Cyclist Mannequin

For Aerodynamics Research

MSc Integrated Product Design - Thesis by Siward Vloemans - July 2022

TUDelft KEEP CHALLENGING FIELDLAB UPPS

Project Title
Develop a cyclist mannequin from 3D scans for aerodynamics tests.

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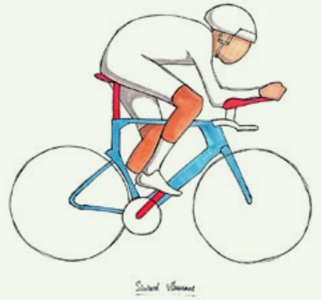

Acknowledgements

My master thesis for Integrated Product Design was an individual project, but it would not have been possible without the support of a helpful group of people.

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Third, I would like to thank *Joris van Tubergen* for his time, expertise and motivating conversations with me. I am grateful to the PMB staff, specifically *Don van Eeden, Wiebe Draijer & Roland van der Velden*, for their invaluable support building the full-scale mannequin.

Furthermore, I would like to thank *Harm Ubbens* for providing an insight into professional cycling. I am also grateful to *Wouter Terra* for providing an insight into aerodynamics research. Thanks to both for a challenging thesis assignment.

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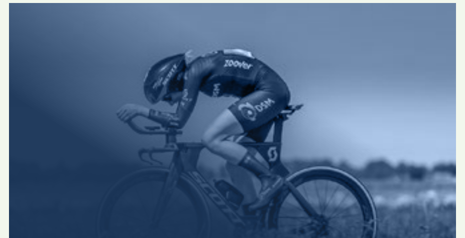
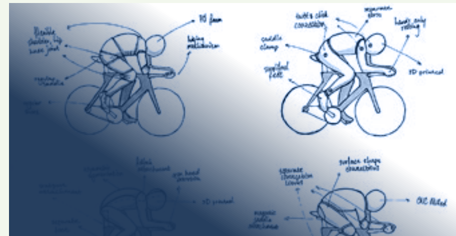
Table of Content





Summary

The aim of this research is to increase the speed of cyclists by reducing aerodynamic drag. Common research methods are digital and physical simulations. The goal is this project is to develop an anthropometric model for each method based on professional cyclists from Team DSM.

Digital Model (Generic)
The first goal of this research is to create a generic cyclist model for research organisations around the world. The Generic Model is an average of ten male, professional cyclists in both road and time trial pose (Figure 0.1). The DINED Mannequin approach is used to divide the method into four steps: Capture, Process, Correspond & Average.

All participants are captured on-site on personal bicycles with two handheld Artec Eva 3D scanners. The 3D scanned data is processed in Artec Studio 12 to correct for movement and unwanted elements captured during 3D scanning. The processed model is corresponded in R3DS Wrap3 with a reference base mesh template to make them interpretable and to patch missing data. The corresponding models are averaged in Paraview to generate the Generic Model.

The Generic Model stays true to the original anthropometric data of the participants where possible. However, exceptions are made where beneficial to the result. The participants are captured in the high-drag leg position with the hands separated. Shoes are digitally removed from the model. Hands, elbows and inner legs are standardizations because these sections are blocked by the bicycle. The base mesh has a resolution of 50K uniform, smoothened triangle polygons.

Figure 0.1: Generic Model of ten male, professional cyclists in time trial pose.

Physical Mannequin (Personalized)
The second goal of this research is to design a personalized cyclist mannequin for aerodynamics researchers. The Personalized Mannequin is the physical representation of an individual cyclist's anthropometry in time trial pose (Figure 0.2). The Centre of Design for Advanced Manufacturing Approach is used to divide the process into four steps: Digitalization, Design Automation, Digital Fabrication & Production.

The 3D anthropometric data of one of the riders captured for the Generic Model is used. Requirements for the mannequin are parametrically defined and partially applied in Grasshopper (automated) and fully applied in Blender (manually). A full-scale model of the mannequin is digitally fabricated using FDM 3D printing. Loose parts are joined, sanded, finished and assembled to complete the prototype.

The requirements and design are the result of an analysis phase where users, context, interactions and competitors are researched. The creative phase structures and clusters challenges and generates solutions to them. The development phase continues with the selected concept and researches individual design features. The final design is prototyped and validated and any recommendations are made last.

Rupert the Personalized Mannequin is CNC milled from rigid polyurethane foam. It is segmented near the wrists, upper arms and upper legs to apply any cycling gear. SLS 3D Printed magnetic, form-fitting interfaces attach the limbs. Rupert is mounted to the bicycle on a regular saddle, with cycling shoes to the pedals and with flexible hands to the handlebar. Rupert has the same surface resolution as the Generic Model.

Figure 0.2: Personalized Mannequin of an individual male, professional cyclist in time trial pose.

"Around the last left hander with 300 metres to go. Cavendish hits the front, Ewan on his wheel, Girmay threatening down the middle. Cavendish and Ewan, Ewan hitting the front now and Démare down the middle. It's close between those three.

Oh, that was tight! Oh, that was tight! Démare, Ewan, maybe just Ewan. Hard to tell, it is a photo finish between those two."

Commentator Matt Stephens about Giro d'Italia 2022 Stage 6

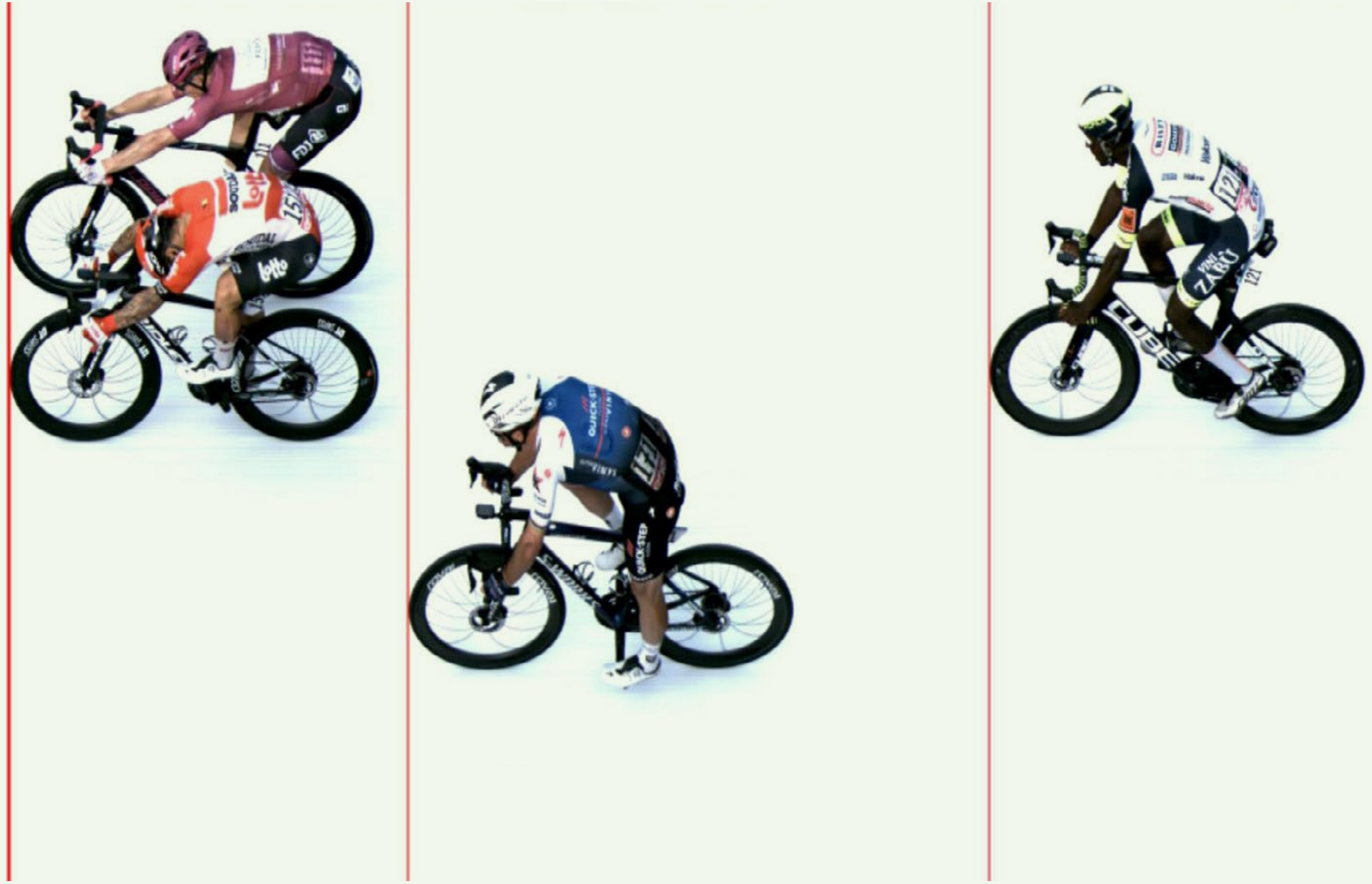


Figure 0.3: Cash, D. (2022). [Photograph of cycling photo finish during Giro d'Italia 2022].

1. Introduction

1.1 Cycling Aerodynamics

"Cycling races are sometimes won by time differences of fractions of a second or a few centimetres. For instance, Primož Roglič won the 2019 Tirreno-Adriatico, a seven-day race, with only 0.31 s advantage to Adam Yates. Kristina Vogel won the gold medal in the track cycling sprint competition of the Rio 2016 Olympic Games with only 0.016 s and 0.004 s ahead of Becky James, in race 1 and 2, respectively. LeMond won the 1989 Tour De France in 87h38m35s, only 8 s ahead of Fignon." (Malizia, 2021).

It is clear that professional cycling is truly about marginal gains considering the small differences on the finish line. As an endurance sport at high speeds, small factors have a large influence. Where the cycling industry was previously minimizing weight of the riders, bicycles and gear, cycling aerodynamics are seeing an increased interest in the last decades. "Aerodynamic drag is the main resistive force a cyclist has to overcome, accounting for up to 90%." (Grappe et al., 1997).

Since aerodynamic optimalization has become a focus point in cycling, the designs of bicycles and equipment have rapidly evolved. The most influential factor on cycling aerodynamics is the rider and his kit, as the bicycle itself is only responsible for about 30% of the total cyclist-bicycle drag area (García-Lopéz et al., 2008). It is the reason all cycling garments are skin-tight and why some gear takes the strangest shapes.

The International Cyclist Union (UCI) follows the development with appropriate regulations, banning dangerous methods from competition. All of this gear has been specifically designed for aerodynamic performance and tested accordingly (Figure 1.1). Aerodynamic research is conducted in a variety of methods by bicycle manufacturers, research institutes and cycling teams alike.

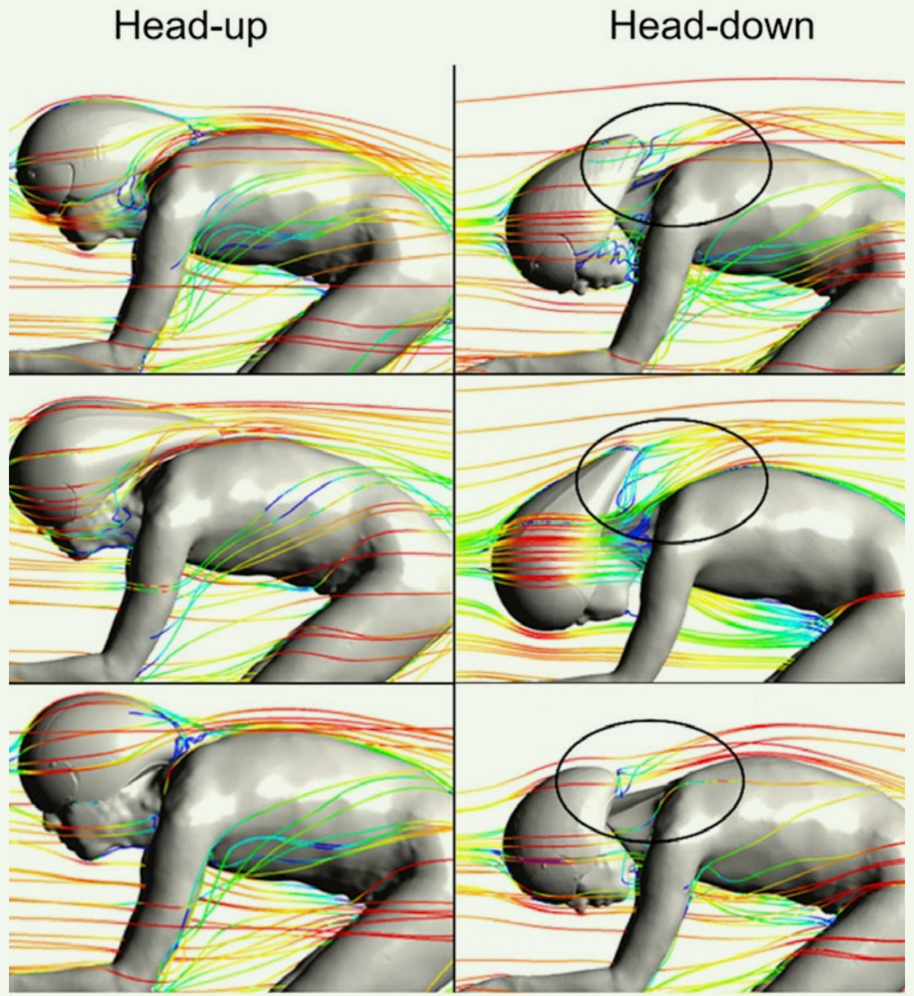


Figure 1.1: Beaumont et al., (2018). [Velocity coloured streamlines for three helmets in two different head positions].

1.2 Problem Definition

Research institutes, bicycle manufacturers and cycling teams are investing in aerodynamics. It is the most influencing factor to increase speed. The most effective methods are digital and physical simulations. Currently, all parties use different cyclist models in their simulations. These are often personalized models of a 3D scanned rider. Because they are all different, research results are not directly comparable. A Generic Model is the solution to create comparable experiments. It generates more knowledge of cycling aerodynamics by setting a benchmark for all research.

Verification and validation address the concern that a model is accurate, as they are only approximate imitations of the real world. A mannequin is the physical form of a cyclist model and may be used to substantiate that the computerized model is accurate for its intended application (Sargent, 2011). Cycling mannequins are used in wind tunnels that accurately simulate air flow in the real world, vitally important to the wind energy group for analysing purposes (TU Delft, n.d.). Live cyclists are unable to function as the model subject to produce the desired results. A Personalized Mannequin is the solution to eliminate movement and other variables. The goal is this project is to develop an anthropometric model for digital and physical simulations based on professional cyclists from Team DSM.

For the original Project Brief, refer to Appendix 1.

Digital Model (Generic)
Digital cyclist models are used in numerical simulations (Figure 1.2). The first goal of this research is to create a generic cyclist model for research organisations around the world. The model is generated by averaging body geometries that are 3D scanned in this project. As cyclist models are personalized, they provide insights applied to a specific rider. Unfortunately, that means the insights are not directly comparable to other research and it becomes difficult to relate findings. The model must stay true to original anthropometric data and providing an accurate representation of it.

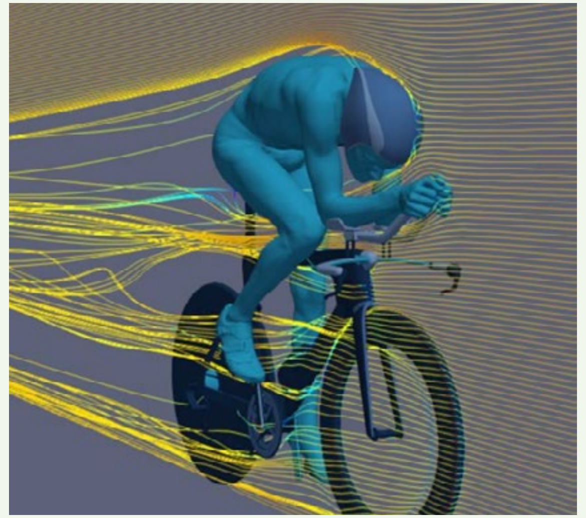


Figure 1.2: Terra, W. (n.d.). [Visualisation of air flow around cyclist model].

Physical Mannequin (Personalized)
Physical cyclist mannequins are used in wind tunnel simulations (Figure 1.3). The second goal of this research is to design a personalized cyclist mannequin for aerodynamics researchers. "In the last five years it has become common practise to use cyclist mannequins in wind tunnels." (Terra, 2021). The cyclist mannequin is a proven concept, but requires user interaction features to become a refined product. It must take multiple rider positions and host interactions such as dressing, mounting and detaching. Material selection and fabrication method are also essential elements in the design of such a personalized product.

Figure 1.3: Terra, W. (2018). [Photograph of cyclist mannequin in wind tunnel].

1.3 Stakeholders

Team DSM – Harm Ubbens
Professional cycling Team DSM is a client in this project. Harm Ubbens is Team DSM's aerodynamics expert. The team was previously involved in the development of the Dumoulin Mannequin and is now looking to develop the product. Team DSM supports this project with a budget for the Personalized Mannequin. All riders 3D scanned in this project are supplied by them.

Figure 1.4: Team DSM. (n.d.). [Logo of Team DSM].

Wouter Terra
Wouter Terra is also a client in this project. He is NOC*NSF's embedded scientist aerodynamics from TU Delft. Terra received his PhD for Particle Image Velocimetry (PIV) research in the wind tunnel and is now looking to develop a broadly applicable cyclist model. He was previously involved in the development of the Dumoulin Mannequin. Wouter Terra supports this project with a budget for the Generic Model. All contact with Monash University is also managed by him.

Monash University
Frequently collaborating with the Australian Cycling Federation, Monash University is working with Wouter Terra to research cycling aerodynamics. Monash has a research group with access to 3D scanned track cyclist geometry and is working in parallel with this project to generate a Generic Model. The research group supports this project by sharing knowledge about the model and by performing aerodynamic validation when it is done.

Fieldlab UPPS
As an Ultra Personalized Product and Service, the cycling mannequin project is connected to Fieldlab UPPS. The Fieldlab supports this project with a budget for the Personalized Mannequin prototype. An assistant hired to process the 3D scans for the Generic Model by Fieldlab UPPS as well.

Figure 1.5: Fieldlab UPPS. (n.d.). [Logo of Fieldlab UPPS].

Bertus Naagen
Bertus Naagen manages the Body Lab at the faculty of Industrial Design Engineering and is the expert involved in 3D scanning all the riders.

Lies Keijser
Lies Keijser is an Integrated Product Design graduate hired by Fieldlab UPPS to perform Digital Human Modelling work on the Generic Model during this project.

Model Making Machine Lab
The PMB, or Model Making Machine Lab, is the workshop at the faculty of Industrial Design Engineering where the Personalized Mannequin is produced.

Joris van Tubergen
Joris van Tubergen is an expert in FDM 3D printing on a large scale and was previously involved in the development of the Dumoulin Mannequin.

1. Introduction

1.4 Report Structure

This report consists of seven chapters in total: Introduction, Analysis, Generic Model, Personalized Mannequin, Conclusion, Sources & Appendix. This is the last page of the first chapter Introduction. The last chapter is the Appendix. A visual overview of the report is described in the Table of Content on page four.

Chapter 1: Introduction opens the report by explaining the topic of cycling aerodynamics and this is the last page of the chapter. Chapter 2: Analysis is the first chapter to discuss content of this project being the research phase. It describes the Context, Product & Competitors and dives deeper into the Dumoulin Mannequin, the predecessor of this project.

The body of this report is chapter 3: Generic Model and chapter 4: Personalized Mannequin. They are structured similarly, showing the design result first and then elaborating on the method used. The Personalized Mannequin is discussed more extensively by following up with chapters about its Development, Design Features and Validation of its design.

Chapter 5: Conclusion starts by giving Recommendations based on results of the Validation chapter. The report is rounded up by giving an Overall Conclusion. Chapter 6: Sources describes all references made in the report. Chapter 7: Appendix includes any extra content not directly discussed in the report. It is the last chapter in this report.

1. Introduction

2. Analysis

3. Generic Model

4. Personalized Mannequin

5. Conclusion

6. Sources

7. Appendix

2. Analysis

2. Analysis

2.1 Context

Open Jet Facility visit and interview with TU Delft's PhD aerodynamics expert Wouter Terra on Monday 21-02-2022.

What is the OJF?
The Open Jet Facility (OJF) is a low-speed wind tunnel at the faculty of Aerospace Engineering at TU Delft. It is an impressive facility situated in a large room of 13 meters in width and 8 meters in height, able to handle very large models that obstruct airflow considerably (Figure 2.1).

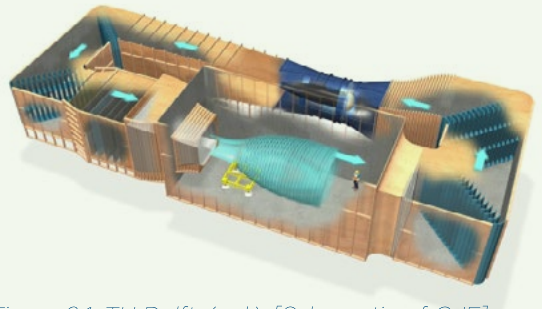


Figure 2.1: TU Delft. (n.d.). [Schematic of OJF].

Why to use the OJF?
For some purposes such as testing with large objects, a large wind tunnel is required. There is no other wind tunnel this size in Delft. Such tunnels are suitable for objects with up to 5% of its test section surface size (0,4 m2).

A wind tunnel can simulate reality, but allows to test in controlled conditions. In this way, research is repeatable by accurately describing conditions.

How to use the OJF?
The facility itself is a wind tunnel and only that. This means you can only influence wind speed. Temperature and other factors are negligible. To test air resistance of a rider or any other values, an additional setup is required.

Drag of a cyclist is measured using a special scale developed by the Netherlands Aerospace Centre. Any such setups are placed on the platform, lowered flush to 'ground level'. Bicycles are typically fixed with a connected stand. The scale measures the effect of wind on the bicycle and rider. It automatically calculates the air resistance.

The bicycle may face straight into the orifice to simulate head winds (Figure 2.2), but it may also be rotated to simulate side winds. Winds speeds typically reach up to around 50 km/h. The bicycle-rider setup may wobble at such speeds, so the mannequin must be attached firmly.

Measurements in the OJF wind tunnel are never 100% accurate. Wouter typically repeats measurements five times to gain accurate results.

How is PIV applied in the OJF?
Particle Image Velocimetry (PIV) is an age-old technique, but only until recently applied in cyclist aerodynamics research. It requires thousands of tiny 'weightless' bubbles to capture air flow. The development of such enabling devices was the bottleneck in this process. The bubbles must

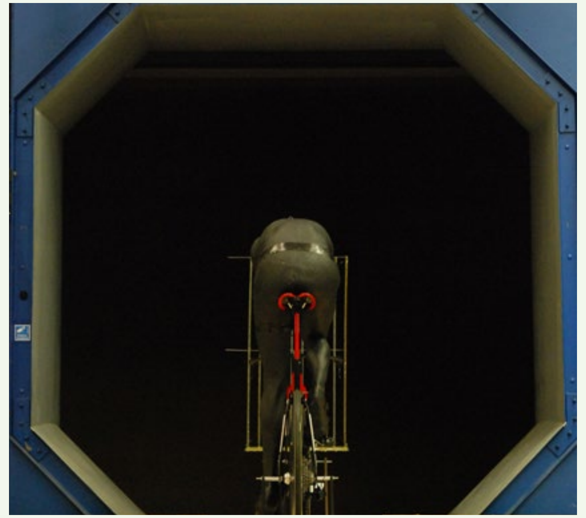


Figure 2.2: Terra, W. (2018). [Photograph of Dumoulin Mannequin in Open Jet Facility].

reflect light created by a laser in order to be captured by cameras. In turn, the mannequin must absorb light not to hinder the cameras. It is therefore preferably coloured matte black.

