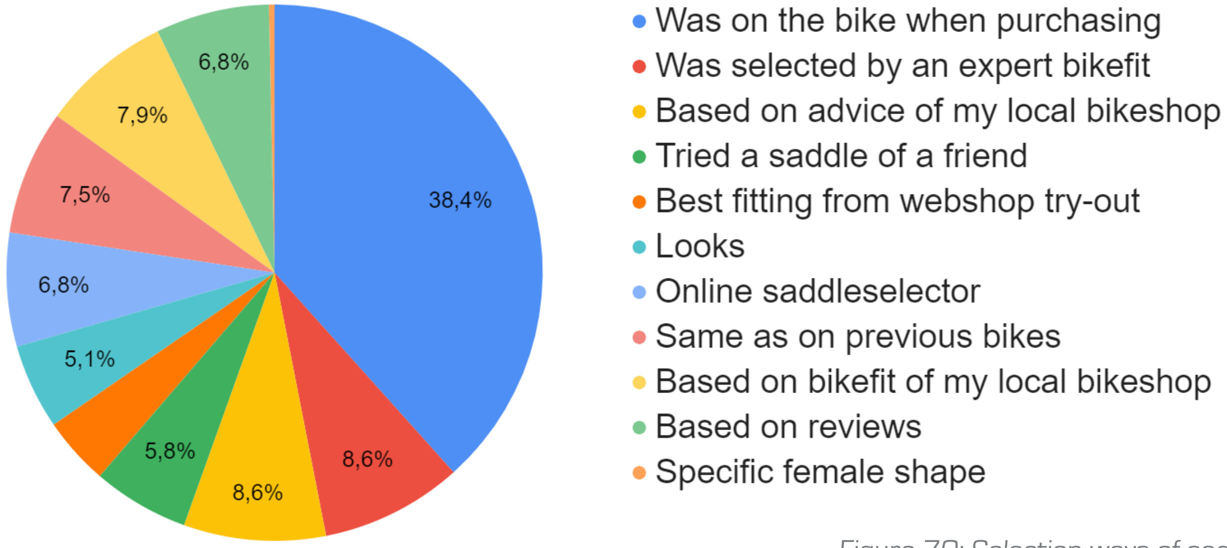


Figure 70: Selection ways of saddles

APPENDIX 7 ERGONOMIC RESEARCH

Second research has been done regarding bike comfort. To see if people have problems with current saddles and where most issues occur. For this research the same restrictions as in appendix 6 count, regarding respondents' age and gender. For this research 85 respondents were taken into account, of which 51 were male and 34 female.

Their current saddle brand can be seen in figure 65. PRO, Specialized, Bontrager, Fizik and Selle Italia are the main saddle brands. However, the questionnaire can be affected by PRO colleagues filing in the research.

As can be seen in figure 66 saddle width differs between males and females. As can be seen, male participants have an average narrower saddle than females. In literature it can also be found that on average, male sit bone width ranges between 100mm – 150mm and female range between 110mm – 160mm (peoplesize, 1998).

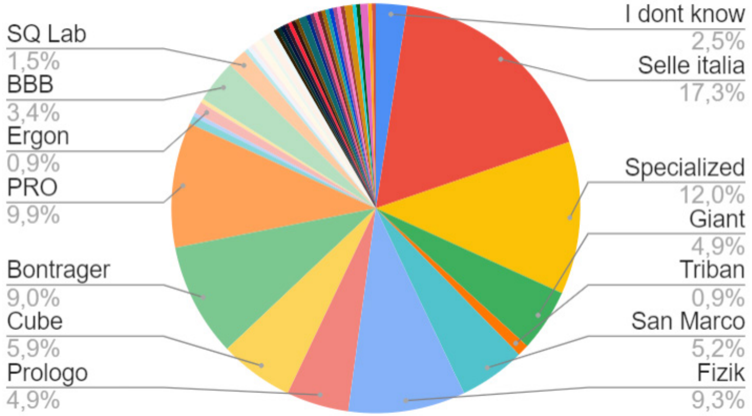


Figure 71: Saddle brand of respondents

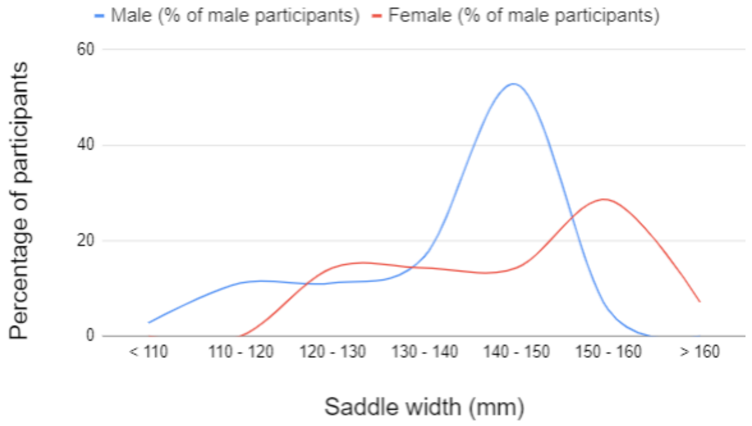


Figure 72: Male female saddle width

Participants were asked to fill in their often experienced discomfort. The answers among males and females differed quite a lot: 0% of females have no discomfort when riding a bike. 50% of the females feel discomfort at the reproductive organ. 39% of the males have genital numbness when riding a bike. Having a correct pressure division between the front (genital pressure) and backside (sit bone pressure) is essential, especially for females. Based on these results females experience more problems with saddles than males. This might come because of the super-sensitive nerve ends discussed in the ergonomic PC and the fact that most saddles are designed for males.

The current saddle was divided up into 9 pieces so respondents could rate the (dis)comfort of every saddle zone. 1 and 2 are the saddle nose, 3 and 4 the bridge of the saddle, 6 and 7 in the middle of the saddle, designed to support the sit bones. Zone 5 and 8 are called the side of the saddle, where the angle influences chafing on the legs. Zone 9 is there to relieve the tailbone and is called the back.

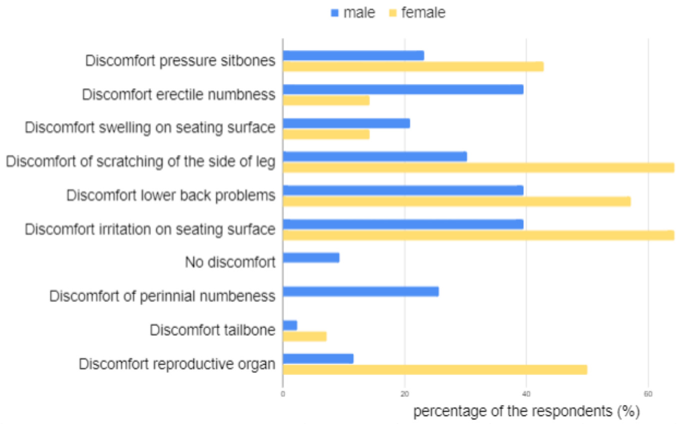


Figure 73: Male female discomfort

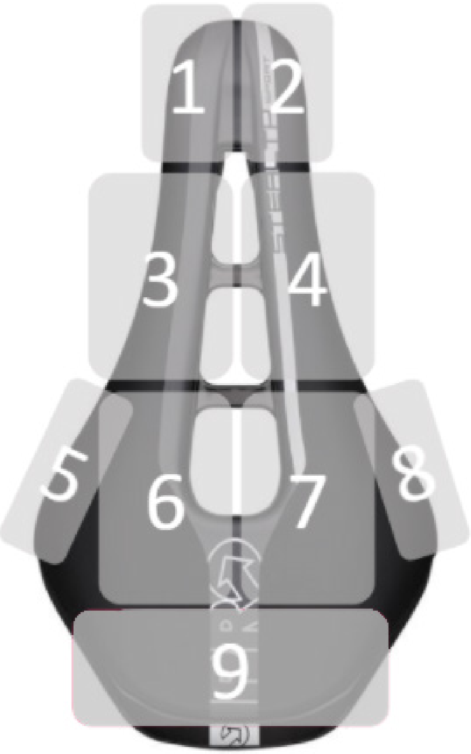


Figure 74: Discomfort devision

The results when asking participants to rate the comfort of a particular area were quite remarkable. In total, the side, nose and back are the least comfortable spots on a saddle, according to the participants. Both the bridge and the middle of the saddle were rated more comfortable. This perception varied a lot between participants.

Because of this difference, several analyses were done. One I did regarding the amount of endurance (>2 hours) rides. Where you might think that endurance riders will experience less comfort, no clear difference can be found. The average score of experienced endurance riders is a little lower compared to others. They also experience more discomfort in the front of the saddle, compared to other respondents and less discomfort in the back of the saddle. This could be explained because they ride more often in an aerodynamic position.

This was research with my cycling network, further research has not yet been done regarding pressure cooker time restraint. This research is not representative of the complete user group. Having a large group of fellow students influences the results. This was not scientific research but a questionnaire to get quick results. External factors can influence the results.

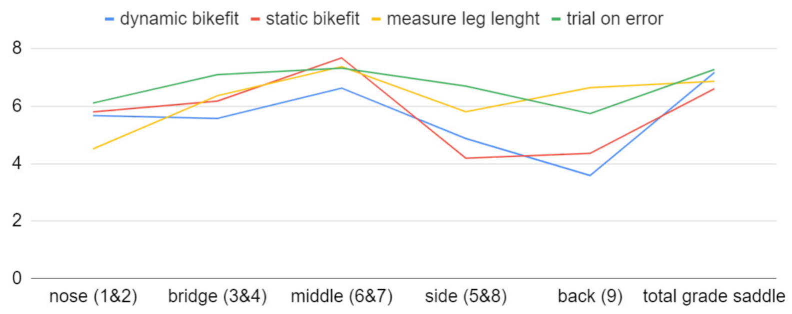


Figure 75: Perceived discomfort in different saddle zones

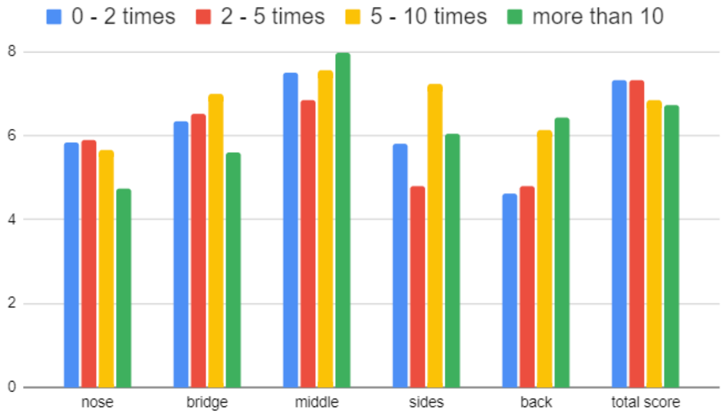


Figure 76: Comfort scores for longer than 2 hour rides

APPENDIX 8 COMPRESSION TEST

To validate if 3D print structures with TPU could have the same ductility characteristics as conventionally used PU foam, a basic compression test was performed. In total three different structures were compared with the original PU foam of one of the current saddle models. All three structures were printed with a 10% and 20% infill percentage with TPU 95. Both infill and the three structures were selected together with Tim Kuipers, a 3D print expert, because of their compression qualities. The different structures can be seen in figure 71.

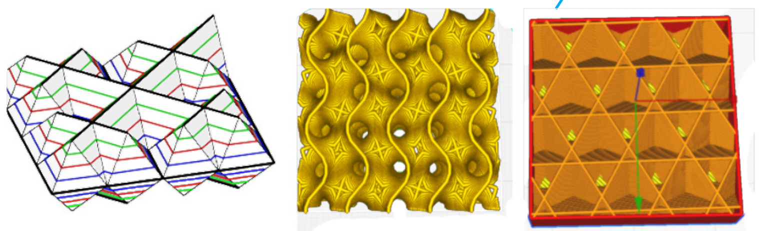


Figure 77: Infill structures: crossfil 3D (left), gyroid (middle) and cubic subdevision (right)

In this experiment, these printed TPU 95 cubes were compared for compressive stiffness using a Zwick machine. The cube dimensions were printed at 56x56x25 mm. The machine measured the force needed to compress the material until the height of the cube was 10mm (15mm compression). As can be seen in figure 72 the infill pattern highly influences the compressive stiffness.

As reference also a block of PU foam in the same dimensions were cut out of one of the saddles. This test might not be completely representable since the shape of the PU foam was influenced by the saddle design and therefore had not exactly the same dimensions (why the blue line starts increasing at 6mm).

The graph plots reaction force against compressive deflection. The angle of the curve represents the stiffness of the infill pattern and material, the bigger the angle, the stiffer the pattern. Different infills have different gradients, so the type of infill patterns highly influence the stiffness of the material

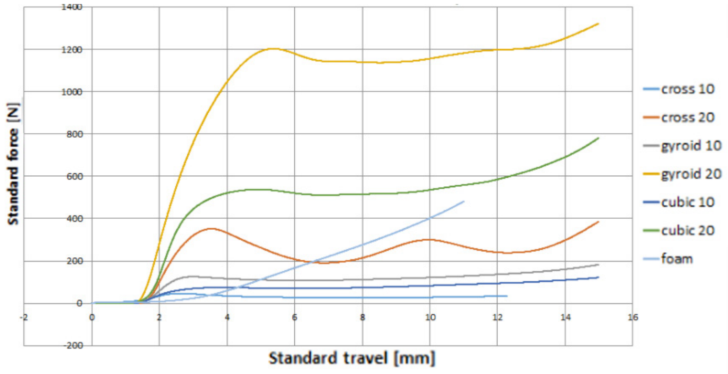


Figure 78: Different structures under compression

APPENDIX 9 PROGRAM OF REQUIREMENTS

PRODUCTION

- The product should be able to be produced in a series of at least 10.000 saddles per year
- The total production time of the saddle should be below 4 hours, assembling included
- The production of the saddle should preferably be using a technique with short lead times

MATERIALS

- The materials of the product should be able to be water, UV and moisture resistance
- The materials of the product should be able to withstand temperatures from -20 to +80 degrees
- The materials should be able to support the weight of a 120-kilo rider
- The product should preferably weigh less than 300 grams
- The materials of the saddle should be preferably commonly available, so PRO is not depending on one vendor.

ASSEMBLY

- The assembly of the product should preferably not use hazardous glues
- The user assembly of the product should be able without special tools

TRANSPORT

- The product should preferably be produced locally for at least 50%

LIFESPAN

- The product should be able to be used for over 4000 hours of riding with normal use.
- The materials used for dampening should hold 75% of their dampening specifications for over 4000 hours of riding in a load test.
- The user should preferably be able to repair the saddle at home or local bike shop without using specific tools

PACKAGING

- The product should preferably have as little as possible packaging
- The product should include a user's manual
- The packaging should be optimized for container loading
- The packaging should preferably be able to be sent via direct transport (online sales)

AESTHETICS

- The product should be in line with the PRO product style manual, however, the specific concept should be visible

SUSTAINABILITY

- The materials of the product should preferably be from renewable sources
- The materials of the product should preferably be fully recyclable

PRICE

- The retail price of the product should be below 150 euro for a stainless steel saddle, to compete with saddle brand Selle Italia and Specialized (appendix 21)

TARGET GROUP

- The product should be made with adjustments regarding the comfort level of females
- The product should be suitable for the target group with padded bib shorts

APPENDIX 10 MECHANISMS TOP COVER

For concepts 1 and 2 to work a certain mechanism should be applied to attach the top cover to the base of the saddle. For investigation of the best option, quick prototypes have been made. Because Colorfabb's printer prints on a belt, the bottom of the print has to be flat. This is challenging for attaching parts to the saddle base. Because the saddle cover should be able to be changed for a new one, glue is not taken into account for connecting the two parts. The glue will also interfere with the recycling of TPU, according to Ruud Rouleaux.

Elongate the print	Clamping the print	Clamping top cover	Two prints together
			
Elongating the print and taking the sides to fix the cover on the bottom of the product	Clamping the cover with clamps to fix it. Style elements as the spoiler and nose design can function as clamps.	A PU cover is attached on top of the printed cover and attached in a traditional way, with a kind of brace	In order to make the bottom of the saddle match the current saddle base, two printer parts can be attached to each other.
+ Fixation in every direction - Depending of stretch material	+ Using style elements - No element at side of saddle	+ Proven fixation + Protection against wear and water - Looks of print lost	+ Fitting with the current base - Tape/melding of both parts

Figure 79: Top cover mechanisms

APPENDIX 11 COMPARING 3D PRINTING

To select the most suitable additive manufacturing method for producing saddles, multiple production methods were investigated first. In this way, the pressure cooker could focus on a more detailed investigation of this method. Together with 3D print expert Tessa Essers, these five types of printers were selected because of their availability to the TU Delft (Ultimaker, Formlabs, Stratasys), usage in the cycling saddle industry (DLS carbon 3D) and previous cooperation with PRO (Colorfabb). For rating these different techniques, interviews with various experts took place: Tim Kuiper (expert on Ultimaker), Tessa Essers (expert on MF Stratasys and SLS Formlabs), Ruud Rouleaux (Colorfabb) and Justin Harpster (DLS carbon 3D). Together with these experts, the following information was retrieved:

	FDM Ultimaker	SLS Formlabs	DLS Carbon 3D	MF Stratasys	FDM Colorfabb
Material costs /saddle	Low	Medium	Medium	High	Low
Production time	High	Medium	Low	Medium	Medium
Investment costs /printer	Low	Low	High	High	Medium
Post treatment	Low, only possible support removable	High, support removal in several washers (~6 hours)	High, 4- 8 hours heat treatment. Can be done multiple at once	High, Impossible support removal, should be printed as solid	Low, only possible support removable
Strength	Low strength low ductility	medium strength, medium ductility	High strength, medium ductility	Medium strength, High ductility	Medium strength, medium ductility
Surface finish	Poor	Medium	High	High	Medium

Figure 80: Ranking different printing methods

Depending on the scope of the product printing a suitable method can be selected. FDM printing at the company Colorfabb was selected as the option with the most potential. The method has less surface quality and strength than the DLS method for example. But the investment costs are significantly lower, also production costs and the after-treatment process is rather short. Also, Colorfabb makes material for printing and can adjust the process to personal demands. On top of that, they also have already worked with Shimano.

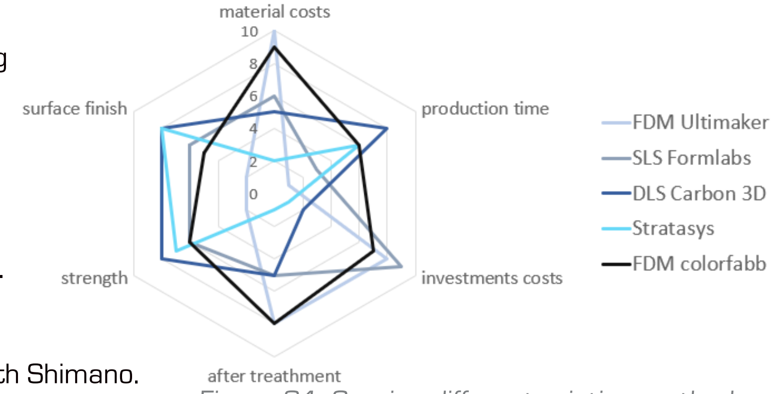


Figure 81: Scoring different printing methods

APPENDIX 12 SENSITIVITY RESEARCH

INTRODUCTION

A study with 10 female participants was performed in order to test the pressure decision on various types of saddles and to determine the sensitivity of the sitting area of females.

PURPOSE OF THE STUDY

Nowadays many females struggle to find a good cycling saddle. Most saddles are based upon male ergonomics. Out of a questionnaire with 120 females, all of the respondents experienced discomfort. With this research, I want to determine sensitive female zones to relieve pressure at those zones. This sensitivity map could provide designers and engineers with a theoretical base for adapting the softness, contact area and shape of a competitive road/gravel bicycle saddle model.

PREPARATION

For performing this research I performed an HREC application, which is responsible for the ethical approval of tests. My prototype plan, research, consent form, data management plan, device report for prototype and ethical sheet were first assembled and afterwards approved by the HREC commission. After that 10 participants, from my local cycling contacts, were asked to participate in this research. They all signed the consent form and brought their bike, wore padded cycling shorts and brought their cycling shoes.