Since the development has progressed, PIV is seeing increasing application in cyclist aerodynamics research. It is able to not only measure performance, but to explain it too. However, PIV is expensive so traditional wind tunnel testing is still the norm.

Repeatability in the OJF?
To perform comparable measurements, a test setup must be repeatable. Wind tunnels sometimes feature a green screen with cameras capturing the test subject. It allows visual adjustment of the subject. The OJF uses cameras installed in the ceiling and markers on the subject to accurately calibrate the setup.

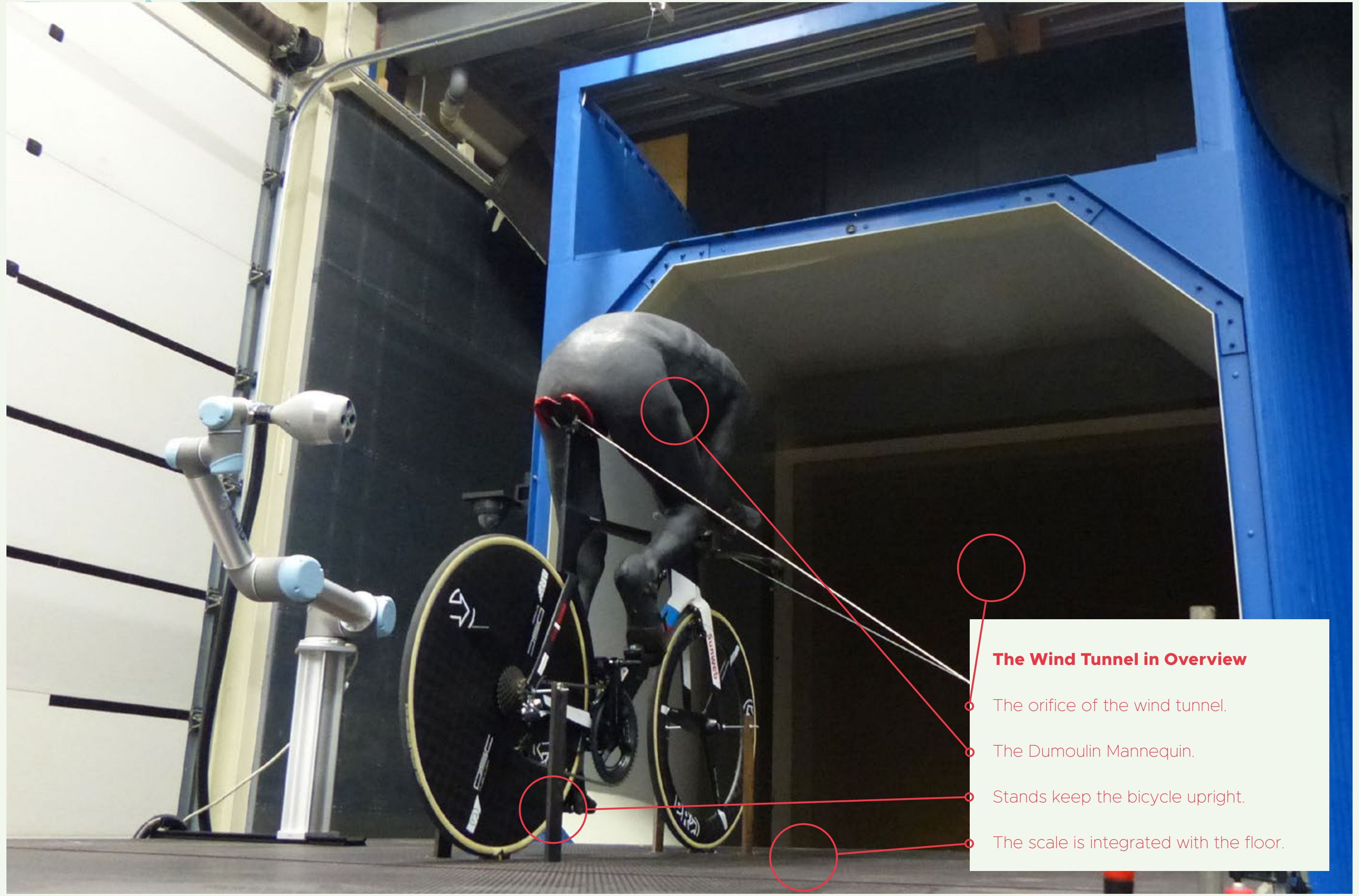


Figure 2.3: Terra, W. (2018). [Photograph of Dumoulin Mannequin in Open Jet Facility with annotations].

2.2 Product

Team DSM facility visit and interview with Team DSM's aerodynamics expert Harm Ubbens on Wednesday 10-02-2022.

Position
The mannequin serves as the replacement subject of the rider. It is used only to test rider and bicycle equipment, such as helmets, suits and wheels. It is not used to test body poses. However, it is required that the mannequin can be used on both a time trial (Figure 2.7) and a road bike (Figure 2.8) in corresponding poses. The mannequin principally requires no movement on the body in joints or limbs. It would be valuable if it were able to pedal (motorized), but that is no deal-breaking requirement. Generally speaking: the more moving parts, the less stable the mannequin and the less accurate the measurements.

Attachment
The mannequin must be rigid and stable on the bicycle, but practical in use. It must therefore utilize the three primary body attachment points to the bike: feet to pedals, bottom to saddle and hands to handlebar. The elbows also rest on the handlebar in time trial position (Figure 2.4). The saddle is the most important attachment point, as it carries the most weight. It is also the most challenging point, as the legs are close together and cycling shorts have a cushion (Figure 2.5). The cleats on cycling shoes could be used to attach to pedals (Figure 2.6). The hands are more challenging and cycling gloves are therefore avoided with these mannequins.

Limbs
A cycling mannequin consists of multiple pieces because of practical reasons in handling. It must be stored, transported and most importantly dressed. A cycling suit is made in one piece, so it is not easily applied. Generally, the legs and arms are separate from the torso and sometimes the head too. The mannequin model is preferably 'nude', so it can be tested with all sorts of apparel. As the mannequin must be unmounted from the bicycle and its limbs detached for every outfit, a quick and easy interaction is required.

Figure 2.4: The Dumoulin Mannequin's hands are placed around the handlebars.

Figure 2.5: The Dumoulin Mannequin has a small contact area with the saddle.

Figure 2.6: The Dumoulin Mannequin's feet are not easily attached to the pedals.

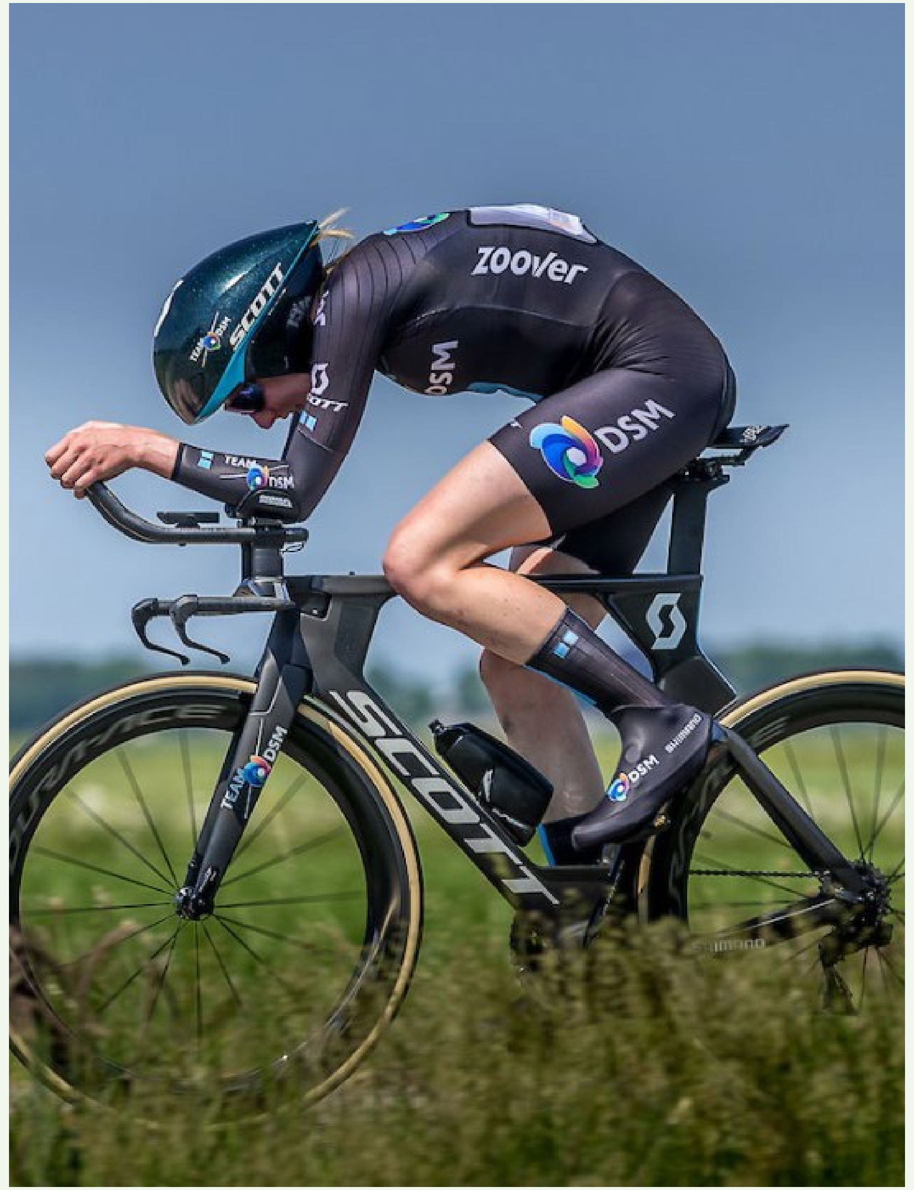


Figure 2.7: Sportfoto. (2021). [Photograph of cyclist Esmee Peperkamp on time trial bike].

Figure 2.8: Scott. (2021). [Photograph of Team DSM cyclist on road bike].

2. Analysis

2.3 Competitors

Personalized cycling mannequins are modern tools seeing increasing popularity. In recent years, a few mannequins have been modelled after professional riders. This competitor analysis provides an overview of personalized cycling mannequins and their specifications. The goal is to learn from the competitors, applying successful features and improving where possible. Desk research is performed to make the analysis and all sources are mentioned in the overview (Figure 2.11).

Professional Cyclist Mannequins

The overview of personalized mannequins based on a professional cyclist shows a development in the past decade and a variety of product features. The mannequins mostly vary in terms of fabrication method and special features. All except one example are in private ownership.

Other Cyclist Mannequins

Vorteq and Voxdale show a development into commercial application and fully articulating limbs. As recent innovations, these examples serve as the most relevant competitors to this project. The Vorteq and Voxdale mannequins are briefly described in the following section. The Dumoulin Mannequin is an older example created and used by the case owners of this project. The mannequin is accessed in this project and described more extensively on the following pages.

Figure 2.9: SSEH. (n.d.). [Photograph of static cyclist mannequin in wind tunnel].

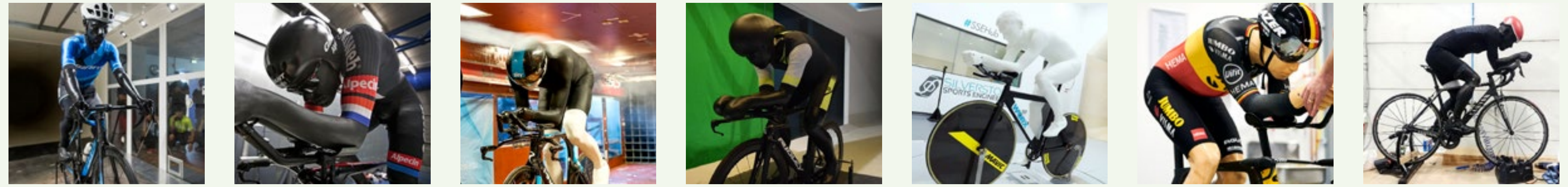
Figure 2.10: Garimella, R. (2020). [Photograph of articulating cyclist mannequin].

Vorteq

Since 2018, Vorteq is the only company to commercially produce personalized cyclist mannequins (Figure 2.9). Based in Silverstone Sports Engineering Hub, Vorteq has access to an open-jet, closed-end wind tunnel. With 12 Raise 3D Pro printers, they are able to fabricate mannequins within 24 hours. Mannequins are available in three configurations with different features (Vorteq, n.d.).

Voxdale

In 2020, Raman Garimella published a scientific report about the development of an articulating, personalized cycling mannequin (Figure 2.10). Working together with the University of Antwerp and TU Delft, an elite cyclist was 3D scanned and processed. The 3D model features both road and time trial bicycle poses. The mannequin features articulating limbs to realize the 360° pedal stroke (Garimella et al, 2020).



Rider	Grischa Niermann	Tom Dumoulin	Chris Froome	Tony Martin	Anyone	Van Aert & Roglic	Elite cyclist
Organisation	Giant Bicycles	TU Delft	TU Norway	Bike Valley	Vorteq	TU Eindhoven	Voxdale
Year	2010	2016	2017	2017	Since 2018	2020	2020
Fabrication	FDM 3D Printing	FDM 3D Printing	FDM 3D Printing	CNC Milling	FDM 3D Printing	Gel casting	FDM 3D Printing
Features	Articulating limbs Multiple positions	Resolution	White colour	Fibreglass layer Knee joint	Magnetic limbs Disc joints	Smooth coating Skin colour	Articulating limbs
Hands	Open hands	Open hands	None	Rounded	Bolted hands	Closed hands	Open hands
Feet	Cycling shoes	Integrated shoes	Integrated shoes	Custom mount	Cycling shoes	Cycling shoes	Cycling shoes
Saddle	Custom mount	Regular saddle	Regular saddle	Regular saddle	Custom mount	Regular saddle	Custom mount
Source	Giant Bicycles, n.d.	TU Delft, 2016	Norwegian SciTech News, 2017	Cycling Weekly, 2017	Silverstone Sports Engineering Hub, 2020	Team Jumbo-Visma, 2021	Garimella et al, 2020

Figure 2.11: Overview of competitor personalized cycling mannequins and their features.

2.4 Dumoulin Mannequin

The Dumoulin Mannequin description and evaluation is based on interviews with Team DSM's aerodynamics expert Harm Ubbens on Wednesday 10-02-2022 and TU Delft's PhD aerodynamics expert Wouter Terra on Monday 21-02-2022.

Description

A life-size mannequin of Tom Dumoulin (Figure 2.12) is created in 2016 as part of a research by the TU Delft Sports Engineering Institute. The mannequin allows unlimited access to an athlete's geometry in order to conduct extensive wind tunnel tests. The Dumoulin Mannequin is used to develop a time trial suit and has been a valuable tool for cycling Team DSM. It is one of the first personalized cycling mannequins in the world and only a handful have followed since.

Tom Dumoulin is professionally scanned by Th3rd in a scan studio with 130 DSLR cameras. The studio captures humans in high resolution in a second. Th3rd processed the digital model. The mannequin is designed and made by IDE students in four months. The 3D printing method is chosen deliberately to research its large-scale capabilities.

Features

- High resolution model and smooth surface.
- Matte black colour for PIV testing.
- Limbs connect with nuts and bolts.
- The 3D printed shoes attach to pedal cleats.

Figure 2.12: Vos, C. (2016). [Dumoulin Mannequin in Open Jet Facility].

Interaction Scenario

Harm Ubbens performs the interaction of assembling and mounting the Dumoulin Mannequin to a bicycle. The interaction is always involved multiple times when testing with the mannequin.

Figure 2.13: The bicycle is easily installed in a fixed stand.

Figure 2.14: The suit is most challenging to handle and has to be applied first.

Figure 2.15: Some connection points are broken, so duct tape is used as an alternative.

Figure 2.16: The Dumoulin Mannequin's hands are placed around the handlebars.

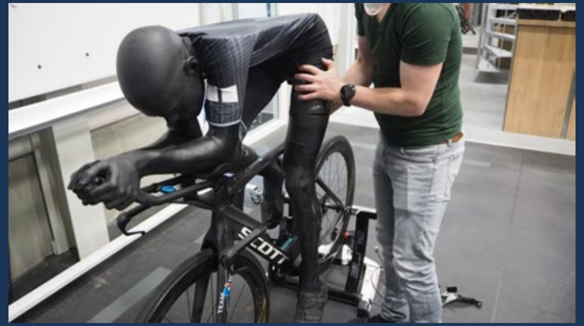


Figure 2.17: The legs are attached to the body, but do not actually connect to the pedals.

Figure 2.18: Limbs are manually secured to the torso with integrated nuts and bolts.

Figure 2.19: The back is added last after all limbs are secured.

Figure 2.20: The mannequin now rests on the bicycle in four places.

User Evaluation
Since the research project by TU Delft, the Dumoulin Mannequin served for about five research sessions by Team DSM from 2016-2022. The mannequin is discussed during interviews with Harm Ubbens and Wouter Terra. Both used the mannequin in the wind tunnel and provide feedback based on personal experiences to improve its design. The results are clustered and listed below.

Overall
- The mannequin has produced great test results.
- It has proven a useful tool in aerodynamics research.
- It has a good level of detail, but lacks in engineering and user interaction.

Apply cycling gear
- The shoes are 3D printed with the body.
- Cycling suits are difficult to apply and the fragile zippers sometimes break.
- Some believe that tight, aerodynamic suits stretch over time and become useless. Easy application is essential.

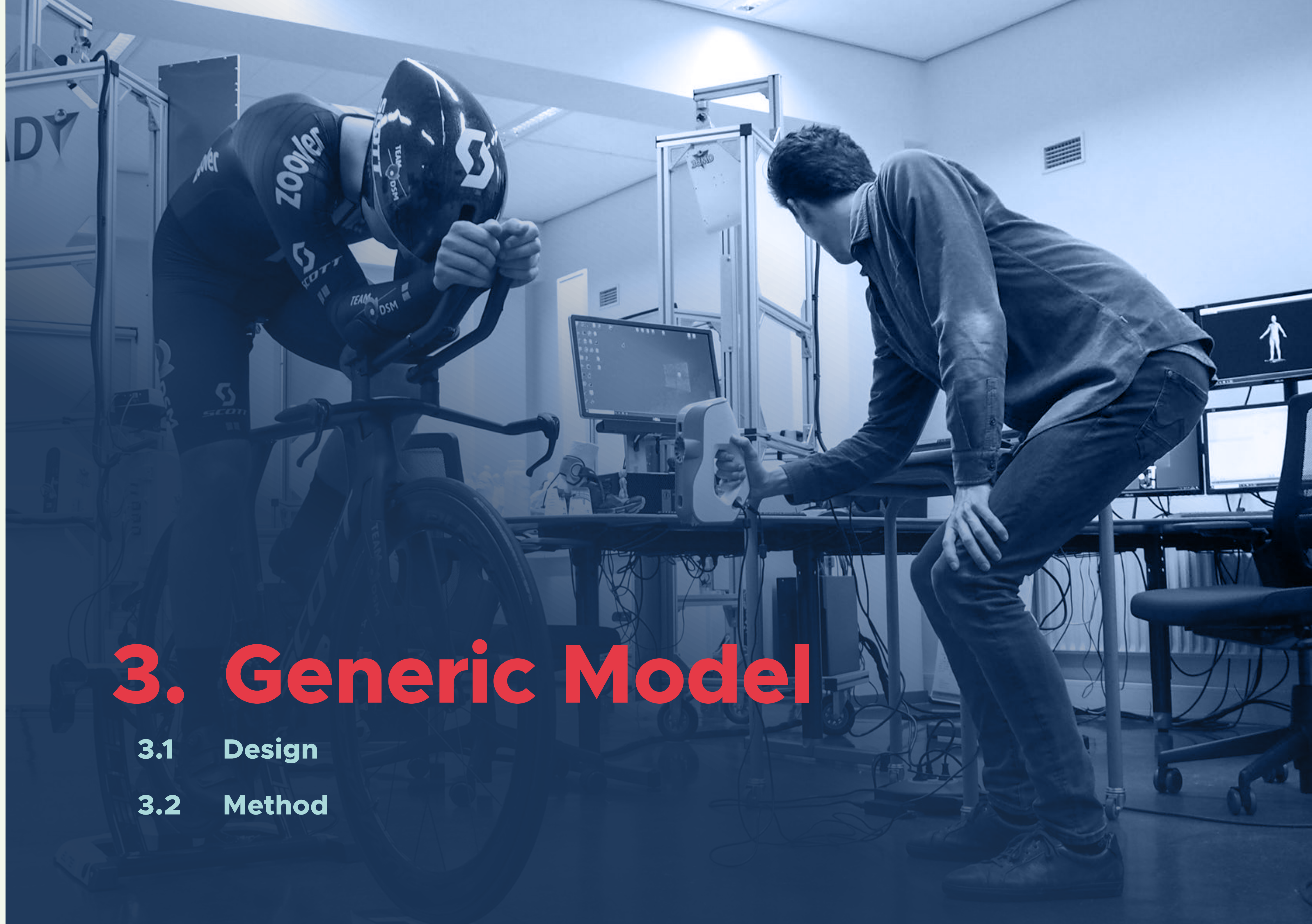
Connect limbs
- Connection pieces are broken (Figure 2.21).
- Difficult to connect with nuts and bolts (Figure 2.22).
- Mannequin configuration is challenging to restore as joints allow rotation.

Mount to bicycle
- Due to its stiffness, the mannequin can only mount to the bike in a single configuration. It is difficult to mount, but easy to reproduce.
- During the first use-case, the model fit well with the bicycle. It mounted to the pedals using cleats.
- During later use-cases, the model did not fit correctly with the bicycle. Bicycle configuration may have changed and could not be restored.
- Attached to the bicycle with tie-wraps.

Durability
- The mannequin may have deformed during storage in a hot environment (40°C). One leg seems to be twisted.
- A storage solution would be useful.
- It is now at the end of its life and has become too fragile.

Figure 2.21: Elements connecting limbs have become too fragile and duct tape is used instead.

Figure 2.22: Limbs are connected to the torso using nuts and bolts, the back piece is attached last.



3. Generic Model

3. Generic Model

3.1 Design

The first goal of this research is to create a generic cyclist model for research organisations around the world. The Generic Model represents a population of professional road cyclists to replace personalized models in aerodynamics research. It is generated from 3D scanned anthropometric data of ten male road cyclists from Team DSM. The Generic Model is as realistic as possible, although some modifications are used to improve its quality. Environmental elements and double surfaces are removed from the 3D scan. Standardizations are applied to the hands, elbows and inner legs to compensate for missing data. The base mesh has a resolution of 50K uniform, triangle polygons and is smoothened to eliminate noise.

The Generic Model is of value in digital simulations in the research of cycling aerodynamics. It generates knowledge not only applicable to an individual, but to the whole professional cycling population. The model is going to be shared publicly, so anyone has access to it. Research becomes directly comparable when several parties use the Generic Model in their simulations. It generates more knowledge of cycling aerodynamics by setting a benchmark for all research.

Standardization
Hands accurately standardized.
Shoes replaced with bare feet.
Bicycle mounts digitally removed.

Position
High-drag leg position.
Aerodynamic competition pose.
Hands separated on time trial bars.

Resolution
High resolution mesh.
Uniform, triangle polygons.
Smoothened surface eliminates noise.

Procedure
Wearing Team DSM cycling kit during 3D scan.
Wearing head cap instead of helmet.
3D Scanned on personal bicycle.

The Model In Six Questions

Who?
Sports aerodynamics expert Wouter Terra and other aerodynamics researchers & institutes.

What?
Using a generic cyclist model for aerodynamics research to compare cycling gear for both rider and bicycle.

Where?
In digital simulation software used worldwide.

When?
During the digital simulation phase of aerodynamics research projects.

Why?
First, to generate comparable results between different researchers by eliminating a variable.
Second, to generate representative results for a larger population.

How?
A personalized cyclist model is replaced by a generic cyclist model during aerodynamics simulations.

3.2 Method

Based on the DINED Mannequin (Huysmans et al, 2020), the method for the Generic Model is divided in four sections: Capture, Process, Correspond & Average. Additionally, a base mesh is required as input to the corresponding workflow. The last two sections of the method are iterative, removing reference bias by continuously iterating on the base mesh. The workflow is based on an interview with Toon Huysmans included in Appendix 3.2. Work on the Generic Model is performed in collaboration with Monash University. The workflow is improved several times in discussion with the research group working with anthropometric data of Australian track cyclists. The goal is to eventually combine the work and to publish about generation and validation of the Generic Model together.

Dataset

Ten professional male cyclists of Team DSM are 3D scanned in this project. The group includes riders from six nationalities and varying cycling expertise: General Classification, Sprinters, Time Trialists, Punchers and Classics. All participants are captured in road, time trial and standing pose.

Mean age: 19.7 years
Mean height: 182.0 cm
Mean mass: 71.0 kg

Figure 3.1: Capturing rider using 3D scanner.

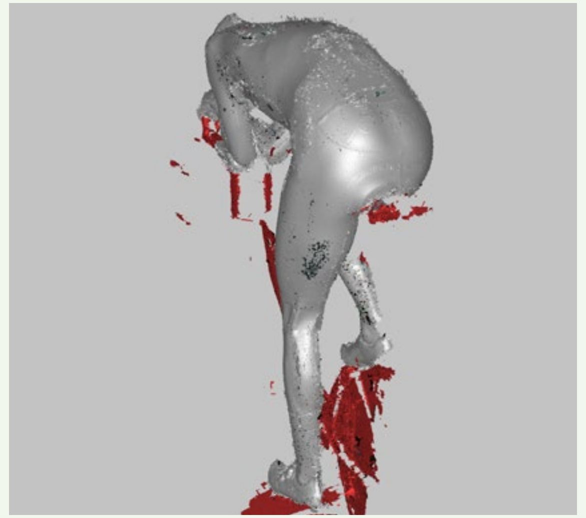


Figure 3.2: Processing model in Artec Studio 12.

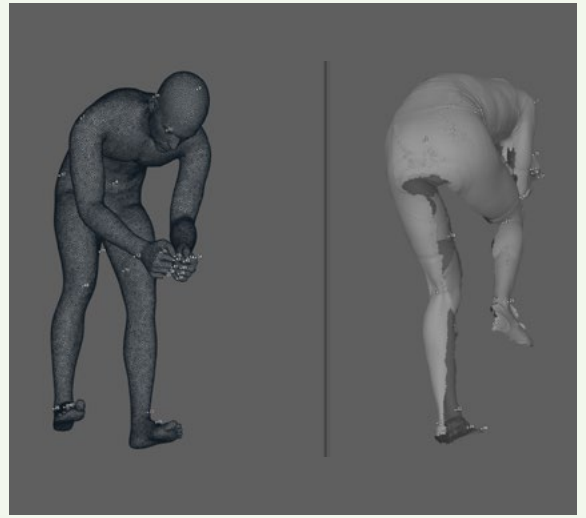


Figure 3.3: Corresponding model in R3DS Wrap.

Figure 3.4: Averaging model in Paraview.

Capture
The riders are 3D scanned to capture their anthropometric data. All participants in this research are captured on site, so portable handheld Artec Eva 3D scanners are used (Figure 3.1). Captured data is only a random collection of points and must be processed before it is usable.

Process
The captured data is processed in Artec Studio 12 (Figure 3.2). Any unwanted elements such as the bicycle are erased. Scan sections are aligned and excess information is removed. All points are fused into a single model.

Correspond
The processed data is corresponded in R3DS Wrap3 (Figure 3.3). A base mesh template is used to make the model interpretable. It is applied to the model by pairing landmarks to a template. The base mesh replaces any missing data and gives the model a smooth surface.

Average
The corresponding models are averaged in Paraview (Figure 3.4). A mean average is calculated based on the mesh applied to the models. The average model is also smoothened to compensate for inaccuracies.

Research Ethics

Due to the highly personal data acquired during this research, data protection is a priority. The research proposal is approved by the Ethical Committee of the TU Delft. The participants are given full disclosure and anonymity. Only anonymised or aggregated data will be shared with others. The following steps are taken to protect the data of the participants involved:

Participants are briefed beforehand.

Participants sign informed consent form.

Data stored anonymously.

Data stored on secure server.

Back-up is kept on remote hard drive.

Screenshots only of mannequin model.

3.2 Generic Model: Method

3.2.1 Capture

All participants in this research are captured on site, the Keep Challenging Center in Sittard in this case. This involves a number of challenges, mainly that portable 3D scanners are required where a full-body setup would have otherwise been used (Figure 3.5). Two Artec Eva handheld 3D scanners are used to scan the participants from the left and right side. The capturing process is performed together with TU Delft's 3D scanning expert Bertus Naagen.

A pilot is performed to prepare the research method (Appendix 2.1). Improvements are implemented and concern primarily clear stimuli to the participants, so they all strike an identical pose. All participants are briefed at least one day ahead of the session (Appendix 2.2). Two sessions are performed to capture a total of ten riders. All riders sign an informed consent form (Appendix 2.3). The participants are captured in standing, road and time trial pose on their personal bicycles.

The 3dMD full-body 3D scanner of the Body Lab at the faculty of Industrial Design Engineering captures models of superior quality to the Artec Eva handheld 3D scanner. It captures the subject from all angles in a moment, so movement does not impact the model. However, the participating riders of Team DSM are unable to visit the facility due to busy schedules during the cycling season. Using the Body Lab is therefore not an option.

Figure 3.5: Capturing a participant in the Body Lab using a handheld 3D scanner.

Participants

A variety of about 20 male, professional cyclists from Team DSM participate in this research. During the first session, five riders are 3D scanned.

Apparatus

- Time trial bicycle (rider-specific)
- Road bicycle (rider-specific)
- Cycling kit (rider specific)
- Bicycle trainer stand

- Artec Eva 3D handheld scanner (2x)
- Laptop with Artec Studio 16 software (2x)
- Cable reel (2x)
- Trolley table (2x)

- Portable hard drive
- Head caps
- Balance bar
- Anthropometer

Stimuli

The participant is asked about personal demographics. The questions include: gender, age, ethnicity, cycling type, length, weight, kit size, and shoe size. Furthermore three body measurements are taken.

Shoulder breadth (biacromial)
Horizontal distance between shoulder joints.

Hip circumference
Maximum circumference of the hip.

Thigh circumference
Maximum circumference of the thigh.

The participant is positioned in cycling kit. The participant is instructed to remain still while being captured by the researchers for about 5 minutes. This research involves three poses:

A-pose standing up
Feet separated, positioned below shoulders.
Arms separated, holding balance bar ends.
Wearing no shoes. Wearing socks.

Riding pose on time trial bicycle (Figure 3.6)
Shoes clipped into pedals.
Left leg stretched, right leg retracted.
Hands separated on time trial bar ends.
Elbows in time trial bar rests.
Wearing no helmet. Wearing head cap.

Riding pose on road bicycle (Figure 3.7)
Shoes clipped into pedals.
Left leg stretched, right leg retracted.
Hands deep in handlebar drops.
Wearing no helmet. Wearing head cap.

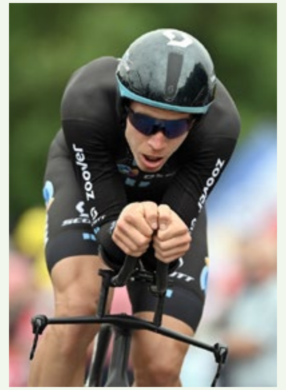


Figure 3.6: BELGA. (2021). [Photograph of cyclist Cees Bol during time trial].

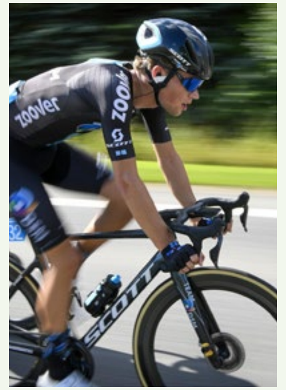


Figure 3.7: Team DSM. (2021). [Photograph of Tim Naberman in drops].

Procedure

Location: Keep Challenging Centre, Sittard.
Time: 11:00-16:00 (60 minutes per participant).

Introduction

1. Participant is introduced to the research.
2. Participant reads and signs informed consent form.
3. Participant changes into cycling kit.

Preparation

4. Participant is asked about personal demographics.
5. Participant's body measures are taken.
6. No anatomical markers are applied to the participant.
7. Participant's bicycle is installed in stand.

3D Scanning

8. Participant enters scanning setup (bicycle or empty floor).
9. Participant cycles for 2-3 minutes to feel natural pose.
10. Participant strikes selected pose.
11. Participant's 3D model is captured by the researchers from left and right side.
12. Process is repeated for remaining poses.

Processing

13. Researchers confirm captured 3D model for quality.
14. Raw 3D scan data is stored on portable hard drive with correct name.
15. Participant is asked about their experience and questions.

3.2 Generic Model: Method

3.2.2 Process

The data captured by the Artec Eva 3D scanners is a raw point cloud and requires processing before it can be used. The Artec Studio 12 software (Artec 3D, 2017) is used to clean up the 3D scan, fuse points and combine both halves. The workflow is established in collaboration with Bertus Naagen and Lies Keijser.

The final results show gaps where the bicycle blocks the 3D scanner's lens, most notably around the inner legs, hands and face. Other inaccuracies occur near dark or reflective materials which the 3D scanner fails to capture. The quality of the model is also influenced by any movements of the participant, which are unavoidable on a bicycle. The road bicycle in particular is challenging, because it does not have elbow rests.

Processing the captured models is a time consuming task due to the quality of the 3D scans. The handheld Artec Eva 3D scanners produce a result of lower quality than the 3dMD full-body 3D scanner of the Body Lab. Incompleteness and movements are the main limitations. The full-body 3D scanner is preferable in this scenario as the scans are of superior quality and they are faster to capture and process. However, all participants must visit the faculty to use the full-body set-up as it is not portable. That involves bringing all gear such as the cycling kit and both personal bicycles for each participant. The Artec Eva handheld 3D scanners are used as logistic limitations did not allow the participants to visit the IDE faculty.

Figure 3.8: The raw scan data contains gaps and environmental elements.

Half 3D Scan
Each halve must first be processed individually as the subject is 3D scanned in two halves.

File > Open Project
Open raw 3D scan data. The model is still a random point cloud at this moment and loose sections are floating around each other (Figure 3.8).

Editor > Eraser
Remove unwanted elements. Mainly the bicycle is erased from the 3D scan, but contact points with the bicycle are also cleaned up (Figure 3.9). Elbow supports must be completely invisible, for example.

Tools > Registration
Adjusting and optimizing frames. Scan sections are automatically aligned, but may need manual adjustment for an accurate results (Figure 3.10). Any double or non-aligned data is excluded from the model.

- Rough Serial Registration
- Fine Registration
- Global Registration

Tools > Smooth Fusion
Smooth Fusion is useful for scans of moving objects with patchy missing regions. Hole filling is applied with a threshold of 10 mm. The loose sections of the model are joined at this point (Figure 3.11).

File > Export Meshes
Store processed half 3D scan data in OBJ format. Confirm the model for no floating points, double or deformed surfaces.

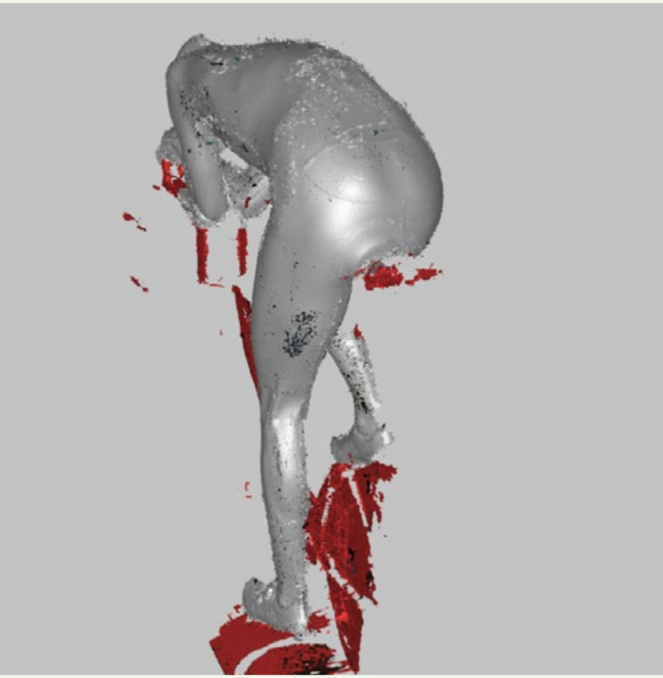


Figure 3.9: Unwanted, selected elements appear in red before erasing.

Figure 3.10: Registration tools automatically optimize the scan data.

Figure 3.11: Create a polygonal 3D model using Fusion to unify half the body.

Full 3D Scan
The halves must be combined after initial processing to create a complete 3D scan model.

File > Import
Open processed half 3D scan data. Two halves of the model are oriented randomly (Figure 3.12).

Align > Automatic
Assembling scans. The software automatically aligns the scans, but sometimes needs manual adjustment (Figure 3.13). The non-rigid alignment is applied as compensate for small differences between the halves.

- Best Fit
- Non-Rigid

Tools > Smooth Fusion
Smooth fusion compensates for slight movements by the participant. The halves of the models are joined at this point (Figure 3.14).

File > Export Meshes
Store processed 3D scan data in OBJ format. Confirm the model once more for no floating points, double or deformed surfaces.

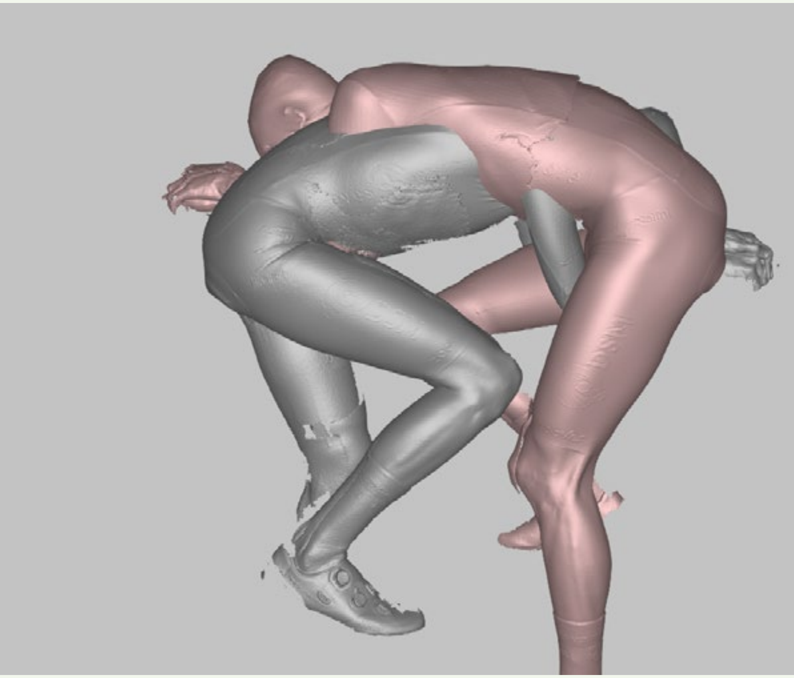


Figure 3.12: The second half is added, but needs position adjustment.

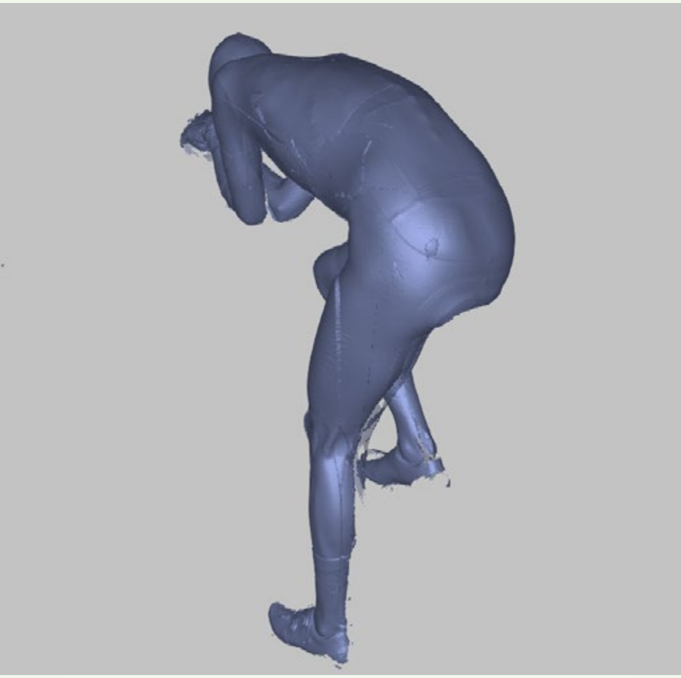


Figure 3.13: Align tools automatically pair scans and can be repeated for better results.

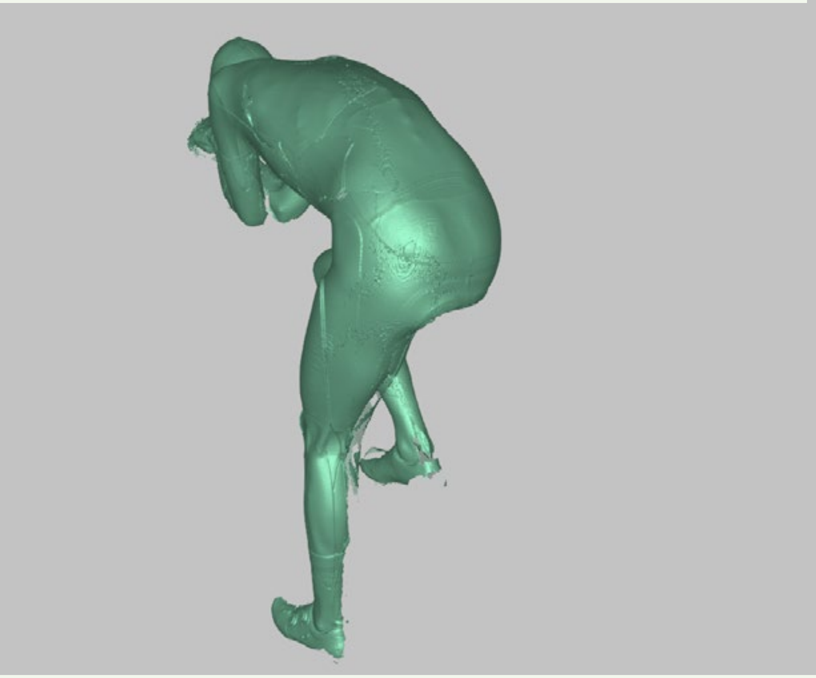


Figure 3.14: Create a polygonal 3D using Fusion to unify the body halves.

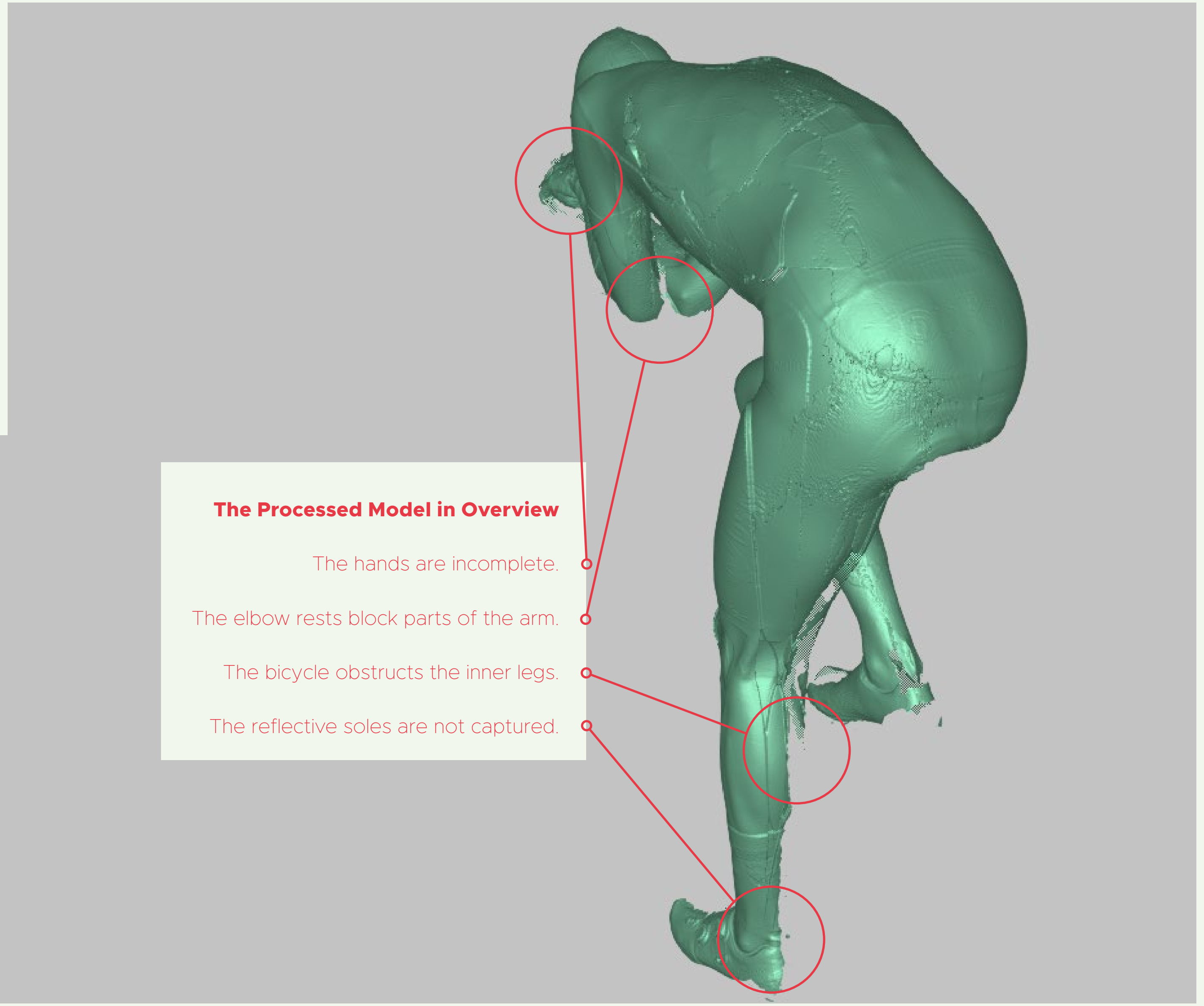


Figure 3.15: The processed model shows holes near areas that are challenging to capture.

Evaluation
The resulting processed model clearly shows where data is missing. The hands, elbows, shoes and inner legs are incomplete. The goal is to avoid holes where possible as they must be filled in the following steps. A complete model means less work patching holes and a result closer to reality. Multiple factors influence the quality of this model.

Some holes are unavoidable. The main obstruction in this context is the bicycle of the participant. Contact points with the bicycle block parts of the body such as the hands, elbows and bottom. The bicycle's top and downtube furthermore block parts of the inner legs (Figure 3.15).

Another limitation is the black Team DSM cycling kit the participants are wearing. While it does not give any difficulties in most areas, the dark bib of the shorts and glossy soles of the shoes are challenging to capture. This is caused by the 3D scanner struggling to capture non-reflective or extra-reflective surfaces.