PROCEDURE

In this study, participants are asked for their weight, stature height, age, gender, saddle type and how they selected their current saddle. As a next step, their hip-width and saddle width were measured. Also, participants are asked if they ever had any injuries, operations of fractions around the pelvic area, because this might influence the results. Their current bicycle position is measured and after that, they are asked to place their own bike on a bike home trainer.
The participants are asked to take place on their own bike and start pedalling, several pictures and videos are then made to measure the trunk and knee angle for later reference.

Initially, their current saddle is analyzed, type and width are noted, and a dynamic pressure map analysis is performed with participants cycling with a pressure mat for 5 seconds. This measurement is done 3 times with the resistance of 100 watts on the home trainer. As a second step participants are asked if they often experience discomfort on their current saddle and asked at which points or zones of the saddle this comfort and discomfort is experienced with the help of figure 76.

As a next step, the current saddle height and handlebar-saddle length are measured and marked. The complete saddle pen is removed from the bike and 3 types of saddles are mounted onto the participant's bikes. They are placed in the same position and are all tested 3 times at 100 watts too. The participants are then also asked if they experienced comfort and discomfort on these saddles and where on the saddle this comfort and discomfort is experienced.

The last test is performed with a modified saddle to measure the sensitivity in the seating area. A saddle with a multitude of holes on different locations on the saddle is assembled in the same reference position on the bike of the participant. A female assistant will apply a slow increase in pressure in one of these holes and measure the force at which you feel discomfort. During this study, a pressure meter will be pressed to your skin until you signal you experience discomfort. The pressure will be relieved directly after. In this process, you should not experience any pain. The measuring point will be rounded and have a diameter of 10mm.

After the last sensitivity test, participants are asked to get off the bike and their original seat post will be installed again at the same original position and participants are thanked for their participation.

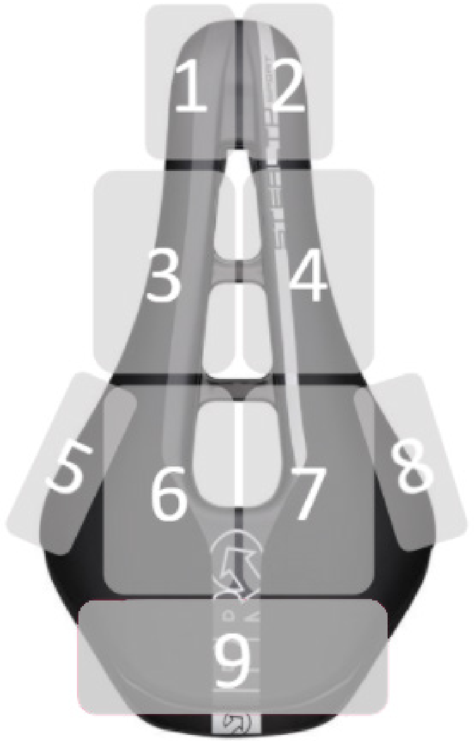


Figure 82: Comfort score zones

OUTCOMES

The force in Newton that was needed on average to be experienced as discomfortable can be seen on the left of figure 77. The numbers of the spots are explained in the middle and the standard deviation of the averages of the force is shown on the right in Newton.

- Points 2, 3, 8 and 12 are considered most sensitive. These spots are placed in the soft tissues of the female body and correspond with the reproductive organ and the anus.
- Points 9, 10, 11, 13, 14, and 17 are considered to be the least sensitive and can be declared by the V shape of the pelvis bone.
  Around the pelvis bone, the standard deviation is also higher, probably because of the difference in weight and fat percentage.
- Gynaecologist Frederieke Siemens (appendix 15) was asked for her opinion of the maps to "validate" it with her experience. Overall the map was on point as far as she could tell, however, points 6 and 7 of the test should be sensitive too. On these points, the model and measuring tool might have influenced the test results.

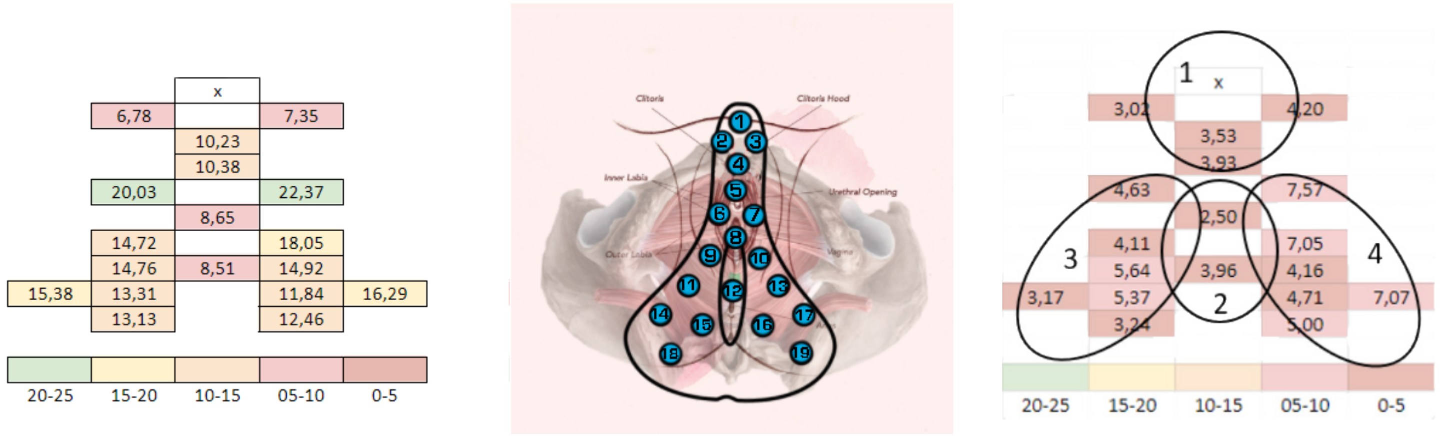


Figure 83: Sensitivity map

LIMITATIONS

This brings us to the limitations of this research

- The research was only done with 10 participants with all ages varying from 18 to 23 and weight varying from 56 to 70 kg. For a more representative outcome, a bigger group with different ages, different fat percentages and different weights should be tested.
- The position of the holes is adjusted to the saddle rails geometry. This results in some blank spots because of the rail construction. Also, some points were difficult to measure perpendicular to the saddle surface because of this construction. This might have influenced the results.
- The force is humanly increased and this affects the precisions of the measurement.

APPENDIX 13 CONSENT FORMS

Informed consent form template for research with human participants

THE PURPOSE OF THIS STUDY

Your participation in this study will help Shimano Europe to examine the difference in pressure sensitivity for sitting areas for females. This sensitivity map could provide designers and engineers a theoretical base for adapting the softness, contact area and shape of a competitive road/gravel bicycle saddle model.

Both Delft University of Technology and Shimano Europe are involved in this research project and will make use of the anonymous generated date (data) regarding the sensitivity map to develop bicycle saddles specifically designed for females.

Nowadays many females struggle to find a good cycling saddle. Most saddles are based upon male ergonomics. Out of a questionnaire with 120 females, none never experienced discomfort. With this research I want to determine sensitive female zones to relief pressure at those zones.

PARTICIPATION

You will take part in a study, in which data of you will be collected. To be able to use these data for research and scientific publication purposes (e.g. Master thesis report, possibly journal paper) we need your permission.

BENEFIT

The is no direct benefit for you (e.g. no financial compensation), however your participation contributes to the development of a sensitivity model of the sitting area of females, which can help designers and engineers of Shimano to design an improved ergonomic bicycle saddle shape of which someday you might make use of.

PREPARATION

Please read this consent form carefully and bring:
- your bike
- wear padded cycling clothes
- your cycling shoes

PROCEDURE

In this study you will be asked to indicate discomfort sensitivity of the sitting area. First, we will ask you weight, stature height, age, gender, sitbone width and hip width. When this data is noted, you will be asked to place your own bike on a bike home trainer.

The participants are asked to take place on their own bike and start pedaling, several pictures and videos are then made to measure the trunk and knee angle for later reference.

First their current saddle is analyzed, type and width are noted, and a dynamic pressure map analysis is performed, participants will cycle with a pressure mat for 5 seconds. This measurement is done 3 times with the resistance of 100 watts on the home trainer. Afterwards, participants are asked if they often experience discomfort on their current saddle and asked where on the saddle this comfort and discomfort is experienced with the help of the image on the right.

After the current saddle height and length to the handlebar are measured and marked. The complete saddle pen is removed from the bike and 3 types of saddles are screwed onto the participants bikes. They are placed in the same position and are all tested 3 times at 100 watts too. The participants are then also asked if they experienced comfort and discomfort on these saddles and where on the saddle this comfort and discomfort is experienced.

The last test is performed with a modified saddle in order to measure the sensitivity in the seating area. A saddle with a multitude of holes on different locations on the saddle is assembled on the bike of the participant. A female assistant will apply a slow increase in pressure in one of these holes and measure the force at which you feel discomfort. During this study a pressure meter will be pressed to your skin until you signal you experience discomfort. The pressure will be relieved directly after. In this process you should not experience any pain. The rod head will be rounded and have a diameter of 10mm.

After the last sensitivity test, participants are asked to get off the bike and their original seat post will be installed again at the exact same height. We will discuss with you any follow up questions you have and then thank you for participation.

DURATION

The study will take 60 minutes or less on average, maximally 90 minutes. Each test will take about 20 minutes.

HEALTH RISK

The health risk of this study is low and has been discussed with the Delft university of technology safety expert and has been approved by the Human Research Ethics Committee of the Delft University of Technology. Please note that participation is at your own risk.

During this study a rod will be pressed indirectly (through padded pants) to your skin until you signal you experience discomfort. The pressure will be relieved directly after. In this process you should not experience any pain. Please note you have to signal when experiencing discomfort, which is not similar to pain, but is a tolerance threshold before pain occurs.

As this study investigates sensitivity of a healthy population, subjects which have had an accident with injuries, fractures, never and/or tissue damage of the sitting area cannot take part in this study.

PLEASE NOTIFY RESEARCH STAFF IMMEDIATELY WHEN NOT FEELING WELL DURING THIS STUDY AND WITHDRAW PARTICIPATION IMMEDIATELY.

PRIVACY

Due to the nature of the data collected in this study (pictures), fully anonymous processing of data is not possible. However, data will be connected to a participant number and will be accessible and handled only by the research team to guarantee your privacy as much as possible.