3D Scanning a cyclist takes about five minutes, meaning the participants must hold their pose for a significant amount of time. The cycling position is challenging to hold as the legs are normally pedalling, applying downward pressure and balancing the body. The 3D scan results are compromised because the participants make small movements during the process, specifically on the road bike which has no elbow rests.

3.2 Generic Model: Method

3.2.3 Correspond

The 3D model resulting from processing in Artec Studio 12 can be edited in any CAD software, but must be corresponded to be recognized as a human body instead of a random shape. The R3DS Wrap3 software (Russian3DScanner LLC, 2021) is used to wrap a base mesh around the 3D model (Figure 3.16). A set of landmarks is identified to pair the model to a template. The base mesh template determines the level of details and defines numbered vertices. Each vertex number eventually corresponds to an identical anatomical location for every corresponded model. Parts of the 3D models are excluded from the process as original data lacks. Hands, elbows, feet and inner legs are normalized by the software.

1. Load & Repair
Base mesh template and processed cyclist model are loaded in R3DS Wrap3. Any singular vertices or non-manifold edges are automatically removed. All components other than the models itself are also removed.

2. Pair & Wrap
A set of 47 landmarks are applied to the base mesh template to identify specific areas. The same set is manually applied to each model to pair it with the template. The software then wraps the mesh around the target model.

3. Exclude Regions
Incomplete sections of the processed model are excluded from the wrap process. These differ per model, but are mainly the hands, elbows, feet and inner legs.

4. Project & Smoothen
The last actions more accurately project the base mesh around the target model. The model is also smoothened slightly to compensate for inaccuracies.

5. Transform & Save
The model is scaled correctly and saved as an OBJ file.

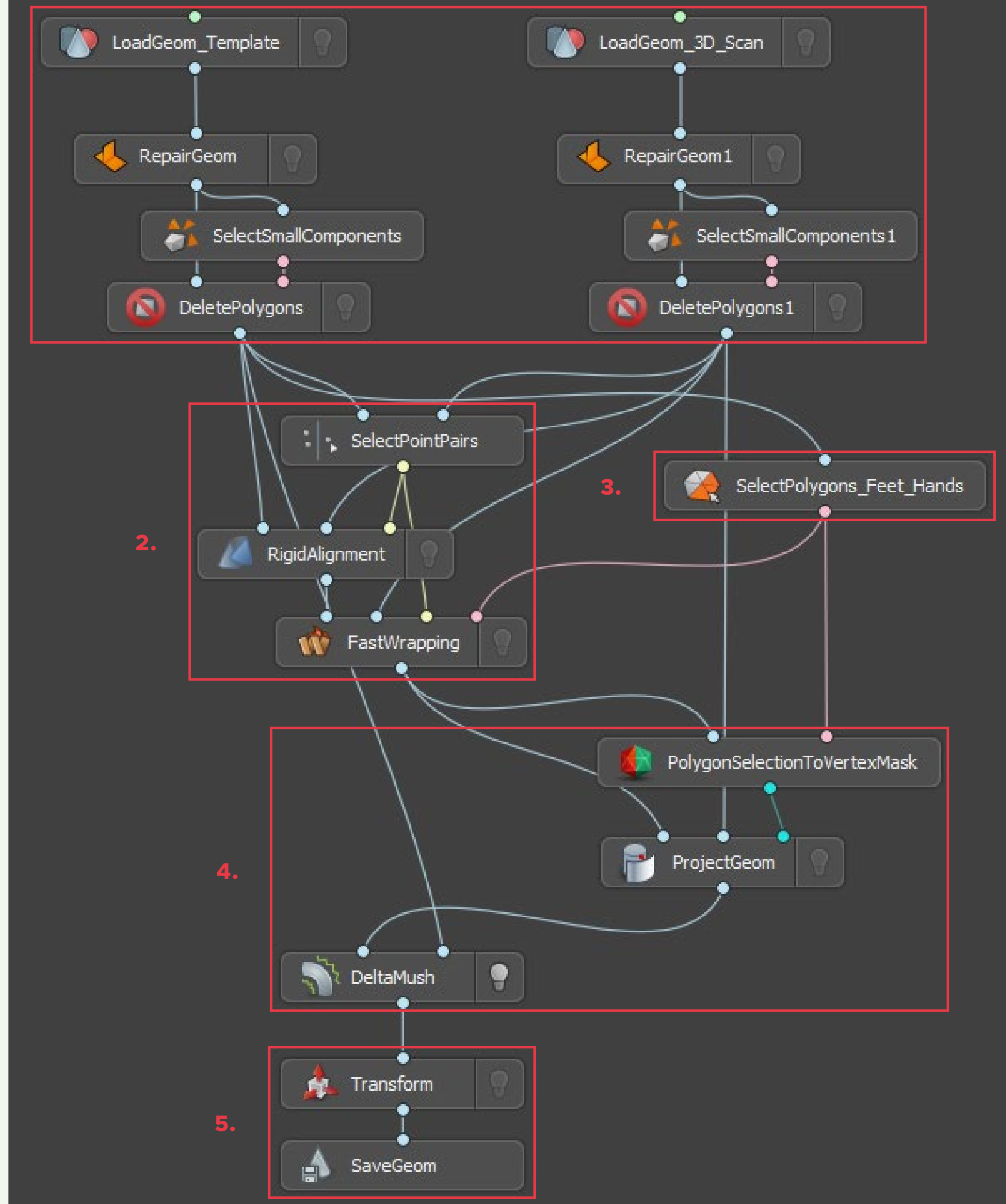


Figure 3.16: Keijser, L. (2022). [Infographic of workflow in R3DS].

In Detail

Landmarks
Most landmarks are applied at anatomical reference points such as joints or limb ends. The middle of the chin, mouth and nose are common landmarks, but the cyclist models specifically lack data there because they are 3D scanned in two halves. The goal is to select a minimum amount of landmarks for the best result, because landmarks are applied to each model manually. A total of 47 markers are applied to correspond the cyclists (Figure 3.17). The landmarks of each model are saved and reused for bias removal iterations.

Excluded Polygons
Polygons are excluded if a model lacks data in specific areas. The processed cyclist models lack information near the hands, elbows, feet and inner legs. A polygon selection is made manually for each individual scan to exclude the regions. Landmarks are removed if they touch any selected polygons. The R3DS Wrap3 software makes a standardization for the excluded polygons instead of attempting to wrap directly to the model (Figure 3.18). Excluded polygons of each model are saved and reused for bias removal iterations.

Figure 3.17: Keijser, L. (2022). [Visualization of landmarks applied to template and processed model].

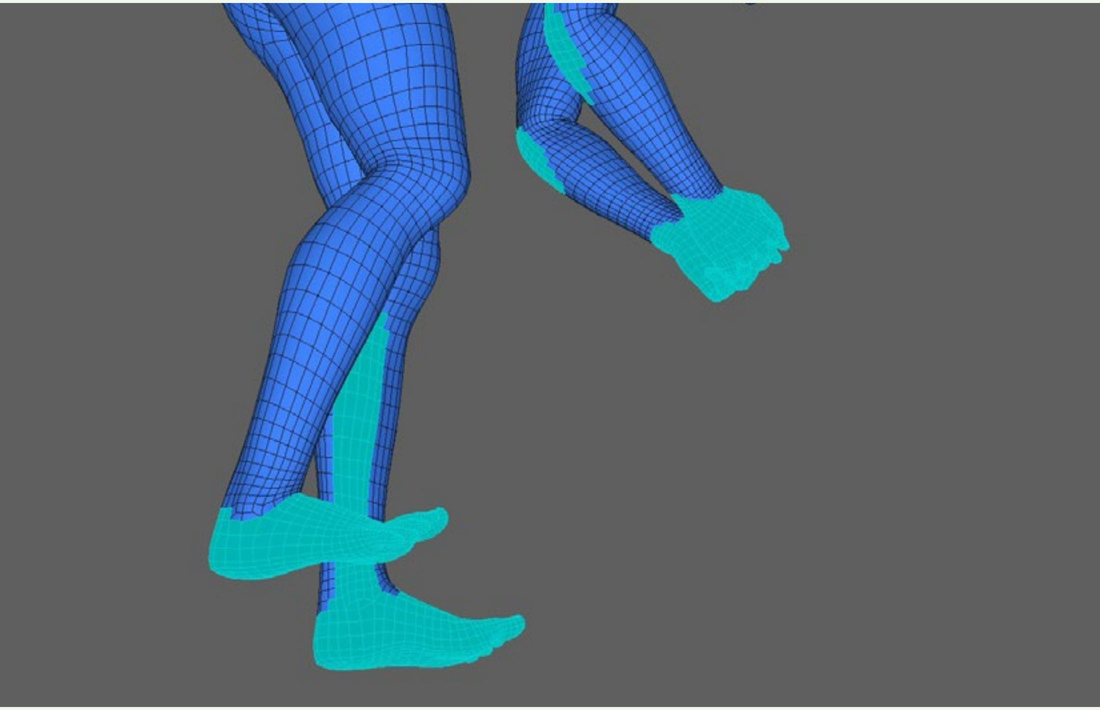


Figure 3.18: Keijser, L. (2022). [Visualization of excluded polygons selected on a processed model].

Base Mesh Template

A base mesh template is required to correspond the first set of models before performing a reference bias iteration (Guigmond et al., 2000). The R3DS Wrap3 library offers a template of a male in standing position, which is manipulated in Blender (Blender Foundation, 2018) to mimic a cycling position. The arms and legs are manipulated slightly and the hands are shaped like fists in the same way a cyclist holds the handlebars.

An accurate base mesh template produces accurate results (Figure 3.19). The base mesh is converted from quadrilateral to triangle polygons. The mesh is also converted from adaptive to uniform polygons, as the model requires the same level of detail everywhere. The total count is increased to 50.000 vertices to improve resolution of the model. The ACVDQ program (Valette, n.d.) is used to perform the simplification of the mesh.

The corresponding process and base mesh template are designed and performed in collaboration with Lies Keijser and Toon Huysmans.

Manipulation of the base mesh template is illustrated on the following page. It is performed to correspond the template to the 3D scan models more accurately. It influences the realism of the base mesh due to the deformations, however. Any deformation is kept to a minimum, but some elements of the model still unnaturally deform near the shoulder, elbow and hip joints. Vertices are distributed differently in these sections and that translates to the Generic Model. The base mesh may be adjusted to overcome such challenges, but that is not performed in this research.

Figure 3.19: The base mesh in original resolution (left) and final resolution (right) in road pose.

Method

The model is reshaped into a cycling pose to create a more accurate template for this project. The open-source software Blender is used to manipulate the template model.

Figure 3.20: The wrap template is imported in Blender and an artificial body skeleton is applied.

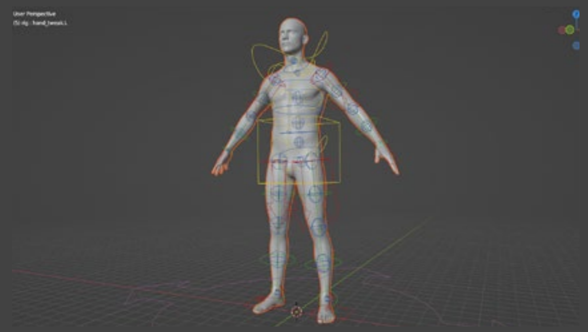


Figure 3.21: The rig allows you to manipulate joints and the overall body position.

Figure 3.22: A side view image of the Dumoulin Mannequin is used as an underlay for the pose.

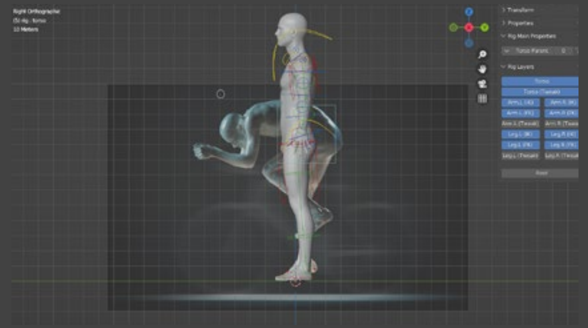


Figure 3.23: By correctly placing and scaling the underlay, it is easily traced.

Figure 3.24: All limbs are carefully manipulated.

Figure 3.25: The body position can be recreated quite accurately with this method.

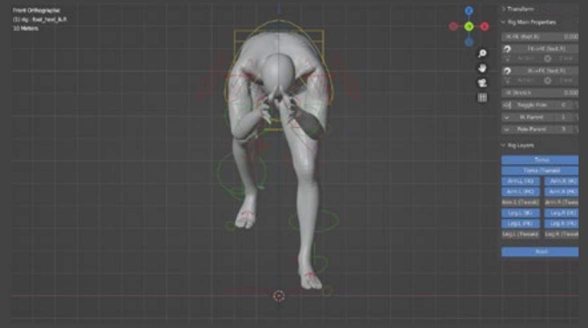


Figure 3.26: Use different view angles to verify the body position.

Development

Pose Version 1

The first base mesh is a template from the Wrap library manipulated in Blender to the pose of the Dumoulin Mannequin (Figure 3.27). The body is manipulated into a close representation of the pose with the fingers spread out.

Pose Version 2

In the second version of the base mesh template, the model's hands are shaped like fists (Figure 3.28) instead of the fingers pointing outward. This helps to correspond the hands.

Pose Version 3

In the third version of the base mesh, the model is placed in a more relaxed position (Figure 3.29). Deformation occurrs near joints where the model is heavily manipulated, causing folds in the mesh. The third version avoids the deformation, while still approaching the cycling pose effectively. A model specific for the road pose is created too.

Figure 3.27: The first version of the base mesh template.

Figure 3.28: The second version of the base mesh template.

Figure 3.29: The third version of the base mesh template.

Smoothing

A standard base mesh is defined by its polygonal structure, but the human body has a smooth surface. The base mesh must be smoothened to realistically correspond the models. The Sculpt Tool from the Meshmixer software (Autodesk Meshmixer, 2020) is used to achieve the desired result (Figure 3.30). The Inflate and BubbleSmooth brushes smoothen facets facing outward and inward respectively . Any smoothing to the model must be performed carefully, as the brushes can manipulate the model heavily. Minimal manipulation is preferred to retain detail of the model.

Resolution

The resolution of the base mesh template from the R3DS Wrap library does not suffice for the Generic Model. It is an adaptive quadrilateral mesh with more details near the hands, face and feet. The resolution is too low, so individual facets are clearly visible. Base mesh variations are created by Toon Huysmans find the optimal model.

The mesh is changed from quadrilateral to triangle polygons to follow the organic shapes of the model. Uniform meshes are created to achieve an equal amount of detail over the entire model. Three different resolutions are made and compared: 50K, 100K and 250K polygons. Comparisons show that higher resolutions emphasize inaccuracies in the processed models (Figure 3.31). The 50K mesh is selected as it causes least deformations is of sufficient quality for the Generic Model.

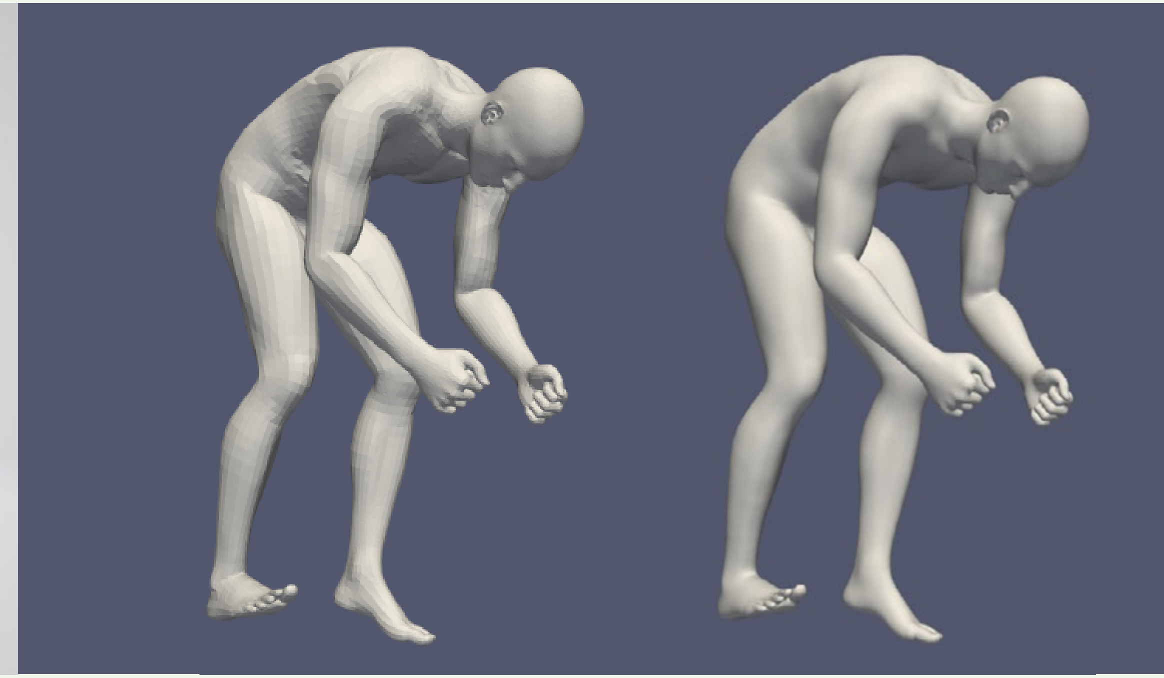


Figure 3.30: Keijser, L. (2022). [Visualization of a regular and a smoothened base mesh template].

Figure 3.31: Keijser, L. (2022). [Visualization of a 250K Fast Fusion, 250K Smooth Fusion and a 50K Smooth Fusion model.

3.2 Generic Model: Method

3.2.4 Average

An average is calculated in the ParaView software (Ayachit, 2015) when all the individual models are corresponded. The models are loaded into the software which recognizes their identical base meshes. The average model is generated and visualized (Figure 3.32).

AlignAndComputeAverage
Custom filters by Toon Huysmans are imported to compute the mean of the models. This commands aligns the individual models and calculates the mean average. A weighted average can be generated to change the importance of individual data, but that is out of the scope of this research. This may be applied to match the anthropometric data of a professional cyclist population.

LoopSubDivision
“The Loop Subdivision filter increases the granularity of a polygonal mesh. It works by dividing each triangle in the input into four new triangles.” (Ayachit, 2015). This command is used to increase the detail and smoothness of the final model, as this is a key requirement of the Generic Model. Individual facets become less apparent.

SimpleClean
“The Clean filter can merge duplicate points, remove unused points, and transform degenerate cells into their appropriate forms.” (Ayachit, 2015). Any unwanted elements are removed by this command and the Generic Model is ready to export.

Figure 3.32: The Generic Model of 10 riders in time trial pose.

Figure 3.33: First version of the Generic Model in road and time trial.

Figure 3.34: Second version of the Generic Model in time trial pose.

Figure 3.35: Third version of the Generic Model in time trial pose.

Generic Model V1
The first version of the Generic Model is generated using the male body base mesh from the R3DS Wrap3 library manipulated into cycling position. An average of four riders is generated in road and time trial pose (Figure 3.33). The low resolution, quadrilateral base mesh is clearly identifiable. The model in road pose has a more realistic face than the model in time trial pose, despite the individual 3D scans being of lower quality. Some of the 3D scans are processed again to achieve this result. The deformations in the face of the other model are caused by the arms blocking the face during 3D scanning. Both models show fabric or skin folds near the armpits and crotch where the base mesh template is heavily manipulated.

Generic Model V2
The second version of the Generic Model is generated using a high resolution, uniform, triangle base mesh An average of ten riders is generated in time trial pose (Figure 3.34). Improving the base mesh resolution highlights small errors in the processed models and they are processed again increase the quality. Due to the time consuming nature of the task, the time trial pose of the Generic Model is given priority over the road pose. The high resolution mesh is an improvement to the model and individual facets become less apparent. The face, hands and feet have an identical level of detail compared to the rest of the body. The base mesh template's pose is relaxed to avoid the fabric and skin folds near the armpits and crotch.

Generic Model V3
The third version of the Generic Model is generated using a smoothened version of the original base mesh. An average of ten riders is generated again (Figure 3.35). The smoothened base mesh creates a more realistic result overall. This result is also achieved by applying the LoopSubDivision and SimpleClean filters in Paraview. The individual models are processed once more to remove elements of the bicycle such as the elbow rests. Smooth Fusion settings in Artec are applied to remove noise from the models and to contribute to the smoothened effect. This is the final Generic Model of this project and the recommendation is to apply the identical modelling steps to the model in road pose.

Data Analysis

Mean Values

The dataset acquired in this research is compared to demographic data of male, road cyclists who competed at the London 2012 Olympic Games (Wood, 2015). The Generic Model must represent the professional cycling population and this database is the most relevant, readily available reference point. Comparing mean age, height and weight (Figure 3.36), mean body size appears similar while mean age greatly differs. The difference is explainable as participants in this research are young riders from Team DSM's development team, instead of the older WorldTour team.

Means compared	Team DSM male road cyclist datase	London 2012 Olympics male road cyclist database
Age (years)	19.7	28.4
Weight (kg)	71.0	74.1
Length (cm)	182.0	178.0

Figure 3.36: Mean values of Team DSM dataset compared to London 2012 Olympics database.

Weight Values

Comparing weight for minimum, maximum, median and mean values (Figure 3.37), characteristics of the dataset become apparent. First, the mean weight differs by 3.1 kg. Second, the dataset range is noticeably limited compared to the database. The database shows a positively skewed distribution.

Weight (kg)	Team DSM male road cyclist datase	London 2012 Olympics male road cyclist database
Minimum	63	55
Maximum	79	86
Mean	70.5	72
Median	71	74.1

Figure 3.37: Minimum, maximum, median and mean weight compared.

Height Values

Comparing height for minimum, maximum, median and mean values (Figure 3.38), even more limits of the dataset become apparent. First, the mean length differs by 4.0 cm. Second, the dataset range is limited in terms of length, similar to the weight. The database shows a positively skewed distribution.

Height (cm)	Team DSM male road cyclist datase	London 2012 Olympics male road cyclist database
Minimum	172	165
Maximum	190	199
Mean	179.4	178
Median	182.0	178.0

Figure 3.38: Minimum, maximum, median and mean height compared.

Weighted Average

As more riders are added to the Generic Model, it becomes a better representation of the professional cycling population. However, the data will always have limits. A weighted average may be generated to make the model more representative. Individual riders each receive a weight to optimize the Generic Model. Optimalization pa-rameters may be an identical mean and median. The database is not completely representative of the population however and that is a limitation of this model.

4. Personalized Mannequin

4. Personalized Mannequin

4.1 Design

The second goal of this research is to design a personalized cyclist mannequin for aerodynamics researchers. The Personalized Mannequin designed in this project is called Rupert. Rupert is a personalized cycling mannequin for aerodynamics testing in the wind tunnel. The mannequin is life-size and can be modelled after any 3D scanned cyclist. Rupert's pose is static, able to precisely repeat position between tests. Any cycling gear can be applied to the mannequin, because of its smooth surface and clever segmentation. The mannequin has a minimal amount of separate limbs which attach & detach with a single motion. Rupert can be mounted to the rider's bicycle without any modifications to it. Its design ensures a great moisture, temperature and impact resistance.

Materials & Production
CNC milled, high density polyurethane foam.
Treated with sealant and a light sanding.
Painted matte black for low light reflectivity.

3D Digital Model
High-drag leg position, hands separated.
Static pose, 3D scanned on personal bicycle.
Uniform, smoothened surface.

Interaction Segmentation
Segmented legs, arms & hands.
Bevelled edges to slide suit over.
Recessed interface slots.

Attachment Interfaces
Magnetic, form-fitting interfaces.
Colour-coded for instant recognition.
Identical for each mannequin.

Bicycle Mounts
Wears cycling shoes to clip into pedals.
Rests most of its weight on a regular saddle.
Flexible hand interface mounts to handlebar.

The Mannequin In Six Questions

Who?
Aerodynamics expert Harm Ubbens and colleagues at cycling Team DSM.