Study results will be anonymously published. Photos and videos will be anonymised (your face will be obscured by means of fade/blur or black bar) and possibly published (e.g. in a master thesis and journal) unless you give us explicit permission to publish recognisable data of you. Your name will not appear on any publication.

DATA STORAGE

All data (ranging from sensitivity data, pressure maps, analysis, and participant info) resulting from this study will be stored on a secure Shimano drive, which can be accessed by the people of the Shimano research team only. This data will be stored for minimally 3 years and thereafter possibly archived in perpetuity on Shimano owned archive.

Shimano Europe is a partner in this research and will have access to sensitivity and pressure maps of all anonymous participants.

RIGHT TO REFUSE OR WITHDRAW

You do not have to take part in this study if you do not wish to do so. Choosing to participate will not affect your relationship with the TU Delft or with Shimano in any way. You may stop participating in the experiment any time without giving any reason. Do inform the researcher of this, enabling us to destroy the collected data and exclude it from the results.

RIGHT TO ASK QUESTIONS

You have the right to ask questions about this study and to have those questions answered by the researcher conducting the test before, during or after the study.

For questions, please contact J. van Montfort via jip.van.montfort@shimano-eu.com
Please tick the appropriate boxes

TAKING PART IN THE STUY

☐ I have read and understood the study information dated [12/01/2021], or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.

☐ I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.

☐ I understand that taking part in the study involves being photographed and filmed, sensitivity mapped and pressure mapped. I declare that I am informed properly about the nature, method, and goal of this study.

RISKS ASSOCIATED WITH PARTICIPATING IN THE STUDY

☐ I understand that taking part in the study involves minimal risks and I declare that I have none of the medical conditions described under 'health risk', which otherwise would withhold me from taking part in this study. I hereby release and discharge in perpetuity TU delft, Shimano Europe and its affiliates of and from all causes of action, obligations, damages, costs, liabilities, judgements, demand and claims, whether known or unknown, anticipated or unanticipated, real or imaginary, actual or potential and whether arising at law or inequity, that may arise out of participating in this study now or in the future.

USE OF THE INFORMATION IN THE STUDY

☐ I understand that information I provide will be used for scientific publication (including, not limited to journal papers, conferences, and master thesis's) and the creation of a sensitivity and pressure model. I understand that the gathered pressure and sensitivity map will be used for the analysis of multiple anthropometric and product design studies.

☐ I understand that personal information collected about me that can identify me, will not be shared beyond the study team. Recognisable photo's will only be published when I have given explicit consent below. I give permission to archive, process and use these anonymised data (e.g. blurred pictures/ video) on Shimano servers for future reference. This data will be stored for minimally 3 years and thereafter possibly archived in perpetuity on Shimano owned archive.

Future use and reuse of the information by others
☐ I understand that the research will take not more than 90 minutes (included introduction and evaluation)
☐ I acknowledge that I will receive no financial compensation for my participation
☐ I acknowledge that I received a copy of this statement for my own records

NO OBJECTION TO PUBLISH RECOGNISABLE PICTURES/IMAGES IN MASTER THESIS AND RELATED PUBLICATIONS

To communicate our research procedure and results clearly, it is important to support the explanation with pictures or images. To explain the overall setup of the research and position on the bike, we need subjects that are willing to be shown recognisable in the master thesis and related publication.

☐ Yes, I give permission to use imagery of me where I am fully recognisable for publication purposes in any and all media in any geographical location, in perpetuity, of my likeness, for any purpose in connection to this study

☐ No, I do not give permission to use fully recognisable imagery of me for publication purposes

Signatures

______________________ ______________________ __________ __________
Name of participant [printed Signature Date Location

I have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

______________________ ______________________ __________ __________
Researcher name [printed] Signature Date Location

Study contact details for further information: Jip van Montfort, 0634251946, jip.van.montfort@shimano-eu.com. Research team: Jip van Montfort, Rozemarijn Ammerlaan, Erik Tempelman, Maurits Willemen and Mark Kikkert

APPENDIX 14 PRESSURE ANALYSIS

CHOSEN SADDLES

For the analysis of the different pressure maps first, general comments are clustered and the average (dis)comfort scores per saddles are calculated per saddle. The four PRO saddles are tested:

- **Stealth Curved**: this saddle is a more rounded version of the Stealth with a sleeker nose than most females in the pro peloton use. They prefer this saddle over the old Stealth. The Stealth Curved is has a weaved side profile, that is designed to relieve pressure on the soft tissue. The weaved side with the upwards facing back of the saddle allows the pelvis to rotate more, enabling users to ride in a more aggressive position, but can also cause more pressure in the front of the saddle. The rear profile is round, allowing the pelvis to rotate from left to right. This is often more comfortable for riders that don't have a fixed position and have movement in their pelvises while cycling.
- **Griffon**: the Griffon has a flat side profile that is designed for riders that sit a little bit more upright on their saddle. The flat-top does not stimulate the pelvis forward but instead is supporting it upright. Because of this position, no pressure relief zones at for example pubic areas are made. The round rear profile enables it to rotate from left to right and makes this saddle the best fit for the more upright rider.
- **Falcon**: the Falcon saddle is extremely flat on both side and rear profile and therefore is designed for competitive cyclists that have a trained core and can keep their position on the bike. Riders that move a lot will get annoyed by the straight angles and can't find an optimal fit. Having such a flat saddle however, has barely room to press onto the soft tissues and therefore features of this saddle might be interesting.
- **Turnix**: the Turnix has again a waved side profile, stimulating the pelvis forward. The saddle has a seme round rear profile. The complete saddle is rounded, where the Griffon and Stealth become more flat towards the nose of the saddle. This makes more room for pressing onto the soft tissue.

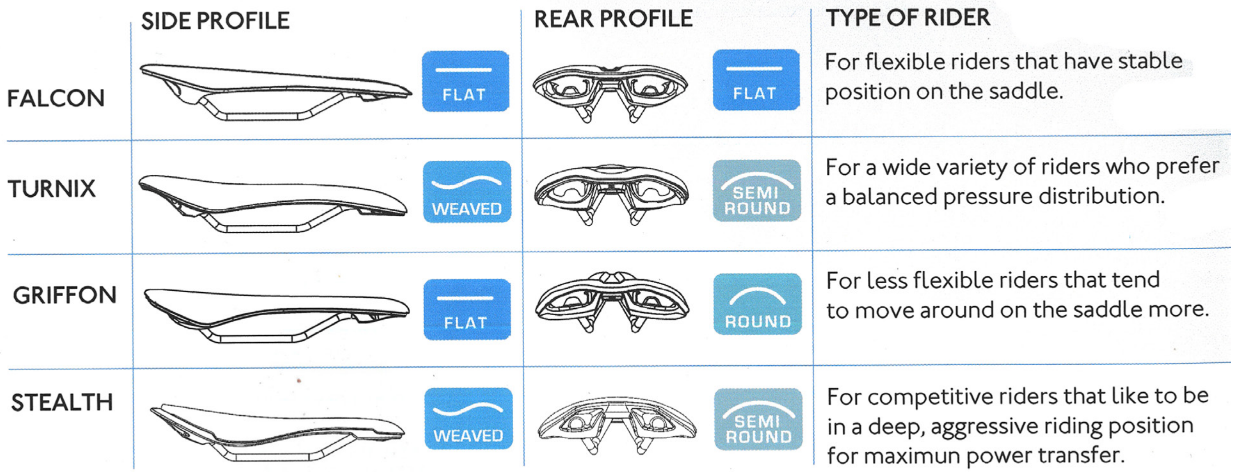


Figure 84: Profile different type of saddles

COMFORT SCOERS AND USER FEEDBACK

Stealth curved:

USER FEEDBACK

- Most women experience chafing of the nose of the saddle because of the wide nose (7/10 participants). This is striking since the nose width has already been decreased compared to its original Stealth Curved.
- The cutout is hurting because of the hard edges and because it is in the wrong spot. The cutout should be softer, especially in the front and should be positioned more to the front (6/10 participants).
- The hardness of the saddle foam is too hard at 4 and 5 (7/10 participants). Compared to other saddles the PRO saddles seem to feel quite hard, especially compared to some female-specific saddles.
- The curvature at sport 6 and 9 limits the movement of some participants (4/10). This saddle has a quite sharp corner that can cause chafing on the inside of the leg.
- Some respondents (3/10) experience more movement of the hips on this saddle compared to their own saddle.

In general, this saddle has a quite positive score. Respondents keep mentioning the hardness of the saddle that is too hard, especially at the cutout area. This cutout is according to most participants placed too far to the back, having pressure points at the edges of the cutout. Looking at the pressure map, two main groups can be found: one group having more pressure at the front of the saddle and one group having more pressure on the back. Generally, this second group rated the saddle better and are less flexible. Of course, human errors in changing saddles could have played a role in this research.

COMFORT SCORE

1&3	5,5
2	6,3
4&5	6,0
7&8	6,8
6&9	6,3
10	x

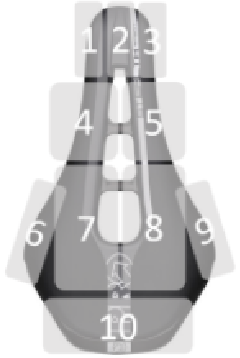


Figure 85: Comfort score Stealth curved

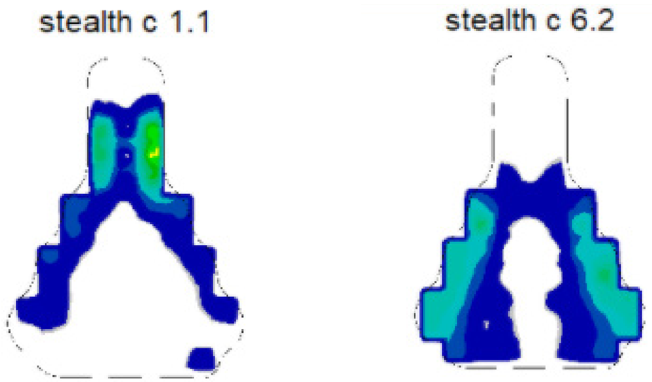


Figure 86: Pressure maps Stealth curved with front loading (left) and back loading (right)

Griffon:

USER FEEDBACK

- The edges in the cutout of the saddle can be felt for some participants (6/10).
- Generally speaking, this is the best-ranked saddle on average, however, there is a lot of difference among participants.
- Some participants experience that they are sitting less stable (2/10).
- Some participants experience that the nose of the saddle is too wide (4/10).
- In general, the curvature at spots 6 and 9 is perceived as the most pleasant of all the tested saddles.
- Extra height at spots 7 and 8 could help for pressure relief at 4 and 5 according to some participants (4/10).

In general, this saddle has a positive score. Respondents keep mentioning the hardness of the saddle that is too hard, also in this saddle. Also, they experience again a too-wide nose and too hard cutout edges. However, the curvature of the saddle is perceived as most pleasant out of this selection of PRO saddles. The saddle shape is flatter and can suit both flexible and less flexible riders. The pressure maps of most participants show a clear upside-down V shape, where the forces of the pelvis bone are supported. The cutout of this saddle is larger compared to the stealth curved which is perceived as more pleasant.

COMFORT SCORE

1&3	7,0
2	7,7
4&5	6,6
7&8	6,7
6&9	7,2
10	x

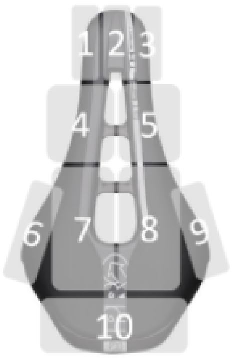


Figure 87: Comfort score Griffon

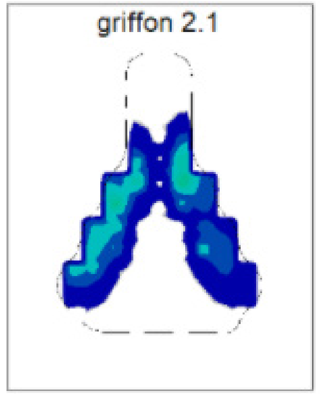


Figure 88: Pressure maps Griffon

Falcon:

USER FEEDBACK

- The Falcon is a more flat saddle that none of the respondents prefers (0/10).
- This saddle is a bit smaller (132mm) compared to other saddles from this test (142mm). This was done to see what a smaller width of a saddle would do.
- It can be seen in various pressure maps that pressure hotspots were experienced. Probably this spot is the point where the pubic rami will leave the saddle. The point where this bone leaves the saddle creates a hotspot.
- There is a lot more pressure on these hotspots compared to the other saddle load. These points were also perceived as very uncomfortable.
- The saddle nose width is perceived as more comfortable. The nose of the Falcon is also a little smaller compared to the other test saddles. The score for this part of the saddle is therefore also higher.
- Some participants (4/10) miss curvature in the saddle shape. The side profile of the saddle is super flat causing pressure hotspots at the soft tissues for some participants.

In general, this saddle has a negative score. Respondents experience the pressure hotspots on the saddle as very unpleasant. The flat shape of this saddle gives more pressure on the soft tissues and therefore does not optimally support the sit bones. However, the saddle nose is experienced as pleasant because it is less wide and for some participants (3/10) a nice upside-down V shape can be seen. However, the majority of the maps show pressure hotspots.

COMFORT SCORE

1&3	6,5
2	5,0
4&5	5,7
7&8	5,1
6&9	5,6
10	X

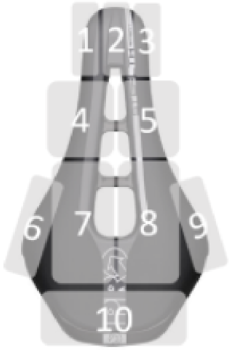


Figure 89: Comfort score Falcon

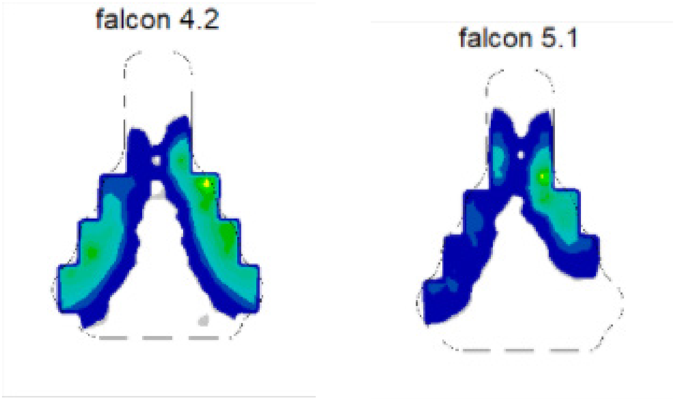


Figure 90: Pressure maps Falcon

Turnix:

USER FEEDBACK

- The Turnix is a more rounded saddle that none of the respondents prefers (0/10).
- This saddle was tested to see the effect of a cutout. Therefore this saddle didn't have a cutout to see what the effect of a cutout was and where most discomforts were experienced.
- All participants experienced discomfortable pressure on their reproductive organs (10/10). This is mainly because of the absence of a cutout and because of the rounded back profile of the saddle. The rounder this shape is, the more it can press into the soft tissues.
- Some participants (4/10) experienced no pressure at zone 6 and 9 and explained that because they experienced higher pressure in other places.

In general, this saddle has a very negative score. Respondents keep mentioning the horrible rounded saddle shape. The absence of a cutout does not help with this problem. The hardness of the saddle is too hard, also in this saddle. Because of this high pressure on the genitals, less pressure is perceived at the sit bone area, the part that can handle pressure. In general, a flatter section at the genital region is preferred among these female participants.

COMFORT SCORE

1&3	7,5
2	6,7
4&5	3,8
7&8	5,4
6&9	6,7
10	x

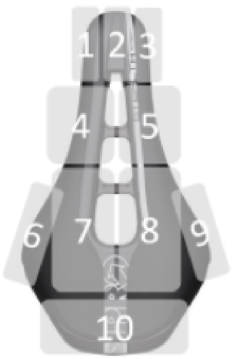


Figure 91: Comfort score Turnix

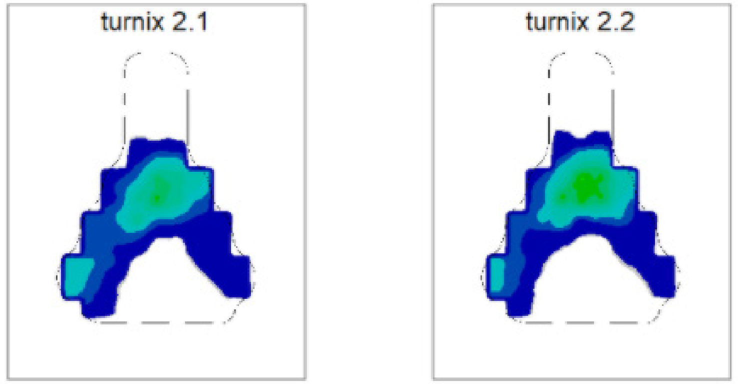
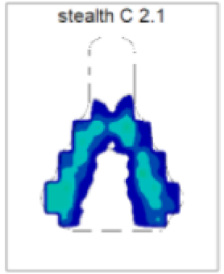


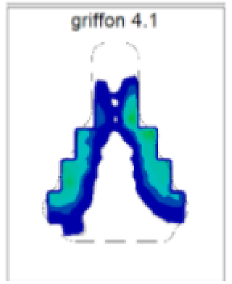
Figure 92: Turnix comfort scores

PRESSURE ANALYSIS

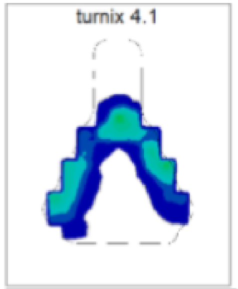
- Additionally, the values of the pressure mats were analyzed and the averages per saddle type were calculated.
- For the Stealth Curved, the maximum pressure on the pubic bone is low compared to its alternatives. This can be declared by the upwards facing back of the saddle and the larger surface area there.
- The Griffon has similar values as the Stealth Curved. It has a little less contact area but the mean of the total force is lower. So it divides the pressure on the saddle more equally.
- For the Turnix, the pressure on the pubic bone is higher compared to its alternatives. This can be declared by the spherical shape of this saddle. This results in the saddle pressing on the soft tissues. Therefore the centre of pressure (COP) is also much more to the front of the saddle.
- The Falcon saddle has a high sit bone pressure. This can be declared because the width of the saddle was too small for most riders. Therefore also the mean force is higher.



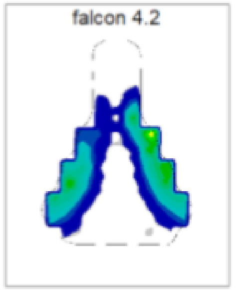
	Pubic bone	Sit bone left	Sit bone right
Max. pressure [mbar]	404,1	381,3	421,1
Mean pressure [mbar]	115,1	121,2	112,4
Loaded area [mm2]	5280,8	5891,7	6040,8
Abs. maximum of force [N]	282,9		
Mean of total force [N]	231,0		
COP	125,9		



	Pubic bone	Sit bone left	Sit bone right
Max. pressure [mbar]	448,7	404,9	442,4
Mean pressure [mbar]	123,3	122,0	119,1
Loaded area [mm2]	5310,0	5533,3	5790,0
Abs. maximum of force [N]	281,1		
Mean of total force [N]	223,8		
COP	120,6		



	Pubic bone	Sit bone left	Sit bone right
Max. pressure [mbar]	442,7	372,3	410,7
Mean pressure [mbar]	155,5	130,0	113,6
Loaded area [mm2]	4528,7	5813,0	5711,1
Abs. maximum of force [N]	288,6		
Mean of total force [N]	231,7		
COP	113,7		



	Pubic bone	Sit bone left	Sit bone right
Max. pressure [mbar]	449,1	450,2	497,0
Mean pressure [mbar]	121,4	144,1	135,8
Loaded area [mm2]	4933,3	5815,0	5941,7
Abs. maximum of force [N]	314,0		
Mean of total force [N]	256,8		
COP	127,1		

Figure 93: Pressure values

APPENDIX 15 GYNECOLOGIST VALIDATION

20/12/2021 @online
To validate the pressure map and to answer questions about the female body an interview with Frederieke Siemens was done. Frederieke also rides a bike herself, which makes her more acquainted with bicycle saddle problems.