What?
Using a cyclist mannequin for aerodynamics tests to compare gear for both riders and bicycles, such as helmets, suits and wheels.

Where?
In a wind tunnel, such as the Open Jet Facility at TU Delft.

When?
Commonly 3-4 sessions a year of 1-3 days at a time.

Why?
First, a mannequin is a constant factor in measurements and eliminates the variable posture of a human subject. Second, a mannequin eliminates the logistical and physical limitations a human subject involves.

How?
The human subject is replaced by the cyclist mannequin on the bicycle during aerodynamics tests.

User Interaction
Rupert is dressed, attached and mounted for every test performed in the wind tunnel. A minimum amount of intuitive actions make the process fluent. The interactions between user and mannequin are visualized in Figure 4.1 and individually described below.

1. Attach hands to handlebar.
Rupert's flexible hands are shaped around the handlebar and remain attached throughout the entire test session. The arms always attach to the same point for accurate repeatability.

2. Apply socks & shoes to legs.
The socks and shoes are applied to the foot so Rupert can mount to the pedals. They remain applied throughout the session if possible.

3. Attach shoes to pedals.
The shoes are attached to the pedals using cycling cleats. Rupert's legs are placed on the ground when the torso is not attached.

4. Apply suit to torso (roll up sleeves).
The cycling suit is applied to Rupert's torso, starting with the legs. The sleeves are rolled up so the attachment interfaces become exposed.

5. Attach torso to limbs.
Rupert is seated on the saddle and attached to the arms for stability. The legs are attached last. Rupert is now fully mounted to the bicycle.

Figure 4.1: Segmentation and user interaction of the mannequin in road pose.

Interaction Scenario Rupert #1
Harm Ubbens & Wouter Terra dress, assemble and mount Rupert to a time trial bicycle. All intended interactions are described here.

Figure 4.2: The cycling suit is applied to the legs first and rolled up.

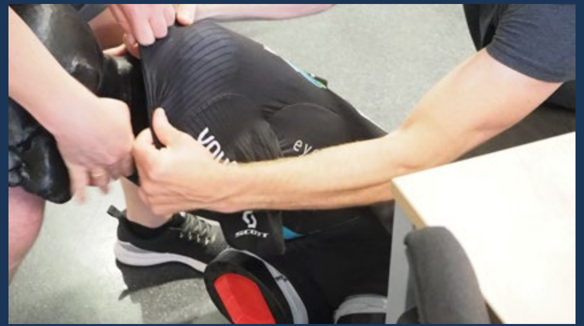


Figure 4.3: The cycling suit is pulled over the shoulders and arms.

Figure 4.4: The legs are attached and the cycling suit is rolled down.

Figure 4.5: The sleeves of the cycling suit cover the seam between the limbs.

Figure 4.6: The assembled mannequin is placed on the bicycle in a stand.

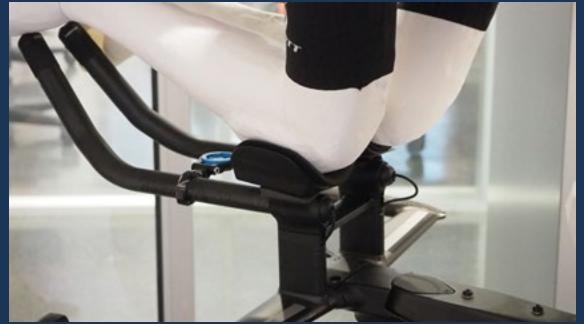


Figure 4.7: The arms are placed on the elbow rests and the hands on the bar-ends.

Figure 4.8: The helmet is applied to complete dressing the mannequin.

Figure 4.9: The mannequin is adjusted for precise positioning.

4.2 Method

A cycling mannequin is an Ultra-Personalized Product, requiring an Automated Workflow as it is different for every customer. Based on the Centre of Design for Advanced Manufacturing (CDAM, n.d.) approach, the workflow is divided into four sections: Digitalization, Design Automation, Digital Fabrication & Human-Robot Coproduction (Figure 4.10). This describes all steps involved in the process from 3D scanning a subject to assembling the mannequin. An interview with Sander Minnoye about Advanced Manufacturing is the foundation of the workflow (Appendix 3.1).

Digitalization
3D Scan a cyclist and process the model to edit in CAD software. It is identical to the Generic Model approach and not discussed again in this chapter.

Design Automation
Automatically apply design features to the model by using parametrically defined requirements.

Digital Fabrication
Precisely fabricate the model by using additive and subtractive manufacturing.

Production
Complete the product by finishing fabricated parts and assembling the mannequin. Only manual production is involved in this project.

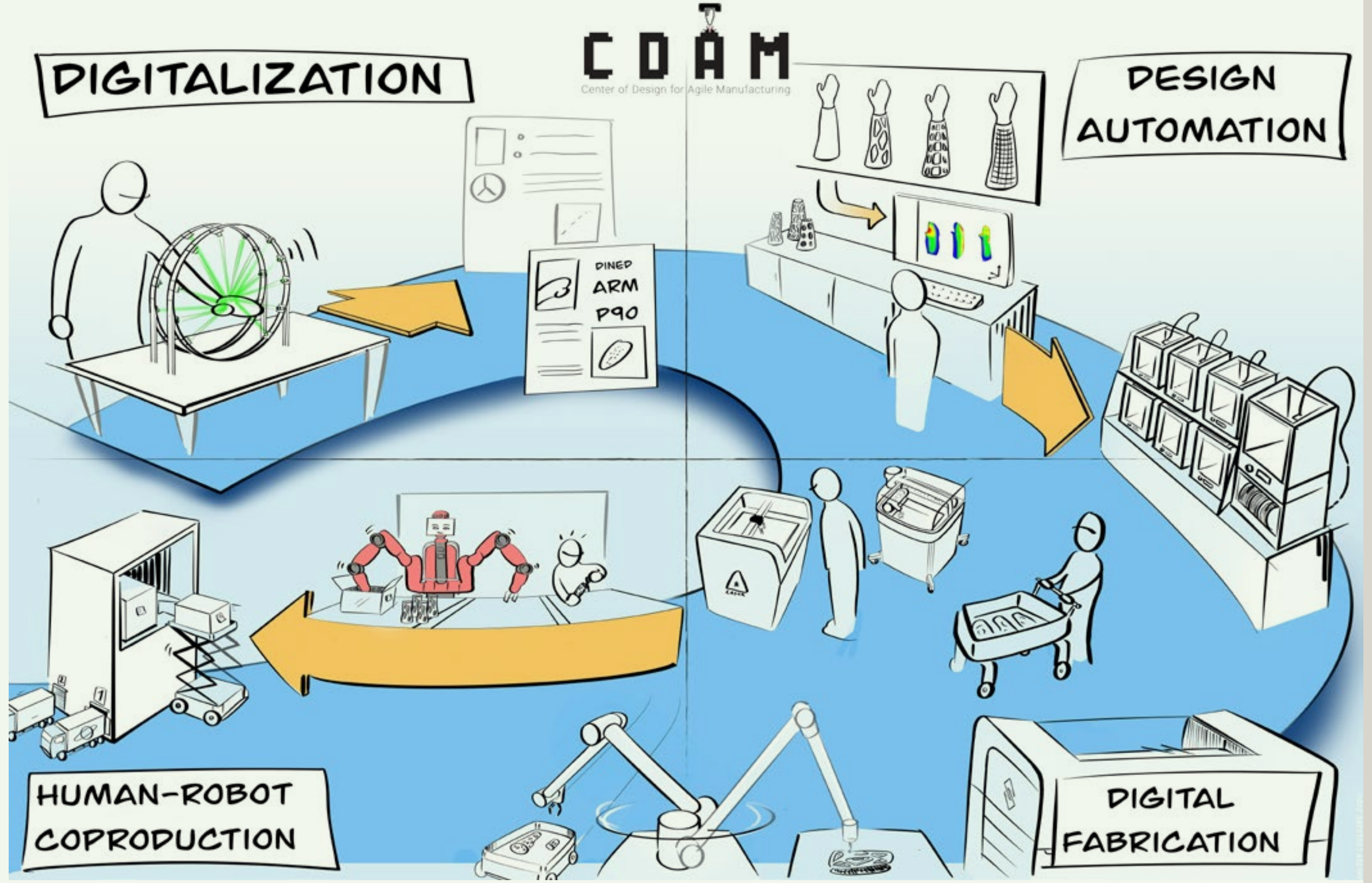


Figure 4.10: CDAM. (n.d.). [Schematic of Advanced Manufacturing approach].

4.2.1 Design Automation

All design features of the Personalized Mannequin are parametrically defined so they can automatically be applied to any model with the same correspondence. The complete process is performed manually in Blender once to fabricate the full-scale mannequin. Part of the process is coded in a Grasshopper script (Figure 4.11) to segment the hands. DINED User Objects allows selection of a specific vertex to apply design features to. The feature is automatically applied to the identical vertex of any corresponded model.

Not all design features are included in the script for this project. A feature tree describes the modelling steps chronologically. The script automatically applies all design features to any cyclist model, automating the digital design process of the Personalized Mannequin.

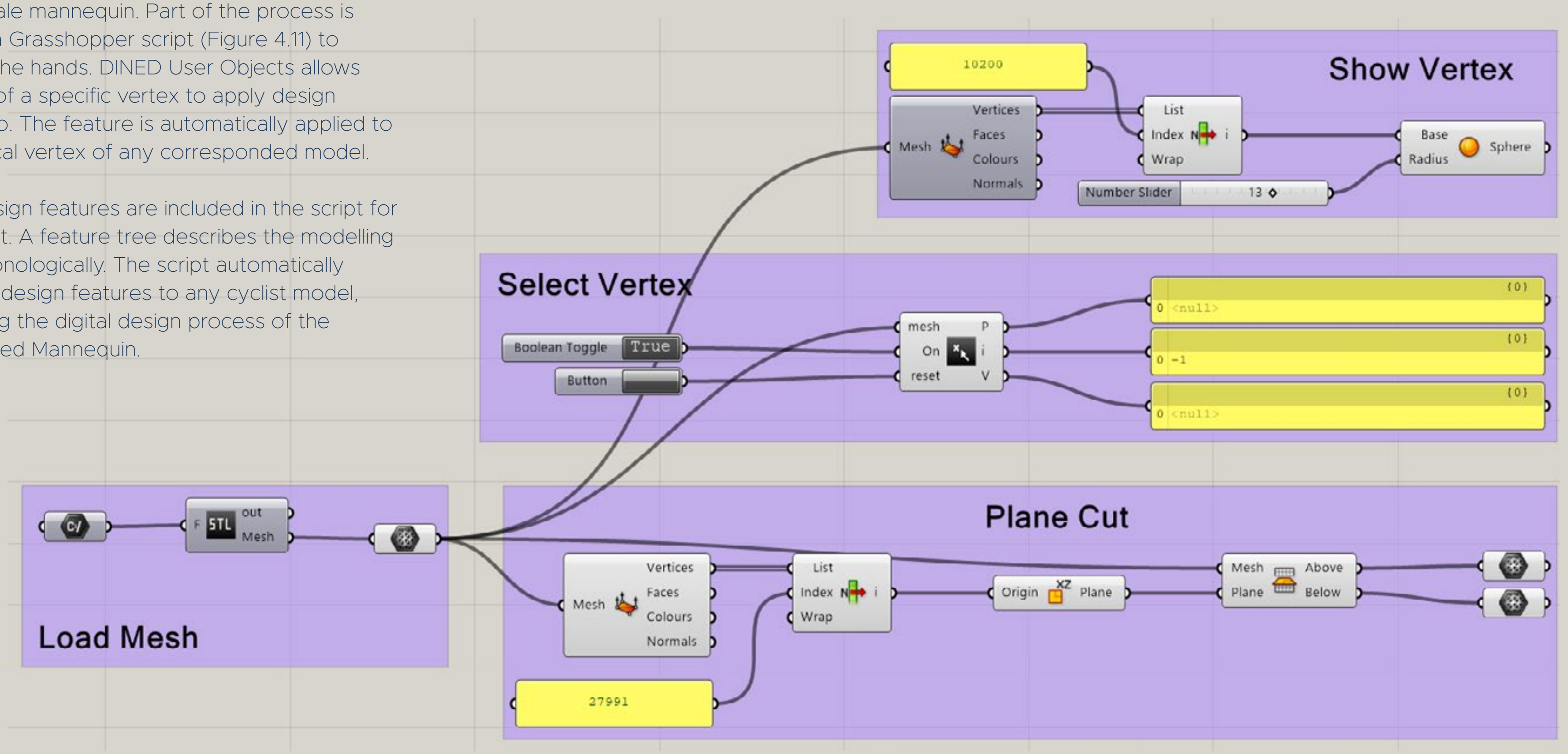


Figure 4.11: Automatically applying a plane cut at the wrists of the model in Grasshopper.

Interaction Segmentation

Segment Arms

The arms are segmented identically to the hands, but on a different vertex in another plane orientation. It is performed by positioning a horizontal plane on the desired vertex to split the limbs (Figure 4.12).

Select vertex at 55 mm arm protrusion.
- Vertex Picker > Select Vertex

Input vertex number.
- Params > Input > Panel

Create horizontal plane.
- Vector > Plane > XY Plane

Apply plane cut.
- Mesh > Util > Mesh Split Plane

Segment Legs

The legs are segmented differently, because the cutting plane is oriented in relation to the model. It is performed by drawing a line through the middle of the upper leg. A plane is positioned perpendicular to the line in its centre to split the limbs.

Select three vertices in line at knee and hip.
- Vertex Picker > Select Vertex

Input vertex number.
- Params > Input > Panel

Draw circle through knee and hip using selected vertices.
- Curve > Primitive > Circle 3Pt

Draw line from centre to centre.
- Curve > Primitive > Line

Select line midpoint.
- Curve > Analysis > Curve Middle

Create plane perpendicular to line through midpoint.
- Vector > Plane > Plane Normal

Apply plane cut.
- Mesh > Util > Mesh Split Plane

Repeat for other leg.

Bevel Edges

The edges are bevelled by applying the feature to the created segment faces (Figure 4.13).

Select segment faces.
- Intersect > Mathematical > Mesh | Plane

Apply bevel.
- Weaverbird > Transform > Bevel Edges

Interface Slots

The interface slots are all applied identically, but on a different vertex. The interface slot model is loaded and positioned on the segment face centre. The model is oriented perpendicular to the face and subtracted from the limb segment (Figure 4.14).

Select vertex at segment face centre.
- Vertex Picker > Select Vertex

Input vertex number.
- Params > Input > Panel

Load interface slot model as STL.
- Params > Primitive > File Path

Convert STL to mesh.
- DINED > STL Reader

Orient interface slot perpendicular to segment plane.
- Transform > Euclidian > Orient

Position interface slot at vertex.
- Transform > Euclidian > Move

Cut interface slot from limb segment.
- Intersect > Util > Mesh Difference

Repeat for other limb segments.

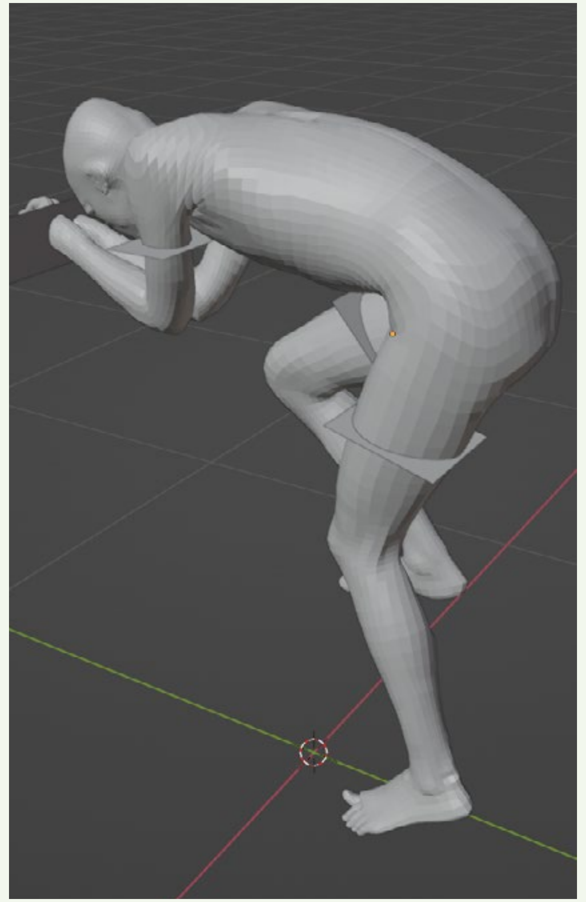


Figure 4.12: Segment the limbs by splitting the model with planes.

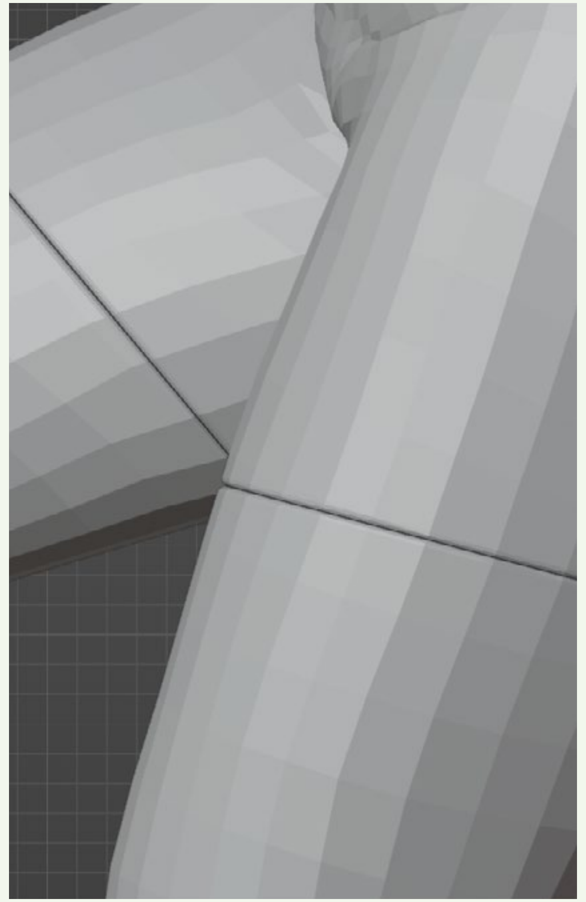


Figure 4.13: Bevel edges of the segment faces on both sides of the cut.

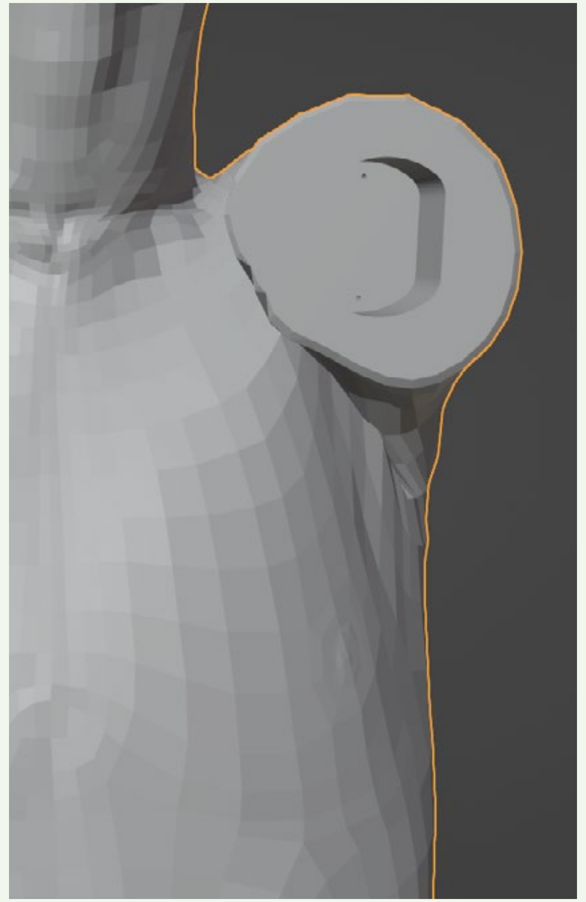


Figure 4.14: Cut the interface slots from all limb segments.

4.2 Personalized Mannequin: Method

4.2.2 Digital Fabrication

The design model is edited once more to begin Digital Fabrication. Requirements depend on the fabrication method, but CNC milling involves segmentation based on machine size, amount of axes, material dimensions and material efficiency. However, such actions are commonly performed by the manufacturing party. The production model is loaded into CNC milling software such as Fusion 360 to select fabrication settings. The polyurethane foam is milled and untreated limb segments form the result of Digital Fabrication.

The Digital Fabrication process is performed multiple times in this project. The process of CNC milling a foot segment in is described in this chapter (Figure 4.15). The following settings in DeskProto are used to digitally fabricate it.

Material:	Polyurethane foam 80 kg/m3
Machine:	FLDM1325 3-axis CNC mill
End Mill Cutter:	Ø 10 mm, 160 mm length
Detail:	1.1 mm
Layer height:	15 mm
Time:	4-5 hours

Figure 4.15: An untreated,, CNC milled foot prototype with box supports.

CNC Milling Process

CNC Milling is performed with the help of expert Don van Eeden at the Model Making Machine Lab of the TU Delft. A support box is added to the limb in the example to flip it halfway the process.

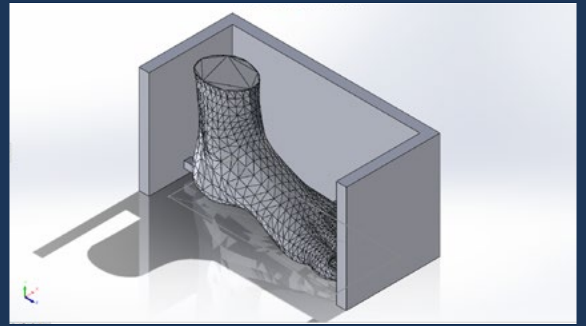


Figure 4.16: A box support is added to the foot segment in SolidWorks.

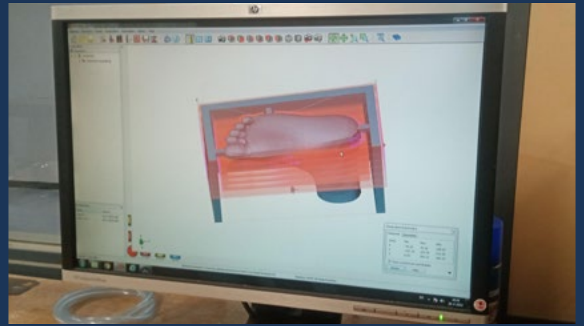


Figure 4.17: Milling paths and layers are selected and adjusted in DeskProto.

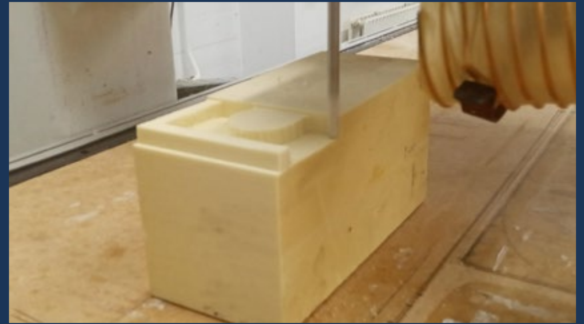


Figure 4.18: The first layer is CNC milled and frame contours become visible.

Figure 4.19: Milling is complete for the top side of the foot.

Figure 4.20: Double-sided tape is applied to the other side of the object.

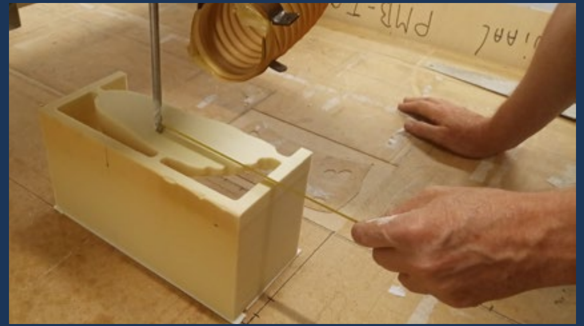


Figure 4.21: The object is placed in the same position on the milling board.