- **Are there often bicycle problems you see in your job? Do you perform surgery on bicycle problems?**
Not often in my job. I sometimes perform labia reductions for females but that's often cosmetic issues. I have the feeling females first need to grow callous or hard skin (eelt in dutch) to be able to cycle without pain. You see that often when females have complaints or pains with a new cycling bib short or new saddle. That often disappears after a while but I also think some females with severe problems silence their problems or quit cycling.

- **In the sensitivity map above I tested myself among participants with a prototype to determine sensitive spots on the sitting area of females. Do you think these values are representative?**
Wow! I think overall they are quite accurate however I doubt the values of points 6 and 7. Females have two types of labia, the labia majora (outer) and labia minora (inner). The inner ones are more sensitive than the outer ones. According to the placement of spots 6 and 7, these should be more sensitive than displayed now. The prototype might have influenced the results here.

- **Is there a difference between females in the sensitivity of the labia?**
Yes, they come in different sizes and some are more sensitive than others. In general, the Labia minora are more sensitive. and you have these two types: where the labia majora are bigger (sometimes referred to as innie) and where the labia minora are bigger (referred to as outtie). This second group is more sensitive at the cutout of the saddle. The labia of females often grow bigger the older they get.

- **Are there any other issues females struggle with within the design of a saddle?**
Yes, the hardness of the saddle is super important, it should be just good. A too-hard saddle would give pressure points but a too soft saddle can cause extra chafing and rubbing on the genitals because it enables the body to move more. Aside from that, the form of the cutout is also important. It should not have hard edges and in my opinion, rather be too wide than too small.

		x		
	6,78		7,35	
		10,23		
		10,38		
	20,03		22,37	
		8,65		
	14,72		18,05	
	14,76	8,51	14,92	
15,38	13,31		11,84	16,29
	13,13		12,46	
20-25	15-20	10-15	05-10	0-5

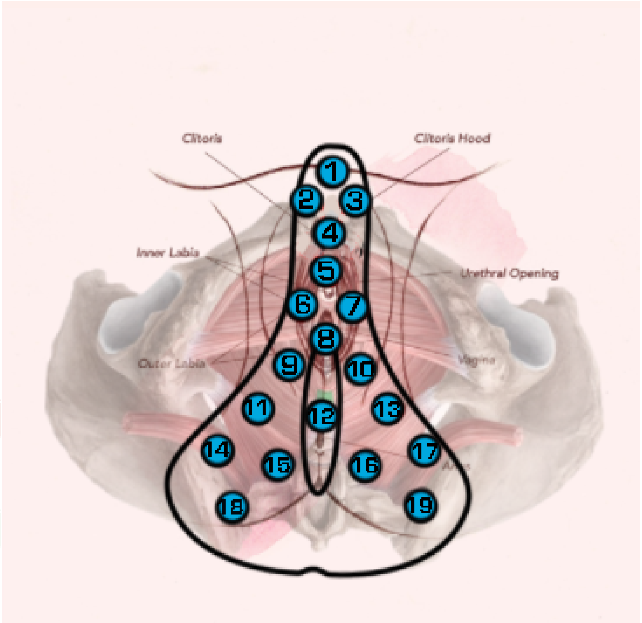


Figure 94: Sensitivity map

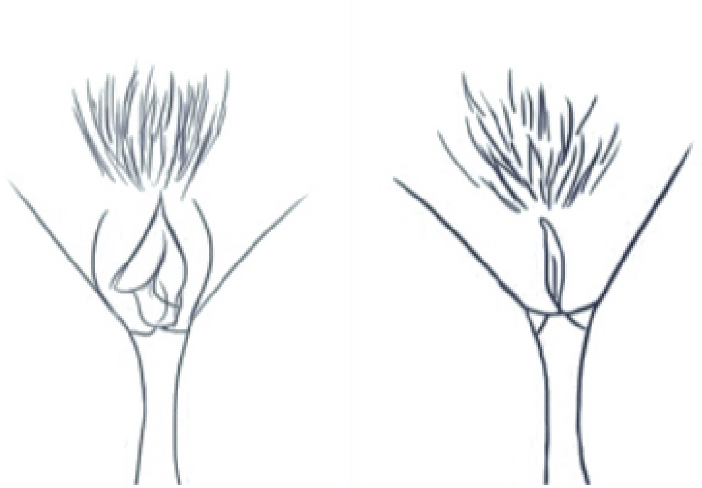


Figure 95: Outtie (left) and innie (right)

APPENDIX 16 ECODESIGN STRATEGY WHEEL

An example from PRO product with a sustainable design strategy tool is given below. This tool is similar to the 7R model explained in the sustainable pressure cooker chapter and was done earlier with a PRO saddle during a workshop with colleagues. It shows that PRO is already consciously thinking about new ways to produce their saddles and considering standardization and modularity.

This model shows various design strategies to produce more sustainably. For all these strategies PRO selected examples. Not only strategies like repairing saddle but also standardization (modularity), easy disassembling at end of life, upgrading saddles, personal attachment (is proven to elongate the product life span) and durability are taken into account.

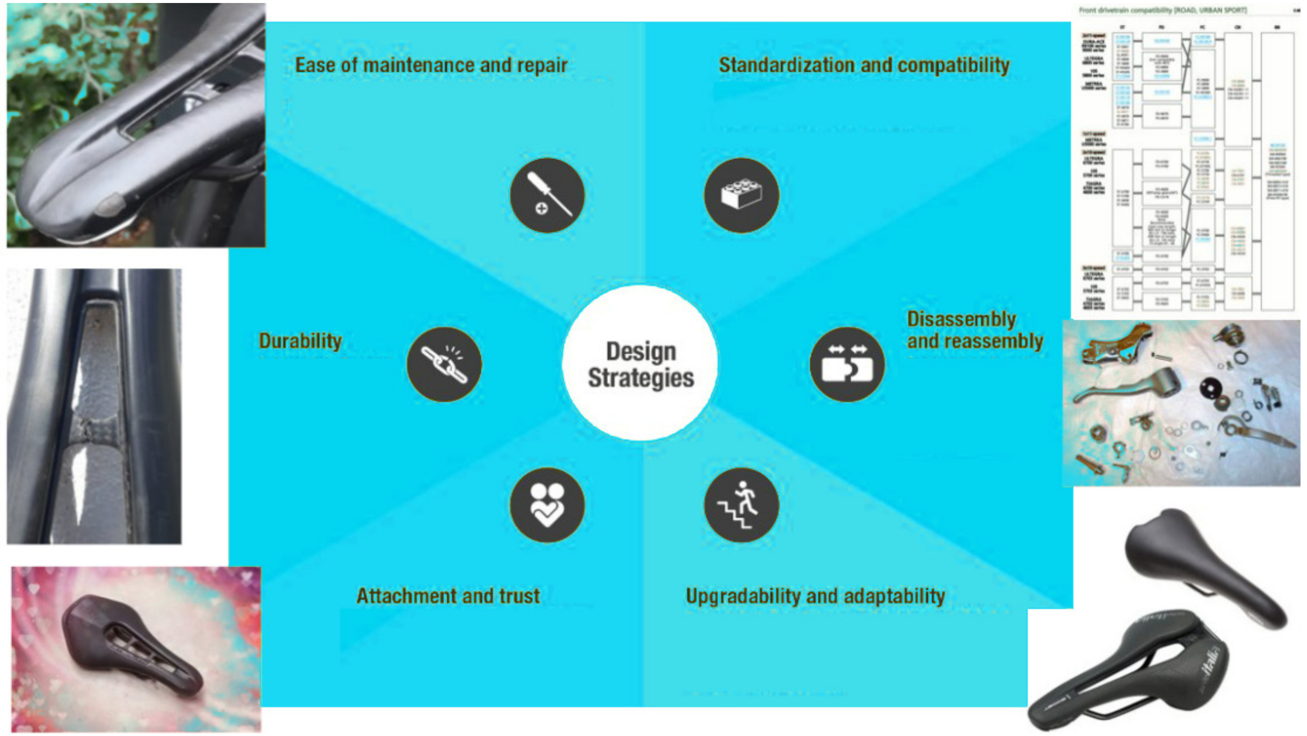


Figure 96: Sustainable design strategie PRO

Shown below is the statement of the sustainable goals of PRO within the future timespans. Their 2025 focus is using recycled materials, 2030 focus is based on modular built saddles and fully recyclable saddles. By 2035 their goal is to introduce a new trading program to introduce customer trade and repair. This model shows PRO's willingness to produce sustainably and their clear focus on modular products.

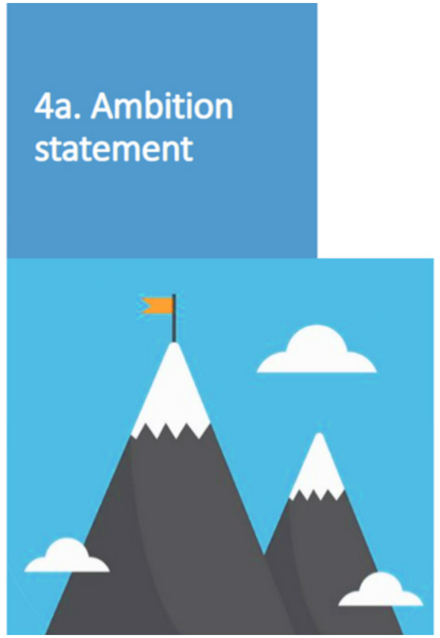


Figure 97: Ambition statement PRO

- For 2025: For the next generation Stealth saddle, PRO is aiming to have a saddle design in the line-up, that is built using 100% recycled materials and/or materials from renewable sources
- For 2030: PRO is aiming to have a recycled saddle line-up that is built using 100% recycled materials and/or materials from renewable sources. Next to that the new generation saddles are built as a modular design and can be fully recycled at the end of their product life.
- For 2035: PRO is aiming to offer a trading program where a consumer can trade in his old (modular) saddle and get a discount on a new modular saddle, to keep customers attached to the brand. Old traded in saddles can be remade into new saddles. PRO is aiming for support by a performance business model for distributors and/or retailers to use.

APPENDIX 17 PARTS MEASUREMENT

These measurements were done to determine the position of the modular parts.

	participant 1 (mm)	participant 2 (mm)	participant 3 (mm)	participant 4 (mm)	participant 5 (mm)	participant 6 (mm)	participant 7 (mm)	participant 8 (mm)	participant 9 (mm)	participant 10 (mm)	gem (mm)	Min (mm)	Max (mm)
mean pressure	211	254	199	278	215	217	275	195	226	251	232,1	195	278
map end	304	320	288	400	320	320	400	302	320	320	329,4	288	400
nose end	45	48	71	45	38	64	42	53	42	37	48,5	37	71
cutout begin	57	68	81	58	45	64	55	57	46	56	58,7	45	81
cutout width begin	12	11	12	11	12	12	10	13	11	11	11,5	10	13
cutout end	124	135	148	112	114	120	109	115	110	107	119,4	107	148
cutout width end	24	30	27	35	23	31	28	25	24	21	26,8	21	35
sitbone distance min	67	72	41	51	39	59	39	52	54	39	51,3	39	72
sitbone distance max	140	130	126	131	115	138	117	143	147	142	132,9	115	147
sitbone length end	197	204	197	195	177	211	195	199	212	197	198,4	177	212

Figure 98: Modular parts measurment

APPENDIX 18 VALIDATION SUBDIVISION

The scores of 6 participants from a 1 to 10 Likert scale are displayed below. It can be seen that different participants prefer different configurations. The weight of participants differ and can influence the choice for ductility; it seems like females with lower weight prefer softer sitting bone parts. Next to that, almost all participants prefer a softer cutout part compared to the sit bone part. 3 modular parts for the cutout and 3 for the sit bone part were tested, varying from low ductility (10) to medium (15) and hard (20).

participant 1: Weight 65 kg

zones	Original Griffon	10 cutout 10 sitbone	10 cutout 15 sitbone	10 cutout 20 sitbone	15 cutout 10 sitbone	15 cutout 15 sitbone	15 cutout 20 sitbone	20 cutout 10 sitbone	20 cutout 15 sitbone	20 cutout 20 sitbone
4&5	2	9	8	8	5	5	6	4	4	2
7&8	7	9	6	4	8	7	5	6	7	8

participant 2: Weight 80 kg

zones	Original Griffon	10 cutout 10 sitbone	10 cutout 15 sitbone	10 cutout 20 sitbone	15 cutout 10 sitbone	15 cutout 15 sitbone	15 cutout 20 sitbone	20 cutout 10 sitbone	20 cutout 15 sitbone	20 cutout 20 sitbone
4&5	6	7	7	7	7	6	7	5	3	3
7&8	6	6	8	9	7	8	8	7	7	8

participant 3: Weight 67 kg

zones	Original Griffon	10 cutout 10 sitbone	10 cutout 15 sitbone	10 cutout 20 sitbone	15 cutout 10 sitbone	15 cutout 15 sitbone	15 cutout 20 sitbone	20 cutout 10 sitbone	20 cutout 15 sitbone	20 cutout 20 sitbone
4&5	8	7	5	5	6	7	5	5	4	3
7&8	6	8,5	7	5	8	8.5	9	7	7	7

participant 4: Weight 74kg

zones	Original Griffon	10 cutout 10 sitbone	10 cutout 15 sitbone	10 cutout 20 sitbone	15 cutout 10 sitbone	15 cutout 15 sitbone	15 cutout 20 sitbone	20 cutout 10 sitbone	20 cutout 15 sitbone	20 cutout 20 sitbone
4&5	7	7	6,5	7,5	6	7	8	6	7	8
7&8	7	6	7	7,5	7	6,5	8	7,5	5,5	7

participant 5: Weight 60kg

zones	Original Griffon	10 cutout 10 sitbone	10 cutout 15 sitbone	10 cutout 20 sitbone	15 cutout 10 sitbone	15 cutout 15 sitbone	15 cutout 20 sitbone	20 cutout 10 sitbone	20 cutout 15 sitbone	20 cutout 20 sitbone
4&5	7	6	5	5	7	7	7	5	7	7
7&8	8	5	7	8	8	8	7	5,5	8	8

participant 6: Weight 74kg

zones	Original Griffon	10 cutout 10 sitbone	10 cutout 15 sitbone	10 cutout 20 sitbone	15 cutout 10 sitbone	15 cutout 15 sitbone	15 cutout 20 sitbone	20 cutout 10 sitbone	20 cutout 15 sitbone	20 cutout 20 sitbone
4&5	6	6	7	8	7	8	7	4	5	4
7&8	6	4	6	8	6	7	6	6	6	5

Figure 99: Ductility test for different participants

The pressure values of the different pressure maps are displayed below. The blue colour represents experienced 'pleasant ' values The interpretation of which values are pleasant is done together with expert Jan Neuheus (appendix 3). As can be seen, by the amount of blue colour their optimal pressure values are found at different configurations per person.

	Original griffon			soft cutout soft sitbone			soft cutout hard sitbone			hard cutout soft sitbone			hard cutout hard sitbone		
Participant 1	Pubic bone	Sit bone left	Sit bone right	Pubic bone	Sit bone left	Sit bone right	Pubic bone	Sit bone left	Sit bone right	Pubic bone	Sit bone left	Sit bone right	Pubic bone	Sit bone left	Sit bone right
Max. pressure [mbar]	583	289	242	261	268	316	257	333	332	326	271	312	300	317	276
Mean pressure [mbar]	160	79	77	109	100	104	94	102	105	110	120	95	118	111	112
Loaded area [mm2]	6200	5825	4825	4875	6175	6425	4825	6025	6000	5150	6275	6375	4800	6225	6475
Abs. maximum of force [N]	276			272			246			274			283		
Mean of total force [N]	214			206			186			215			226		
COP	111			132			133			128			132		
pressure devision front:back	51			48			49			57			50s		
Displacement centre of pressure	diagonal			horizontal			horizontal			diagonal			horizontal		

	Original griffon			soft cutout soft sitbone			soft cutout hard sitbone			hard cutout soft sitbone			hard cutout hard sitbone		
Participant 2	Pubic bone	Sit bone left	Sit bone right	Pubic bone	Sit bone left	Sit bone right	Pubic bone	Sit bone left	Sit bone right	Pubic bone	Sit bone left	Sit bone right	Pubic bone	Sit bone left	Sit bone right
Max. pressure [mbar]	416	475	444	409	493	428	523	494	502	556	439	477	505	472	466
Mean pressure [mbar]	136	190	191	160	155	139	120	165	170	142	147	156	157	180	192
Loaded area [mm2]	6300	4600	4700	6150	5950	6375	6175	6600	6800	5925	6400	5575	6575	5700	5850
Abs. maximum of force [N]	370			415			367			370			310		
Mean of total force [N]	298			313			286			292			280		
COP	125			131			127			128			128		
pressure devision front:back	52			54			48			48			48		
Displacement centre of pressure	horizontal			diagonal			horizontal			horizontal			horizontal		

Figure 100: Presure values participant 1 and 2

	Original griffon			soft cutout soft sitbone			soft cutout hard sitbone			hard cutout soft sitbone			hard cutout hard sitbone		
Participant 3	Pubic bone	Sit bone left	Sit bone right	Pubic bone	Sit bone left	Sit bone right	Pubic bone	Sit bone left	Sit bone right	Pubic bone	Sit bone left	Sit bone right	Pubic bone	Sit bone left	Sit bone right
Max. pressure [mbar]	273	426	536,6	333,5	262	360	440	275	376	430	266	325	360	280	435
Mean pressure [mbar]	76	133	152	86	97	115	97	94	103	101	100	105	95	107	107
Loaded area [mm2]	4250	6250	6775	4725	5400	6550	5250	6300	6150	5500	5925	5950	5250	5900	6400
Abs. maximum of force [N]	291			205			235			240			259		
Mean of total force [N]	224,7			165			190			190			200		
COP	143			132			131			130			130		
pressure devision front:back	35			43			48			50			46		
Displacement centre of pressure	horizontal			diagonal			horizontal			horizontal			horizontal		

	Original griffon			soft cutout soft sitbone			soft cutout hard sitbone			hard cutout soft sitbone			hard cutout hard sitbone		
Participant 4	Pubic bone	Sit bone left	Sit bone right	Pubic bone	Sit bone left	Sit bone right	Pubic bone	Sit bone left	Sit bone right	Pubic bone	Sit bone left	Sit bone right	Pubic bone	Sit bone left	Sit bone right
Max. pressure [mbar]	495	441	368	300	450	430	280	435	580	250	460	490	235	390	405
Mean pressure [mbar]	132	131	121	88	133	121	63	125	125	75	135	135	76	105	120
Loaded area [mm2]	5333	6116	6075	4925	6000	6450	4700	6300	7000	4900	6025	6375	4300	5600	7150
Abs. maximum of force [N]	320			262			300			270			250		
Mean of total force [N]	274			234			250			240			210		
COP	128			139			145			140			145		
pressure devision front:back	44			43			35			35			37		
Displacement centre of pressure	diagonal			horizontal			horizontal			horizontal			diagonal		

Figure 101: Presure values participant 3 and 4

	Original griffon			soft cutout soft sitbone			soft cutout hard sitbone			hard cutout soft sitbone			hard cutout hard sitbone		
Participant 5	Pubic bone	Sit bone left	Sit bone right	Pubic bone	Sit bone left	Sit bone right	Pubic bone	Sit bone left	Sit bone right	Pubic bone	Sit bone left	Sit bone right	Pubic bone	Sit bone left	Sit bone right
Max. pressure [mbar]	547	248	417	750	225	550	630	190	500	485	240	300	460	160	300
Mean pressure [mbar]	165	68	117	136	70	90	150	62	90	140	50	60	145	42	75
Loaded area [mm2]	6250	3991	3883	5600	5100	4300	6000	4300	3350	6000	4000	3800	5500	4000	4400
Abs. maximum of force [N]	250			205			210			187			180		
Mean of total force [N]	208			170			180			165			160		
COP	91			105			95			85			90		
pressure devision front:back	64			64			66			70			72		
Displacement centre of pressure	diagonal			horizontal			diagonal			horizontal			horizontal		