Figure 4.22: The foot is now milled from the bottom side.

Figure 4.23: Result of the foot after CNC milling is completed.

4.2 Personalized Mannequin: Method

4.2.3 Production

Lastly, the Personalized Mannequin is produced by joining the limb segments, finishing the limbs and assembling the product. Recognizable limbs form when the segments are joined and finished. Polyurethane rigid foam has excellent treatment properties, but requires only little treatment after fabrication. The limbs receive a protective coating before assembly with stock attachment interfaces and other hardware. A completely assembled, Personalized Mannequin is the result of the Production step.

The Production process is performed once on a CNC milled, polyurethane limb in this project (Figure 4.24). The foot segment is used to test production steps to achieve the right finish. After all, it still has a rough surface and is connected to a support frame.

Figure 4.24: A partially sanded and coated, CNC milled foot prototype.

Sanding

Sanding paper is applied to prepare the limb for painting. The papers are wrapped around a sanding block to create an even surface. Three types of sanding paper are used here (Figure 4.25).

- P240 grit (medium)
- P120 grit (fine)
- P80 grit (very fine)

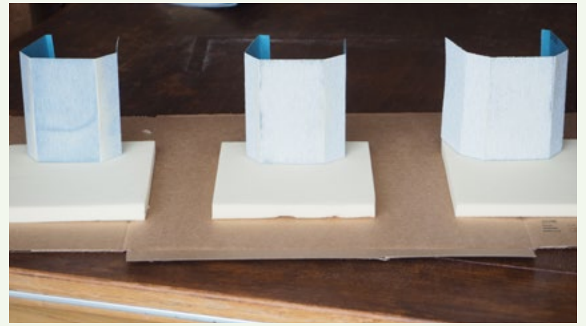


Figure 4.25: The resulting foam tiles after sanding with P240, P120 & P80 (left to right).

All three sanding papers work effectively on the polyurethane foam. The surface finish is good and large inaccuracies are easy to smoothen. The foam remains grainy and lots of dust is created during sanding. A better surface finish would be preferable at this stage for a quality coating.

Coating

Rattle can spray paint is used on the limb after sanding. Two layers of coating are applied to the polyurethane foam tiles. Three types of spray paint are used here (Figure 4.26).

- OK: Matte black
- Spray.Bike: Matte green (self-priming)
- Spectrum: Glossy black

Figure 4.26: The resulting foam tiles after coating.

All three spray paints bond well to the polyurethane foam and form a smooth coating. The foam is hardly grainy and little dust appears. The higher-end Spray.Bike paint creates the most solid, protective layer. While the results only marginally differ, the glossy paint leaves a slight sparkle. The others create a more preferable, matte surface colour. A hard, smooth, top coating would be even better.

Finish

Half of the foot is untreated, half of the foot is sanded with P240 & P80 and coated thrice with OK matte black paint. This allows comparison between each halve (Figure 4.27).

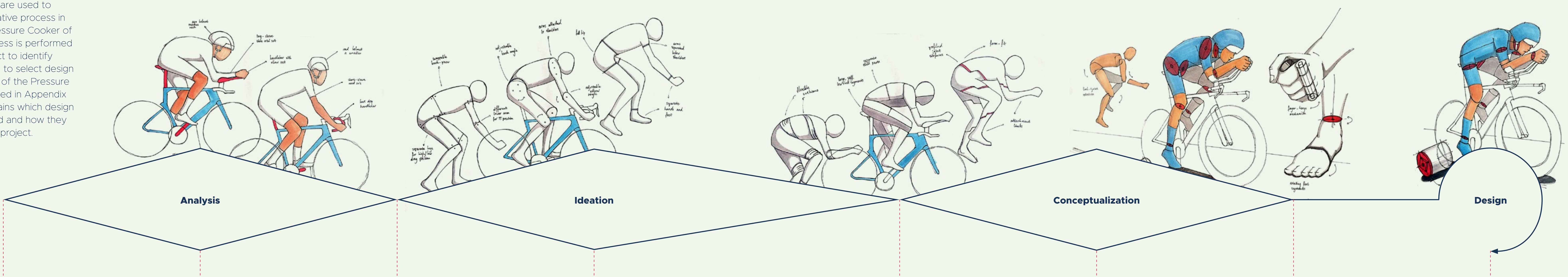
Figure 4.27: Half of the foot is sanded and coated.

Sanding the foot is very effective. Any milling marks are smoothened, but so are essential shape details. Sanding without a block creates uneven pressure and can leave marks on the surface. Sometimes even large scratches appear. Polyurethane foam of 80 kg/m3 density is fragile and damages easily. A higher density foam would be preferable for the mannequin limbs.

4. Personalized Mannequin

4.3 Development

Several methods are used to structure the creative process in this project. A Pressure Cooker of the creative process is performed early in the project to identify opportunities and to select design methods. Results of the Pressure Cooker are included in Appendix 4. This page explains which design methods are used and how they contribute to the project.



Product Life Cycle
With the Dumoulin Mannequin as a project predecessor, the Personalized Mannequin's Life Cycle is well defined. The list of product interactions is detailed and complete to serve as a baseline for the product's design.

List of Requirements
Resulting from the Product Life Cycle, a List of Requirements is defined. Unlike the name suggests, the list contains both requirements and desires. Requirements are used to validate the mannequin's functionality while desires are used to make design decisions.

Function Analysis
Key processes from the Product Life Cycle are also used to conduct a Function Analysis. Selecting and clustering essential product interactions serves as the foundation for structured ideation. This ensures that all design challenges in the project are tackled.

How-Tos
With product functions clearly defined in the Function Analysis, How-Tos generate countless solutions to each one. All design challenges are tackled as they are isolated and generated ideas may return later in the project.

Morphological Chart
By structuring and combining solutions generated following the How-Tos, a Morphological Chart generates varying concepts. Digital Fabrication methods are used as the core of the concept and appropriate solutions are combined in turn.

Concept Design
Designing an integrated concept is the next step when all idea combinations are made. Design Drawing is used to visualize and specify the integrated features of a concept. Interactions with the user and context are essential to include.

Harris Profile
By ranking and clustering desires from the List of Requirements, a Harris Profile rates concept quality. Ratings are quite easily applied as concepts are only rated relative to one another. A concept is selected in consultation with the client.

Concept Redesign
The selected concept is redesigned as new insights arise. As the concept is being developed, the process becomes iterative and the design gradually evolves. This is how a concept becomes a product.

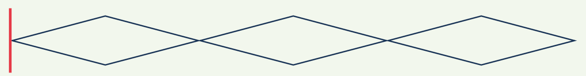
Cyclist Mannequin - Siward Vloemans

4.3 Personalized Mannequin: Development

4.3.1 Product Life Cycle

Product Life Cycle

"A schematic diagram of the activities that a product encounters during its life cycle." (Van Boeijen et al, 2020).



The goal of the Product Life Cycle is to list and order all interactions with the mannequin and user. The Product Life Cycle diagram is divided into three columns: phase, process and sub-process. The standard phases included are the Originate, Distribute, Use and Discard phase. All processes and sub-processes are clustered for each phase and describe the complete Product Life Cycle. The diagram creates an overview of interactions and helps to set requirements and priorities with following methods. The Use phase of the Product Life Cycle is shown in Figure 4.28.

Originate. Processes in the Originate phase are based on the workflows of the Generic Model and Personalized Mannequin. This phase starts by selecting a subject for the mannequin and ends with packaging the product.

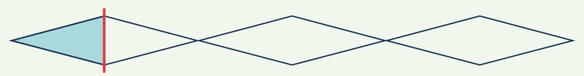
Distribute. The Distribute phase contains processes relevant to the data security of the customer and the delivery of the mannequin. This phase is least important in this project.

Use. The Use phase is based on the interaction scenario with the Dumoulin Mannequin. It lists the mannequin's most important interactions such as assembling, dressing, mounting and testing. Unintended use is also included.

Discard. The Discard phase covers the end-of-life of the mannequin. It covers possibilities of disassembling, reusing, recycling and discarding of product parts. It has relatively low priority.

List of Requirements

"States the important characteristics that a design must have in order to be successful." (Van Boeijen et al, 2020).



The goal of this method is to create a list of demands that can validate concepts and to create a list of desires that can be used for selection. The List of Requirements is extensive as it is based on user interactions from the Product Life Cycle. This ensures that all interactions with the product result in a relevant requirement or desire. The Originate & Distribute phase include requirements for the 3D scan subject. Not all processes result in a requirement, though some result in multiple. Arguments are used to substantiate the requirements.

Requirements are used to verify the mannequin's functionality while desires are used to make design decisions. They are used to design relevant concepts and to make a substantiated selection. They return during validation of the mannequin to evaluate the final design. Requirements and desires based on part of the Use phase are shown in Figure 4.28. Desires are highlighted in red. For the full List of Requirements and Product Life Cycle, refer to Appendix 5.

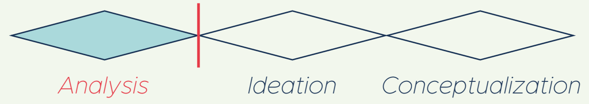
Key requirements
- The mannequin is rigid on the bicycle.
- The mannequin's shape represents its subject.
- The mannequin has detachable arms & legs.
- The mannequin has limited joint flexibility.
- The mannequin can change torso & arm position.

#	Process	#	Sub-process	#	Requirement
3.3	Assemble	3.3.1	Assemble in road position	3.3.1.1	The mannequin can be assembled by a single adult.
		3.3.2	Assemble in time trial position	3.3.2.1	The mannequin can change torso & arm position.
		3.3.3	Re-assemble in between tests	3.3.3.1	*The mannequin's limbs are quickly (dis)assembled.*
3.4	Dress	3.4.1	Dress in cycling suit	3.4.1.1	The mannequin has detachable arms & legs.
		3.4.2	Dress in cycling socks	3.4.2.1	The mannequin has bare feet & lower legs.
		3.4.3	Dress in cycling shoes	3.4.3.1	The mannequin has smoothened feet.
		3.4.4	Dress in cycling helmet	3.4.4.1	The mannequin has a bald head.
		3.4.5	Dress in cycling glasses	3.4.5.1	The mannequin has facial features.
		3.4.6	Change outfit in between tests	3.4.6.1	The mannequin has a smooth surface.
3.5	Mount	3.5.1	Mount to road handlebar	3.5.1.1	The mannequin can hold parallel Ø 35 mm Road bars with its hands.
		3.5.2	Mount to time trial handlebar	3.5.2.1	The mannequin can hold parallel Ø 25 mm TT bars with separate hands.
		3.5.3	Mount to bicycle saddle	3.5.3.1	The mannequin has a 165 mm open area between the legs.
		3.5.4	Mount to bicycle pedals	3.5.4.1	The mannequin can twist its legs.
		3.5.5	Re-mount in between tests	3.5.5.1	*The mannequin is quickly (un)mounted.*
		3.5.6	Mount to different bicycle geometry	3.5.6.1	The mannequin has limited joint flexibility.
				3.5.6.2	*The mannequin's pose is accurately adjustable.*
3.6	Test	3.6.1	Test in wind tunnel	3.6.1.1	The mannequin's shape represents its subject.
				3.6.1.2	*The mannequin's shape is accurately realistic.*
				3.6.1.3	The mannequin's seams are unobtrusive.
				3.6.1.4	The mannequin is rigid on the bicycle.
				3.6.1.5	The mannequin is rigid on the bicycle while wobbling sideways.
				3.6.1.6	*The mannequin's pose is accurately repeatable.*
3.7	Use unintended	3.6.2	Test with Particle Image Velocimetry	3.6.2.1	The mannequin has a matte, black colour finish.
				3.6.2.2	The mannequin is water resistant up to IPX4.
		3.7.1	Drop on the floor	3.7.1.1	The mannequin is impact resistant up to 1.5m.

Figure 4.28: List of Requirements from the Use phase of the Product Life Cycle.

4.3.2 Function Analysis

"A method for analysing and developing the function structure of an existing product or new product concept." (Van Boeijen et al, 2020).



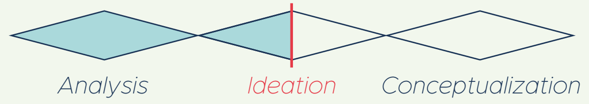
The goal of the Function Analysis is to isolate product functions and solve each design challenge individually. The Function Analysis is based on Product Life Cycle sub-processes Assemble, Dress and Mount (Figure 4.29). The main functions split into sub-functions that are used to generate design challenges. The sub-functions logically follow the analysis of where the mannequin connects to the bike, segments its body parts and wears its clothes. Sub-functions are used as the basis for idea generation in this project. The design challenges are used to eliminate, combine or to tackle each sub-function differently. Sub-functions 2.1, 2.2, and 2.3 pose the same challenge and are effectively combined during idea generation. Sub-function 3.1 poses no challenge at all as the Dumoulin Mannequin effectively tackled it already.

Key function	Main functions	Sub-functions	Challenge
Hold cycling position on bicycle	**1** Apply cycling gear	**1.1** Apply suit to torso	Limb segmentation
		1.2 Apply shoes to feet	Foot-shoe shape
		1.3 Apply helmet to head	Neck segmentation
	2 (Dis)connect body parts	**2.1** Connect arms to torso	Connection mechanism
		2.2 Connect legs to torso	Connection mechanism
		2.3 Connect head to torso	Connection mechanism
	3 (Un)mount to bicycle	**3.1** Mount bottom to saddle	None
		3.2 Mount hands to bar	Repeatable fixture
		3.3 Mount feet to pedals	Freedom of movement

Figure 4.29: Function Analysis of the mannequin based on the 'Use' phase of the Product Life Cycle.

4.3.3 How-Tos

"How-Tos are problem statements written in the form of questions that support brainstorming and idea generation." (Van Boeijen et al, 2020).



The goal of the How-Tos is to generate lots of ideas based on product function design challenges. How-Tos are generated based on challenges found in the Function Analysis. Design Drawing techniques are used to visualize ideas, as that is important with a physical product such as the Personalized Mannequin. Underlays are used to quickly and repeatedly draw the complex body shapes. Nine sub-fuctions are identified by the Function Analysis. Design challenges for sub-functions 2.1, 2.2 and 2.3 are combined and sub-function 3.1 is eliminated. That brings the number down to six sub-functions and the following How-Tos are performed:

How To ...

- Apply suit to torso (Figure 4.32)
- Apply shoes to feet (Figure 4.30)
- Apply helmet to head (Figure 4.30)
- Connect limbs (Figure 4.31)
- Mount hands to handlebar (Figure 4.31)
- Mount feet to pedals (Figure 4.31)

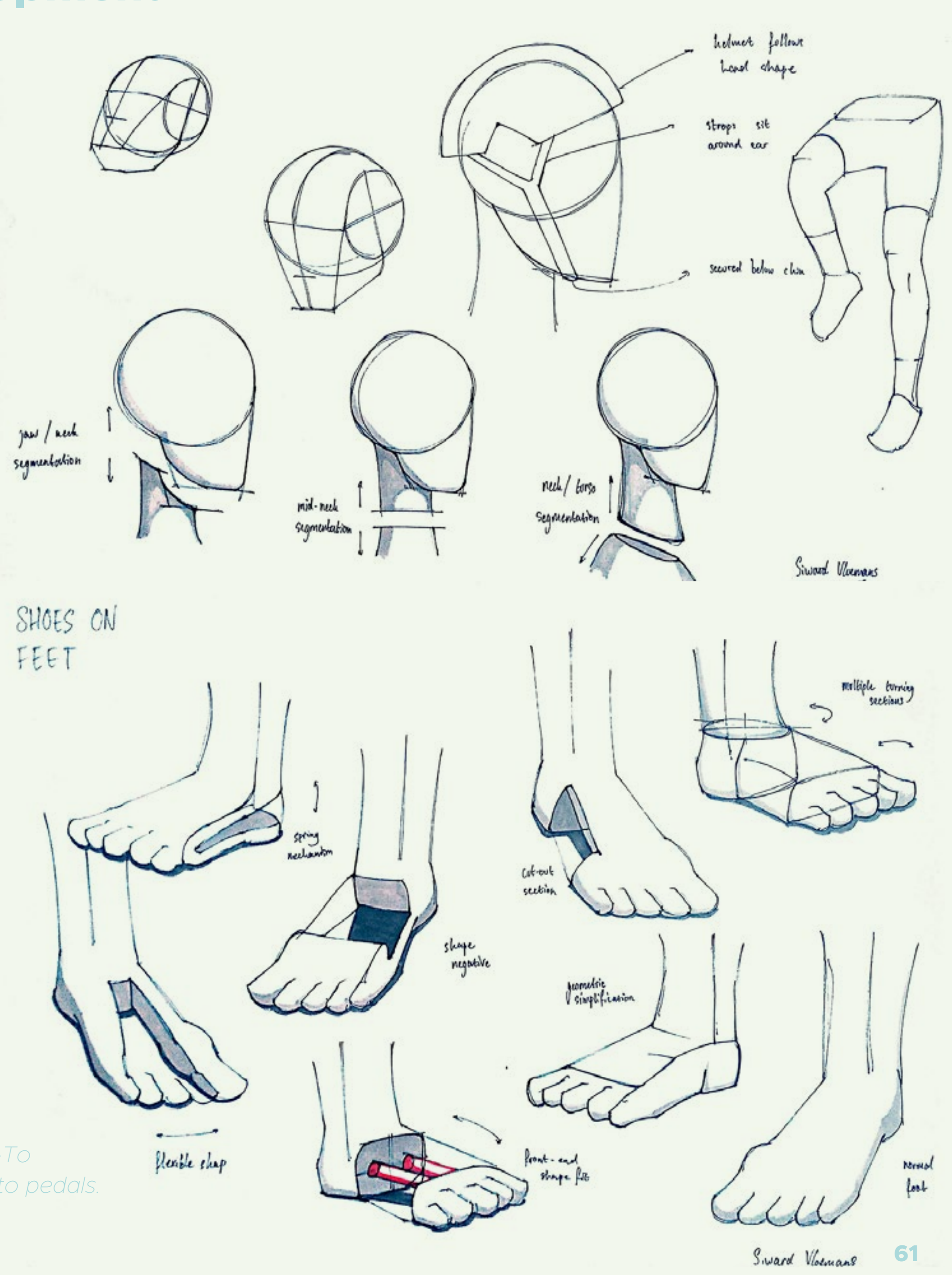


Figure 4.30: Design drawings of How-To connect head to torso & mount feet to pedals.

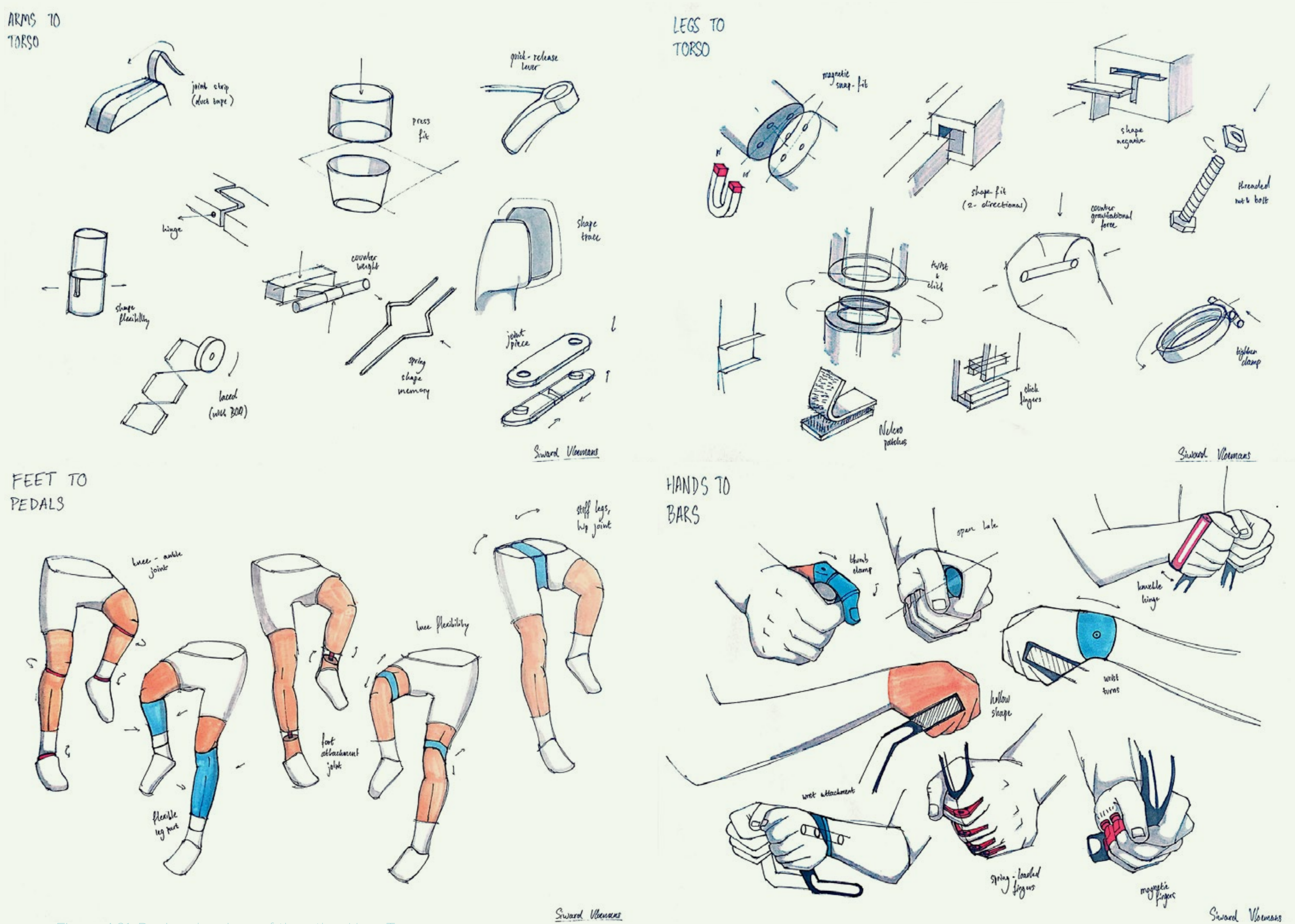


Figure 4.31: Design drawings of the other How-Tos

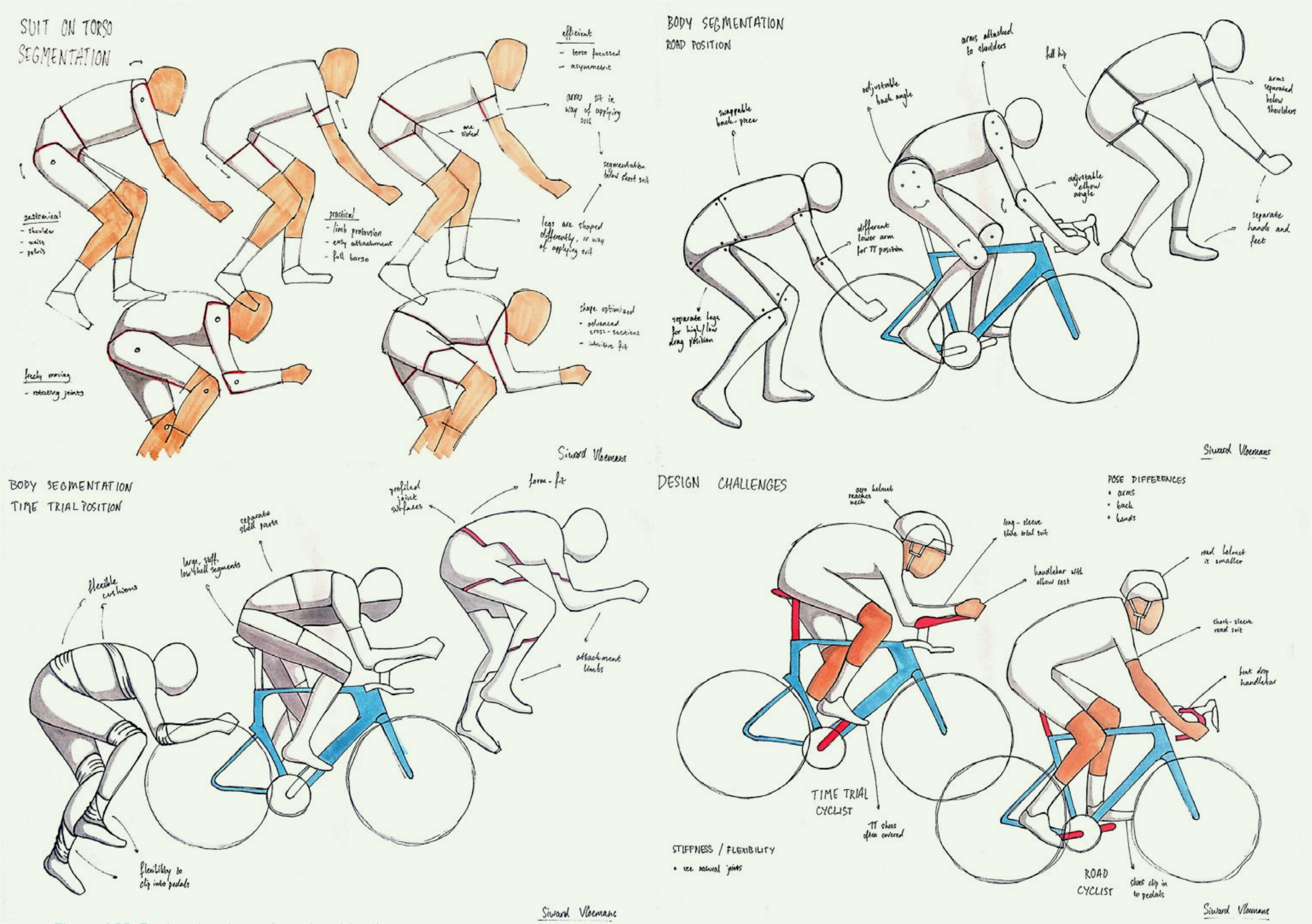
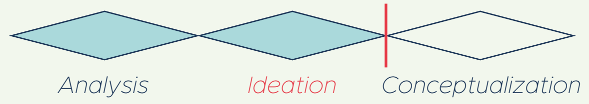


Figure 4.32: Design drawings of random ideation

4.3 Personalized Mannequin: Development

4.3.4 Morphological Chart

"Helps designers generate solutions in an analytical and systematic way." (Van Boeijen et al, 2020).