	Original griffon			soft cutout soft sitbone			soft cutout hard sitbone			hard cutout soft sitbone			hard cutout hard sitbone		
Participant 6	Pubic bone	Sit bone left	Sit bone right	Pubic bone	Sit bone left	Sit bone right	Pubic bone	Sit bone left	Sit bone right	Pubic bone	Sit bone left	Sit bone right	Pubic bone	Sit bone left	Sit bone right
Max. pressure [mbar]	416	488	475	400	444	460	397	490	485	456	440	456	440	525	550
Mean pressure [mbar]	136	124	103	160	166	166	131	133	137	160	144	140	145	150	180
Loaded area [mm2]	6300	4733	5125	6600	5345	5600	5900	5250	5300	6500	4489	4598	5900	4600	4685
Abs. maximum of force [N]	257			280			243			288			300		
Mean of total force [N]	215			255			210			230			255		
COP	106			100			114			98			105		
pressure devision front:back	53			50			48			44			50		
Displacement centre of pressure	diagonal			horizontal			horizontal			diagonal			diagonal		

Figure 102: Presure values participant 5 and 6

APPENDIX 19 ANGLE TEST

The scores on a 1 to 10 scale among the 10 participants.

	participant 1	participant 2	participant 3	participant 4	participant 5	participant 6	participant 7	participant 8	participant 9	participant 10	Average	Std. dev
65 degrees	8	9	9	8,5	8,5	9	8	9	8	9	8,6	0,46
70 degrees	8	8	7	8	9	9	7	8	9	8	8,1	0,74
75 degrees	9	9	8	7,5	8	8,5	8	8	8,5	8	8,3	0,49
80 degrees	7	8	6	5	6	6	7	6	5	6	6,2	0,92
85 degrees	4	6	5	4	4	3	4	4	4	3	4,1	0,88

Figure 97: Angle scores of 10 participants

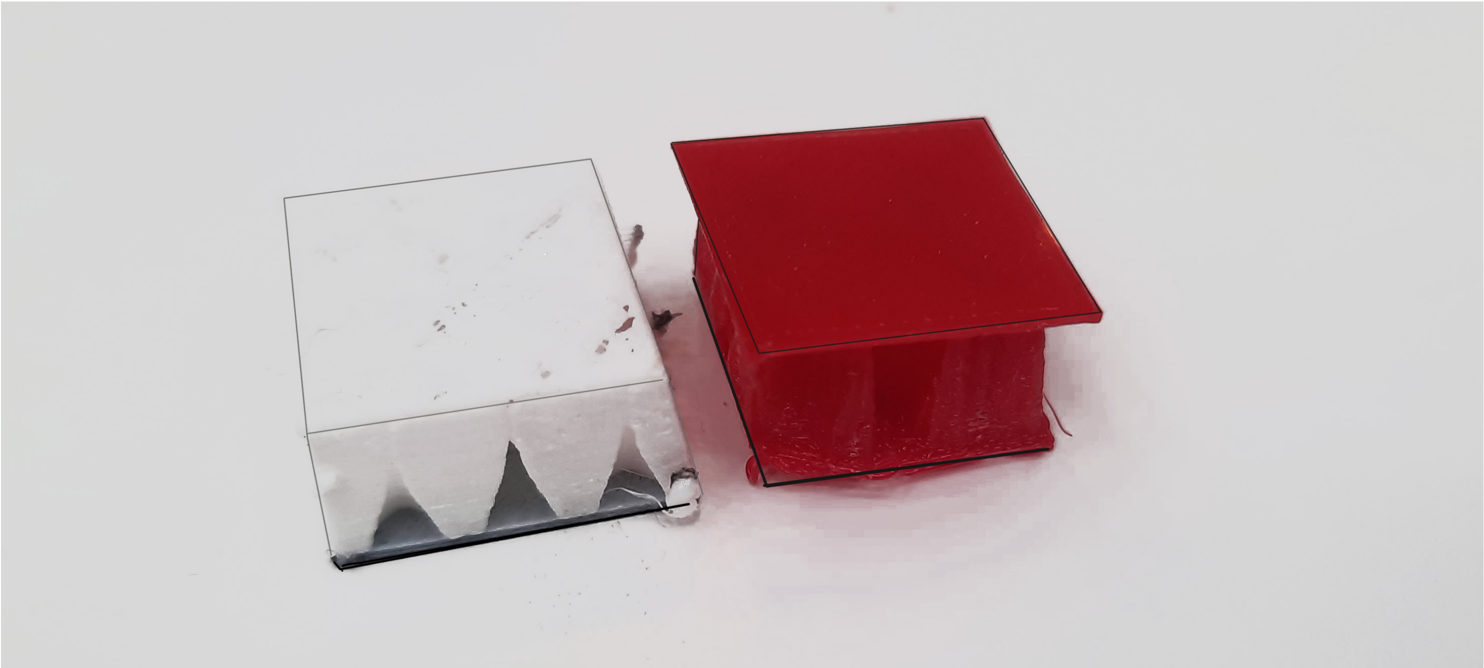
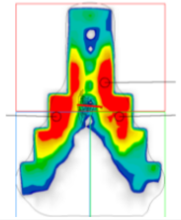
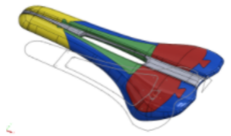


Figure 103: Test blocks, without the test frame

APPENDIX 20 PROTOTYPE OVERVIEW

prototype number	picture	test parameters	conclusions	recommendations/ improvements
1		• Working of printing material Varioshore • Printing quality	• Ductility can be tuned more than regular TPU • Printing quality can be further optimized	• Varioshore is a suitable material that can increase the ductility of TPU
2		• Sensitivity of the female body	• Sensitivity map of female sitting areas created • It can help saddle design to relieve sensitive areas	• Take the map into consideration when designing a females saddle
3		• Modular configuration for concept choice	• Saddle can be divided in modular parts • Brings some difficulties about where and how many zones can be identified	• Further research is needed on the placement of the parts and the edges of the modular parts
4		• Modular parts cut on a standard saddle type based on the sensitivity test	• This division is better than the one from prototype 3	• Sitbone area should be bigger • The nose of the saddle should be connected in a proper way
5		• PU foam was modified to explore the best female saddle shape. A short fit Griffon saddle was used as reference but with a smaller nose	• Smaller nose is perceived as more pleasant • The prototype however has some hard edges and that influences comfort questions	• A short fit Griffon could be a better fitting saddle for females
6		• First modular configuration is tested with form locking different modular parts 	• Edges on the saddle are moving while cycling • Edges are hard and influence te pressure maps • A unpleasant squared front pressure can be seen in the pressuremap	• A minimum amount of edges between modular parts prevents modular parts from moving • Printing without sidewalls is preferred because these hard edges influence the pressure division
7		• Can a rail lock the modular parts in place? 	• Hard rails can be felt, also in the middle (cutout) section of the saddle • It is harder to assemble compared to a velcro prototype	• A mechanism can be felt in the cutout section
8		• Can a puzzle mechanisme lock modular parts in place?	• Puzzle mechanism works intuitive • Assembling can be done in under 5 seconds (with velcro) • Nose is moving a lot while cycling • The edge between two different modular parts in ductility can be felt	• A standard width for nose can help the outer edge to completely lock of the modular parts • The edge should be optimized to make a smoother transition between two parts with different ductility

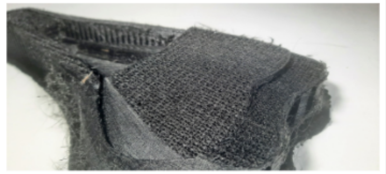
9		• Is a modular nose needed? • Which of the nose widths of 40 mm, 35mm and 30mm is preferred?	• All participants (3) preferred the smallest nose (30mm) • The current nose of the PRO Griffon seems to be too wide for females	• A standard nose is preferred because of construction of the modular parts • Further research for the optimal nose width should be done. This shape can be depending (of 'related to')on the saddle design
10		• Can the preferred selected angle of 75 degrees be assembled? • Does the angle prevent the modular parts from falling out?	• The angle clamps the modular parts in the outer shape • A small velcro strip would help for alliging	• A modular saddle with two sections, one for the sitbone area and another for the cutout is kept in position because of the outer ring. • A angle of 75 degrees and a small velcro strip is keeping (can keep) the elements in position
11		• Do female test persons feel the difference between this and its original? • Do different test persons select different configurations? • Is this dependent on weight?	• For 5/6 participants, looking only at the pressure values, a more optimal saddle than the original PRO Griffon can be assembled. • Participants have different modular configurations that give the best results in the score and on the pressure maps. • It seems that body weight can influence the preferred ductility.	• Further research could be done on how many shape variations are needed to suit the target group. • For a more representative outcome, a bigger group with different ages, different fat percentages and different weights should be tested.

Figure 104: Prototype overview

APPENDIX 21 COMPETITOR PRODUCTS

Pricing comparison for female-specific saddles of the four biggest competitors. Bontrager doesn't have specific female saddles. In blue can be seen that 3D printed saddles are quite expensive. In general, the price of saddles is highly dependent on their weight.

Model	price (€)	weight (grams)
Fizik tempo argo women	65	300
Fizik Luce women	80	250
Fizik Antares printed saddle	400	160
Fizik Tempo Argo women	150	230
Specialized Power Comp Mimic women	120	223
Specialized Romin Comp Mimic women	120	N/A
Specialized Phenom Comp Mimic women	120	N/A
Specialized Power printed saddle	380	200
Bontrager Aeolus Comp Saddle	82	330
Bontrager Verse	100	300
Bontrager Arvada compe	50	300
Selle Italia superflow women	200	210
Selle italia Diva women	120	220
Selle italia Donna women	50	350
Selle italia Novus women	120	250

Figure 105: Pricing competitor products

APPENDIX 22 BIBSHORT ANALYSIS

Bibshorts were compared to each other to see what the influence of bib short can do on the pressure division on the saddle. As can be seen below, 4 different bib shorts padding show big differences in the pressure division. Testing people with the same bib short therefore is something to keep in mind for further testing.

	evolve blue	vermarc PRR	evolve black old	tenku black
Max pressure pubic bone	491	493	363	450
max pressure sit bone left	501	350	307	328
max pressure sit bone right	438	229	298	220
mean pressure pubic bone	166	180	127	165
mean pressure sit bone left	120	102	116	99
mean pressure sit bone right	86	51	86	51
loaded area pubic bone	6475	6575	6450	6675
loaded area sit bone left	5375	4775	5900	4225
loaded area sit bone right	6025	4300	5800	3850
front rear devision	62	70	56	69
left right devision	58	67	57	66
angle pressure	22	47	1	41
maximum force	302	238	304	246
mean force	212	183	220	202

Figure 106: Bibshort comparison

Figure 107: Shimano padding