The goal of the Morphological Chart is to combine solutions to individual design challenges as a way to generate concepts. All individual ideas generated using How-Tos are placed in their respective positions in the Morphological Chart. Irrelevant ideas are removed and similar or duplicate ideas are clustered (Figure 4.33). Solutions to functions 2.1, 2.2 and 2.3 are identical as these share the same requirements. Only one solution is presented for function 3.1 as it proved successful for the Dumoulin Mannequin. Countless idea combinations can be made using the Morphological Chart. Three digital fabrication methods are used as the basis for idea combinations here. The methods are, in order: CNC milling & 3D printing combined (1), mainly 3D printed (2) and mainly CNC milled (3). The fabrications methods are further described on the following pages. The idea combinations are visualized in the Morphological Chart (Figure 4.34). Identical ideas or idea combinations are selected for some product functions. The idea combinations are more structurally presented on the following pages for clarification purposes.

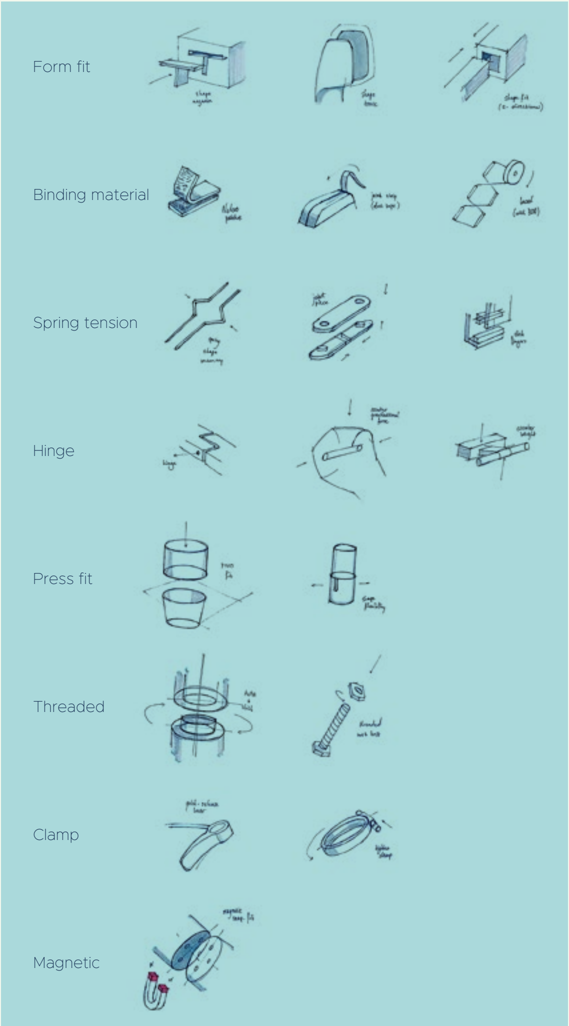


Figure 4.33: Clusters of similar ideas to combine.

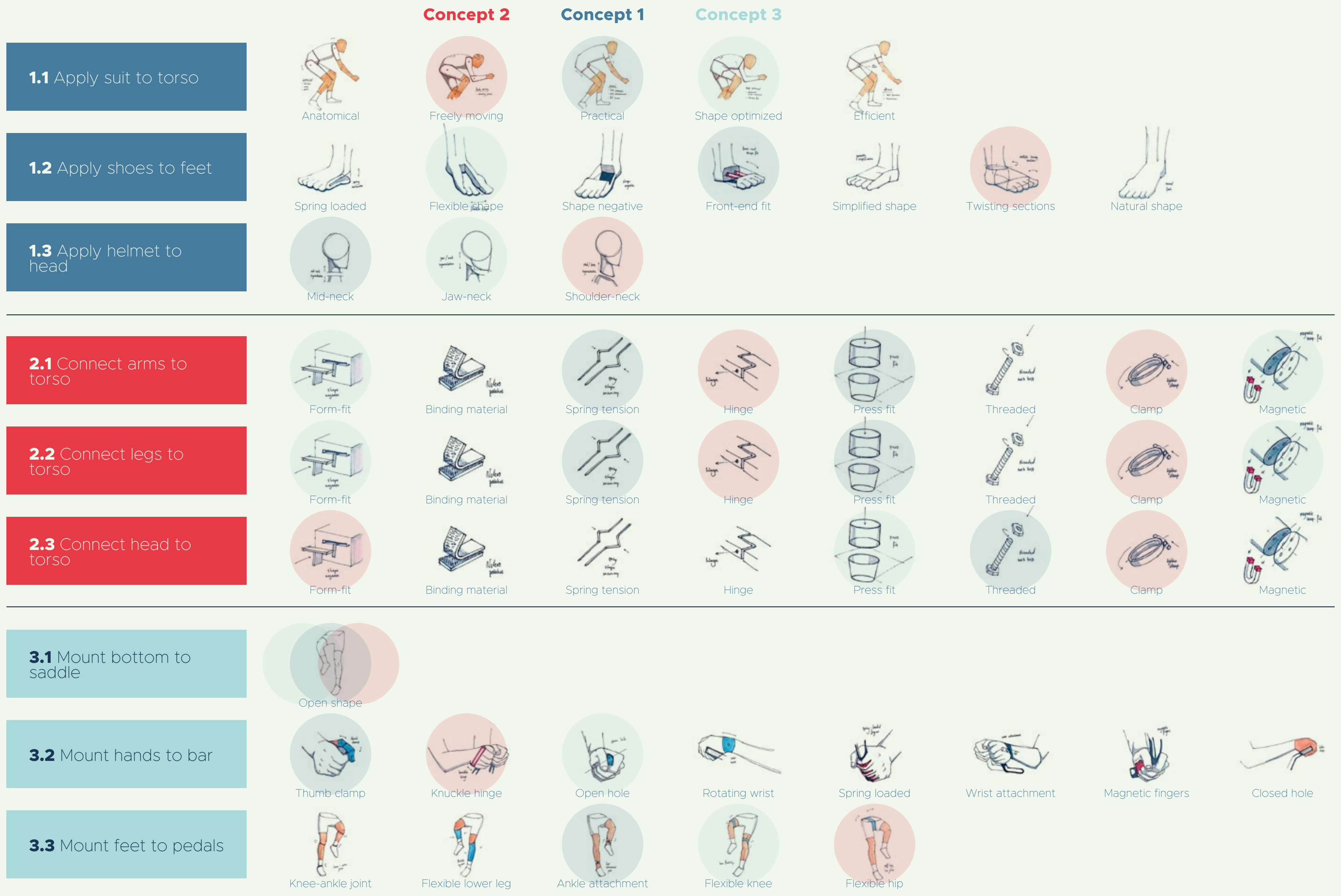


Figure 4.34: Morphological chart with solutions for each sub-function of the mannequin.

4.3.5 Concepts

The concepts generated are the result of a Morphological Chart, based on different digital fabrication methods. The following concepts are generated:

- Concept 1: Perses (Mixed fabrication)
- Concept 2: Astraeus (3D printed)
- Concept 3: Pallas (CNC milled)

Design solutions selected in the Morphological Chart are chosen specifically for the relevant fabrication method. A distinction is made between subtractive and additive manufacturing, as well as the specific method applied. The goal is to explore opportunities where production and design meet.

Subtractive Manufacturing

CNC Milling

"CNC machining uses computer software to control machine tools that cut complex 2D and 3D shapes out of blocks of material. CNC machining is very fast, accurate, and repeatable, capable of achieving precise tolerances." (Figure 4.35).

"Rigid and flexible polyurethane foams are commonly used to make production parts in nearly every industry – including aerospace, automotive, recreation, consumer, and medical markets." (General Plastics, n.d.).

Figure 4.35: General Plastics. (n.d.). [Photograph of CNC milled surfaces].

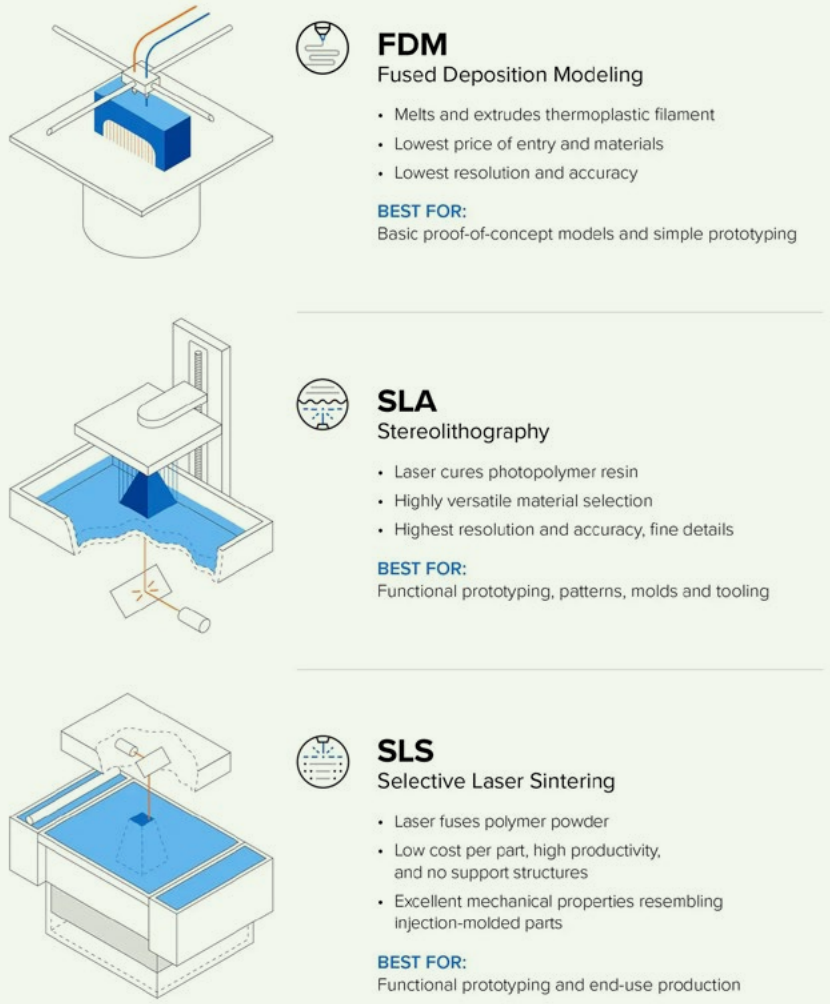


Figure 4.36: FormLabs. (n.d.). [Infographic of plastics 3D printing technologies].

Additive Manufacturing

Using knowledge from FormLabs, the three most established plastic 3D printing processes today are studied more closely (Figure 4.36).

Figure 4.37: FormLabs. (n.d.). [Photograph of FDM parts showing layer lines and inaccuracies in the surface].

Figure 4.38: FormLabs. (n.d.). [Photograph of SLA parts showing a smooth surface that requires little finishing].

Figure 4.39: FormLabs. (n.d.). [Photograph of SLS parts showing a grainy surface, but are easy to finish].

Fused Deposition Modelling (FDM)

"FDM has the lowest resolution and accuracy when compared to SLA or SLS and is not the best option for printing complex designs or parts with intricate features (Figure 4.37). Higher-quality finishes may be obtained through chemical and mechanical polishing processes. Industrial FDM 3D printers use soluble supports to mitigate some of these issues and offer a wider range of engineering thermoplastics, but they also come at a steep price." (FormLabs, n.d.).

Stereolithography (SLA)

"SLA is a great option for highly detailed prototypes requiring tight tolerances and smooth surfaces, such as molds, patterns, and functional parts (Figure 4.38). SLA is widely used in a range of industries from engineering and product design to manufacturing, dentistry, jewelry, model making, and education." (FormLabs, n.d.).

Selective Laser Sintering (SLS)

"The combination of low cost per part, high productivity, and established materials make SLS a popular choice among engineers for functional prototyping, and a cost-effective alternative to injection molding for limited-run or bridge manufacturing (Figure 4.39)." (FormLabs, n.d.).

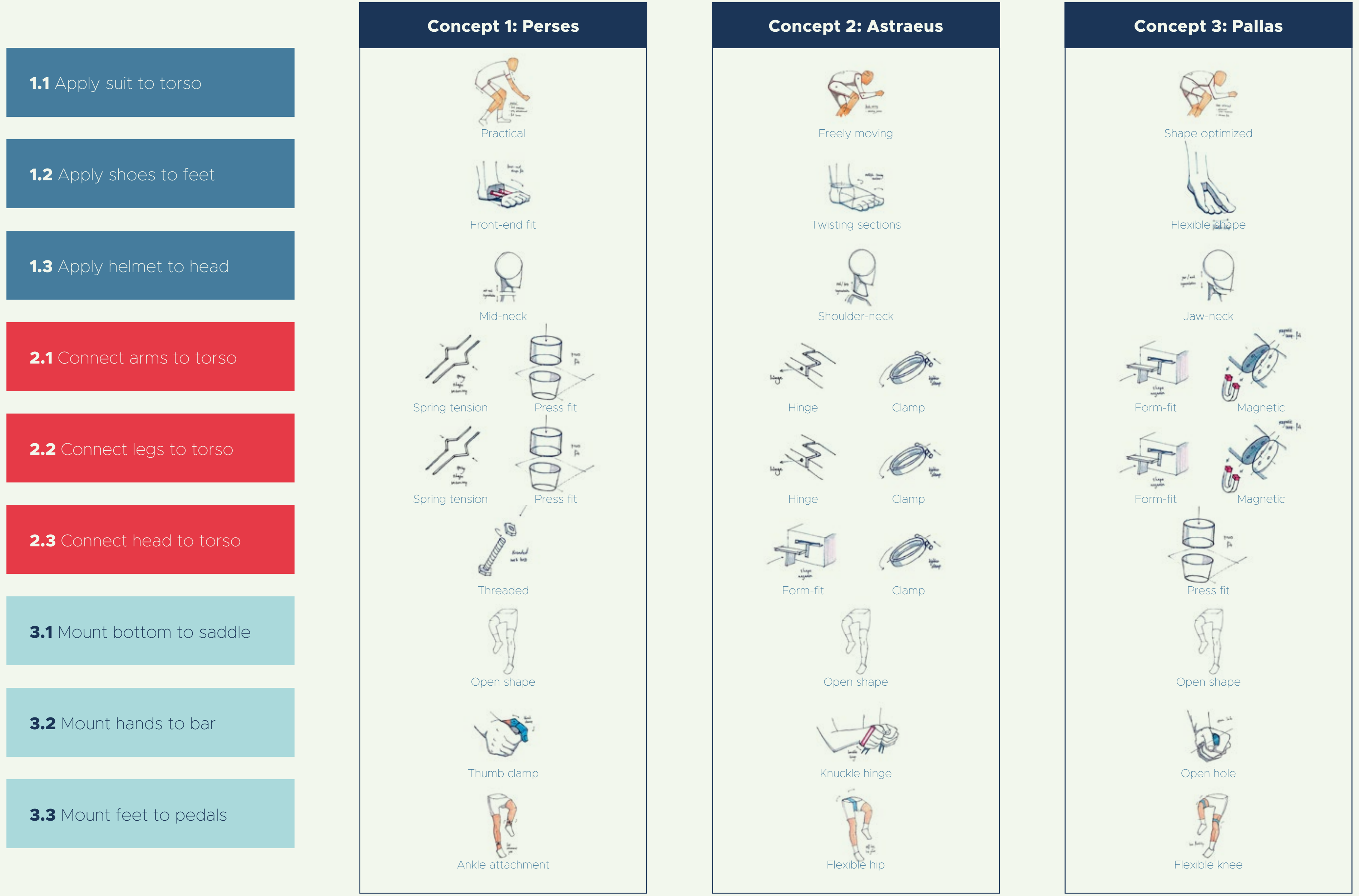
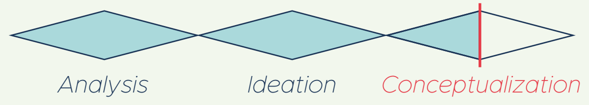


Figure 4.40: Idea combinations from the Morphological Chart for the Perses, Astraeus and Pallas concepts.

4.3.5 Concept #1



Perses is unique in its hybrid-fabrication method. As a combination of additive and subtractive manufacturing, Perses combines the speed of CNC milling with the accuracy 3D printing. Interfaces such as joints and mount have elaborate features due to the possibilities of Stereolithography 3D printing. These parts have a smooth, untreated surface that requires no finish due to the material properties of the ABS-like resin. That allows for some pose adjustability, while limbs itself can remain large because they are CNC milled. That makes Perses an altogether practical mannequin with only a few extra fabrication steps.

Fabrication: CNC milling (limb sections) & Stereolithography 3D printing (interfaces).

Material: Polyurethane foam & ABS-like resin.

Finish: None for 3D printed parts. Coating for CNC milled parts.

Properties: Sophisticated interfaces & largely solid limbs. Regular features & adjustability, but the downside of multiple fabrication methods.

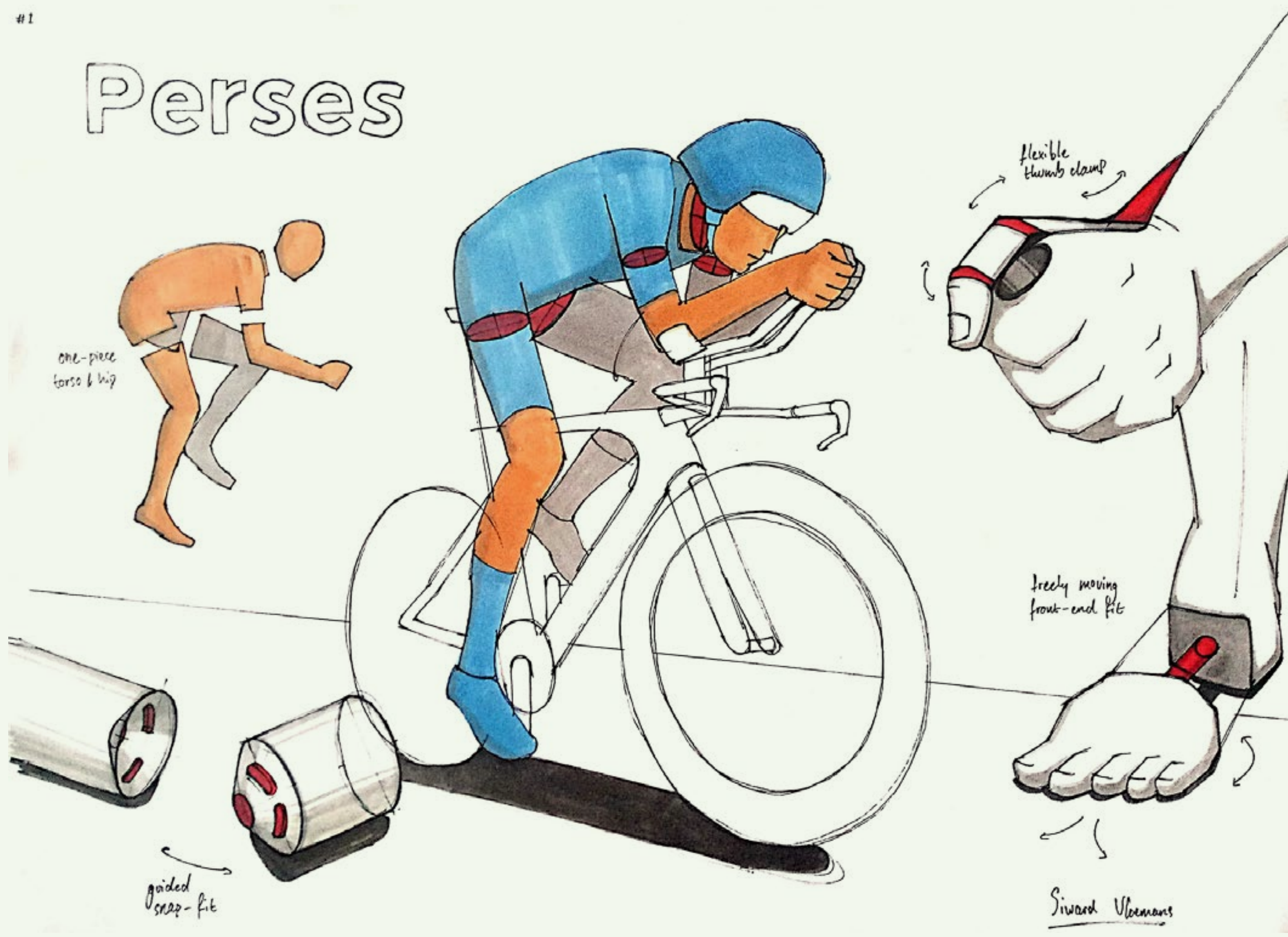


Figure 4.41: Visualization of the Perses mannequin concept.

4.3.5 Concept #2

Analysis — Ideation — Conceptualization

Astraeus is unique in its elaborate product features. Completely 3D printed using Selective Laser Sintering, Astraeus utilizes the fabrication method with extensive pose adjustability. Its many limb segmentations are accurately adjustable with refined, rotating interfaces. Being SLS 3D printed from nylon powder, the mannequin has excellent material properties. However, individual part size is limited so large limbs will consist of multiple parts. The powder-like surface requires extra finishing, but it bonds excellently to coatings. That makes Astraeus a sophisticated mannequin with advanced features, only at the cost of more extensive manufacturing.

Fabrication: Selective Laser Sintering 3D printing.

Material: Nylon powder.

Finish: Sanding & coating.

Properties: Sophisticated interfaces & hollow, combined limb sections. Advanced features & pose adjustability, but sub-optimal fabrication method for a product of this kind.

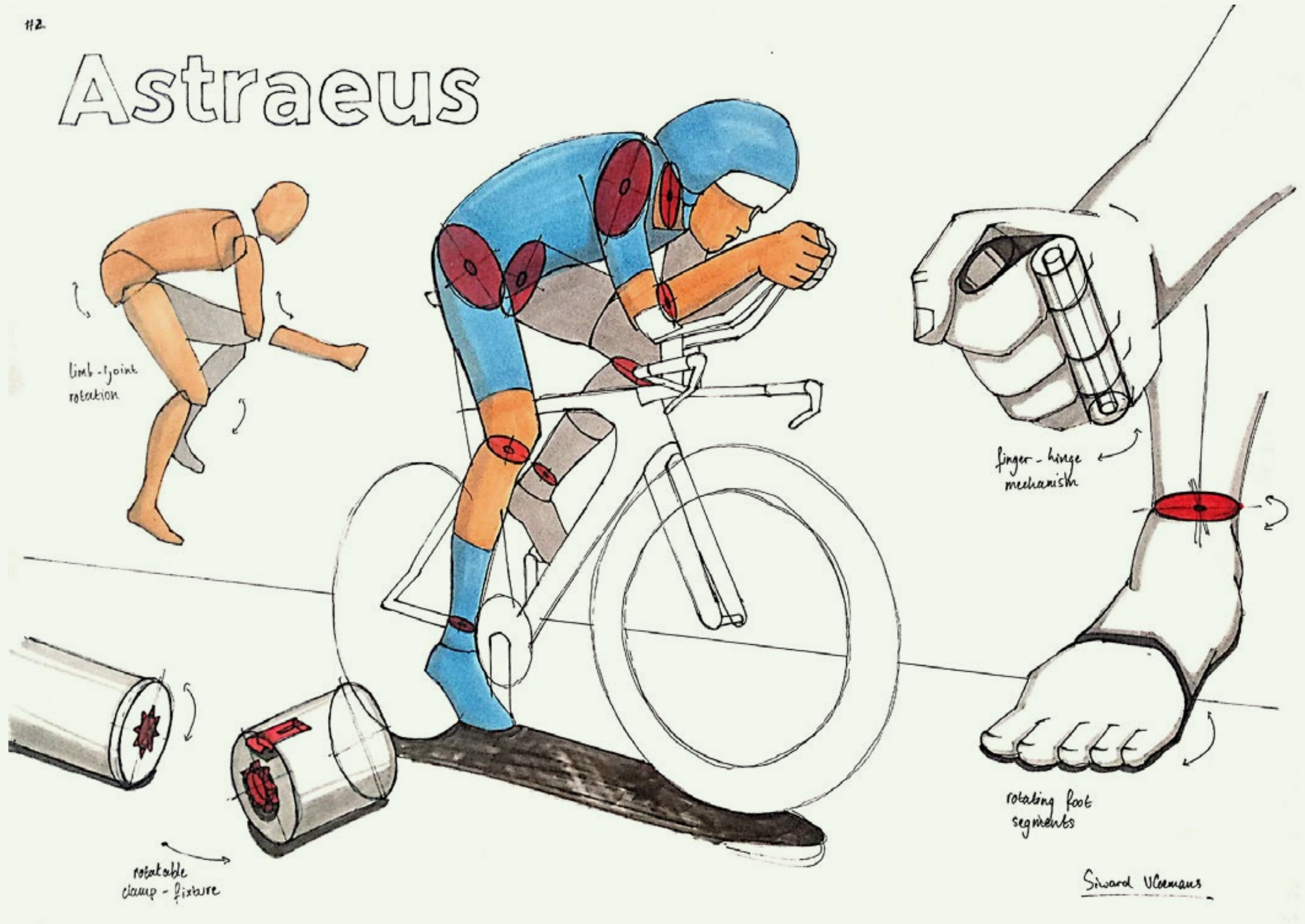


Figure 4.42: Visualization of the Astraeus mannequin concept.

4.3.5 Concept #3

Analysis — Ideation — Conceptualization

Pallas is unique in its overall simplicity and effectiveness. CNC milled from a block of foam, Pallas is manufactured quickly. With the mannequin's primary function being its shape, CNC milling is inherently suitable for this purpose. With shape-fitting limbs and snap-fitting magnets, the mannequin assembles intuitively and fast. Polyurethane foam can be used untreated, but bonds well to coatings if durability is necessary. Its largest flaws are minimal interface and segmentation features due to fabrication constraints. On the other hand, CNC milling fabrication is especially efficient. That makes Pallas a simple, but effective mannequin that does exactly what is required.

Fabrication: CNC milling.

Material: Polyurethane foam.

Finish: Coating.

Properties: Simplistic interfaces & largely solid limbs. Essential features & limited adjustability, but efficient fabrication method for a product of this kind.

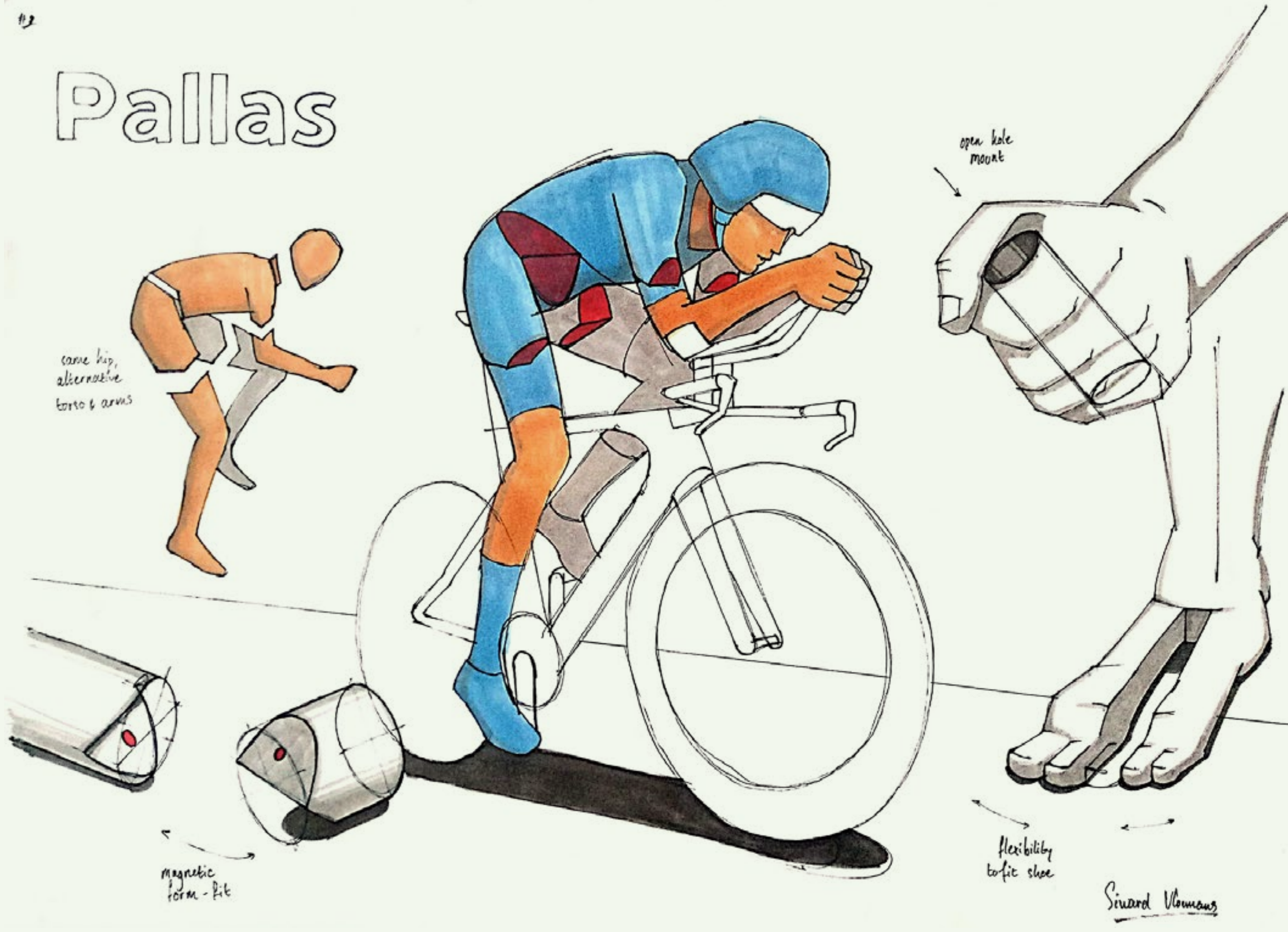
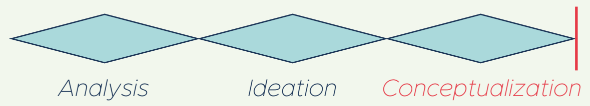


Figure 4.43: Visualization of the Pallas mannequin concept.

4.3.6 Harris Profile

"A graphic representation of the strengths and weaknesses of design concepts with respect to predefined design requirements." (Van Boeijen et al, 2020).



The goal of the Harris Profile is to rate concepts based on the List of Requirements and select the best concept. Desires from the List of Requirements are clustered in three categories to evaluate the concepts for the innovation sweet spot: Desirability, Feasibility and Viability. The Human-Centred Design method by IDEO identifies the potential of an innovation if all three conditions are met. They can be tested by answering some of the following questions (PermissionToPlay, n.d.):

Desirability
Is your idea needed or wanted?
Does it resolve their problems?
Does the intended audience see its value?

Feasibility
Do you have the know-how, skills, resources and technology to deliver?
How realistically can you make it happen?

Viability
Does the business case stack-up?
Is it commercially or economically beneficial?
Is the business model sustainable?

A Harris Profile compares concepts by rating based on product desires. The desires are clustered and ordered hierarchically. The method rates concepts in relation to one another instead of by absolute weight. Ratings towards the right are positive, ratings towards the left are negative. The horizontal red bars show the range of ratings for each category of the Innovation Sweet Spot. The vertical red line shows the average rating for each category.

The ratings are generally favourable for concepts Perses (1) and Pallas (3) with Astraeus (2) scoring lower positive ratings and higher negative ratings (Figure 4.44). The latter specifically lacks in terms of Viability, suggesting it is not a sustainable solution like the other concepts. CNC milling is a more suitable fabrication method as the mannequin relies mostly on its shape rather than its advanced features.

Concept 1: Perses scores well, but lacks in terms of Feasibility and Viability. Concept 3: Pallas outperforms it in each category. This concept is recommended and discussed with the client halfway this project. Concept 3: Pallas is eventually selected, but redesigned once with the best features of the other concepts combined.

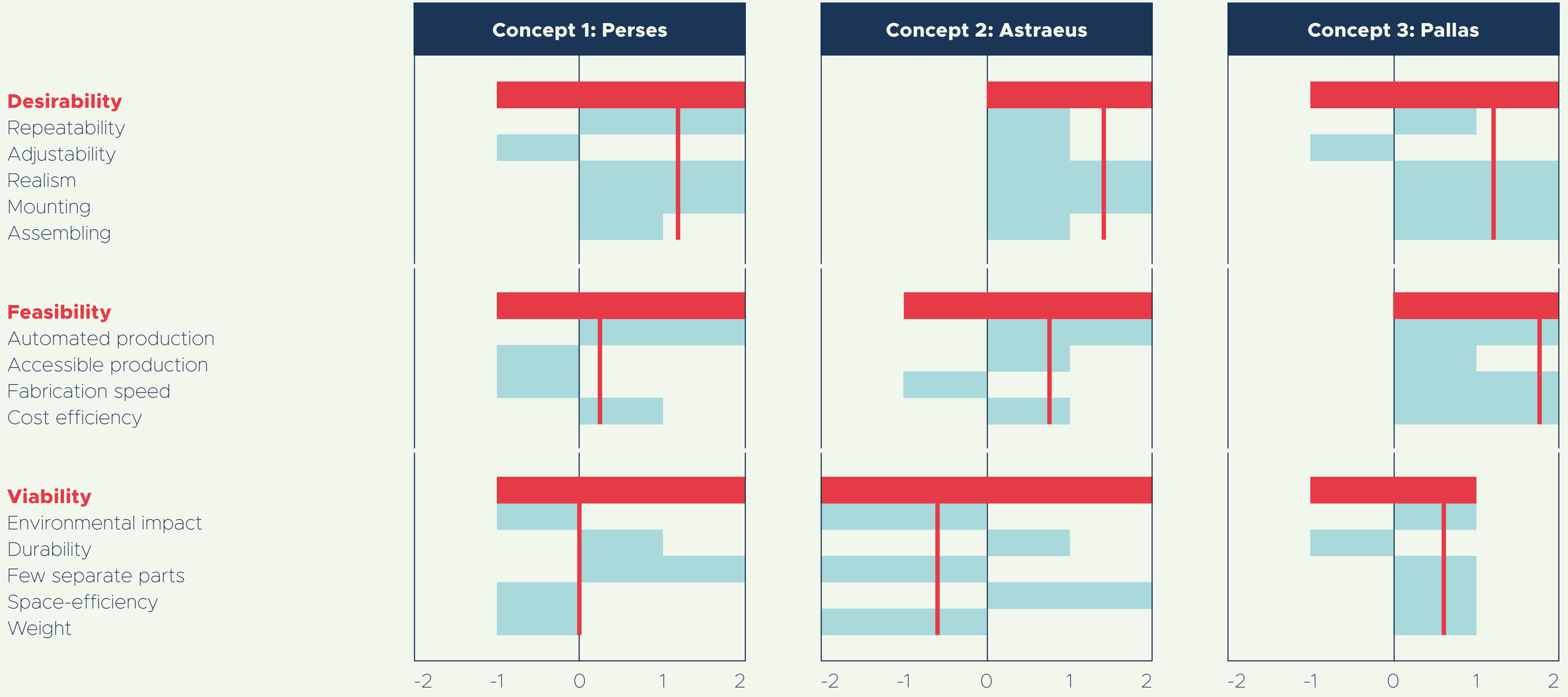
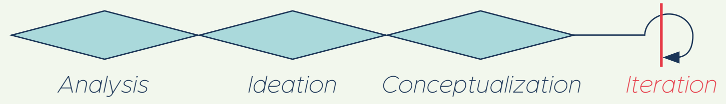


Figure 4.44: Harris Profile concept selection.

4.3.7 Redesign

Atlas is a redesign of the previously selected concept Perses. The Morphological Chart has been applied once again to generate a design based on the most favourable elements (Figure 4.45). The result is the Atlas mannequin design (Figure 4.46). This is the basis of the development phase later in the project.



Atlas is an evolution of the Perses concept, applying its hybrid-fabrication method to a preferred idea combina-tion. It utilizes the speed of CNC milling as much as possible, keeping limb segmentation and the required 3D printed parts to a minimum. This is possible due to the simplicity of all magnetic, form-fitting attachment inter-faces. Unlike Perses, Atlas uses Synthetic Laser Sintering for the excellent material performance properties of nylon PA12. Both CNC milled and SLS 3D printed parts work excellently with surface finishes for a smooth and functional mannequin. That makes Atlas the best of all previous mannequin designs.

Fabrication: CNC milling (limb sections) & Synthetic Laser Sintering 3D printing (interfaces).

Material: Polyurethane foam & Nylon powder.

Finish: Sanding and coating for 3D printed parts. Coating for CNC milled parts.

Properties: Sophisticated interfaces & 2-piece joined limbs. Regular features & adjustability, but the downside of multiple fabrication methods.

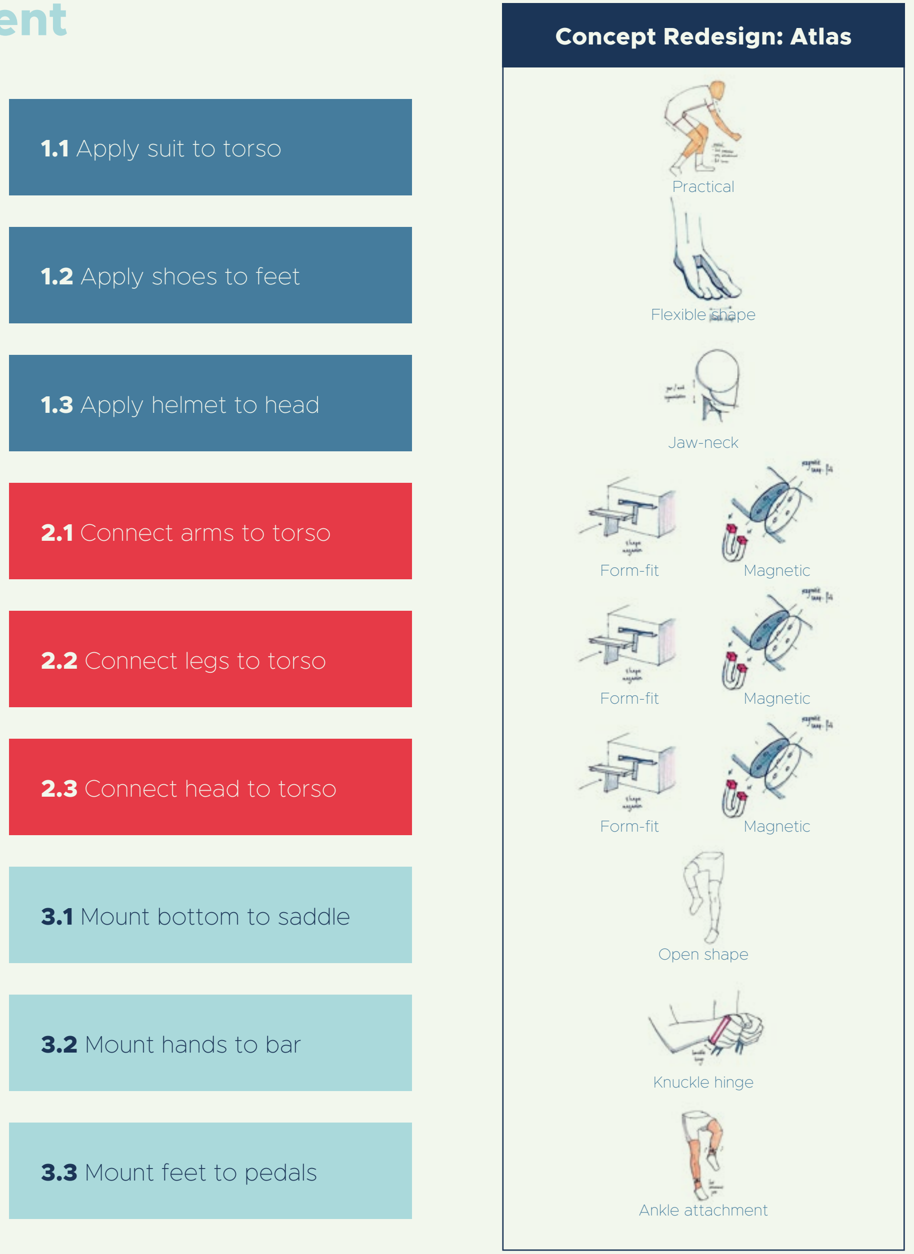


Figure 4.45: Idea combination from the Morphological Chart for Atlas.

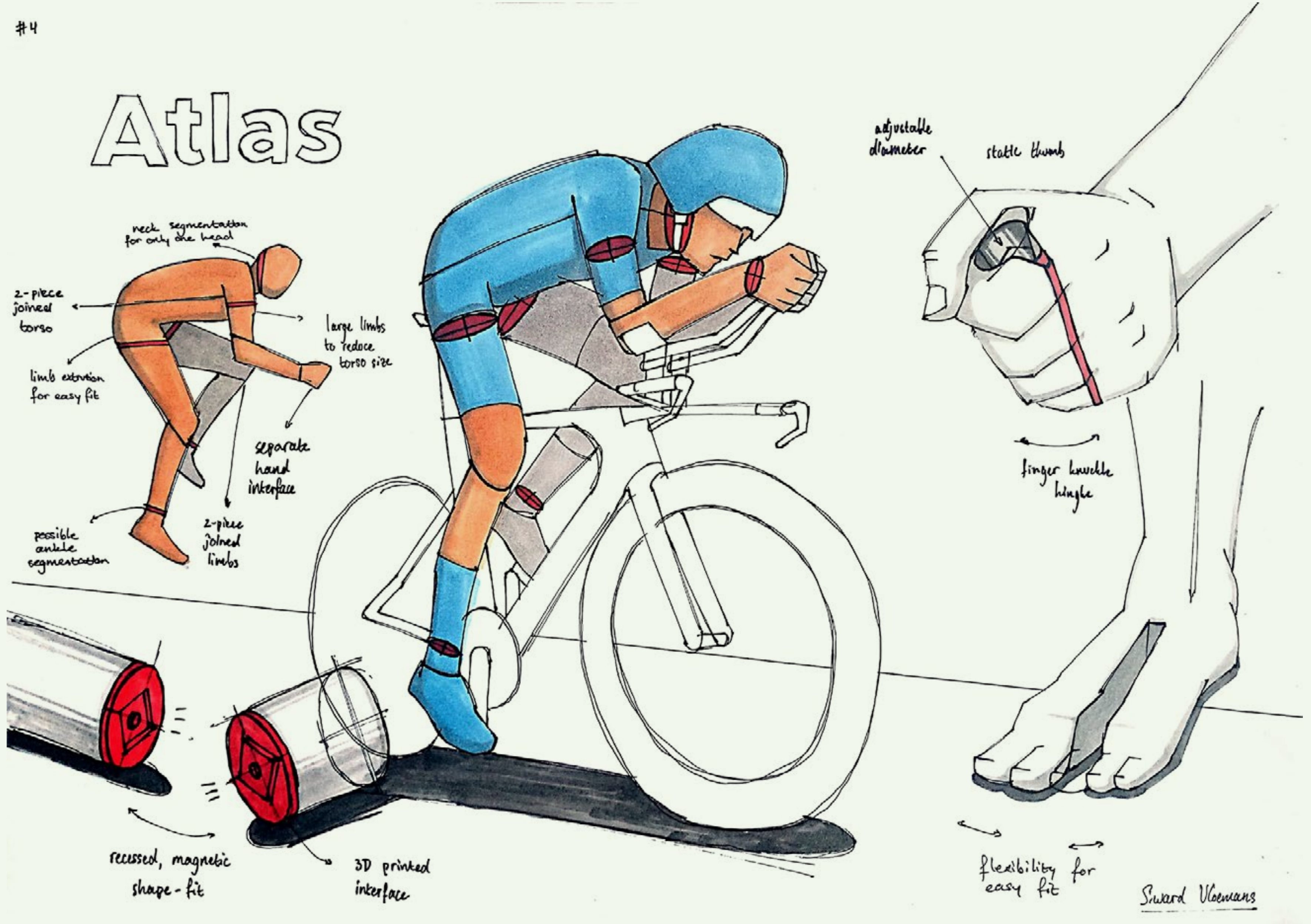


Figure 4.46: Visualization of the Atlas mannequin concept.

4.4 Design Features

Methods from the development phase of this project lead to separately identified product features. Each feature is given individual attention to design it further. The design features are split into six groups: 3D Digital Model, Interaction Segmentation, Attachment Interfaces, Bicycle Mounts, Materials & Production and Full-Scale Prototype. Each design features is briefly discussed on this page and further in depth on the following pages.

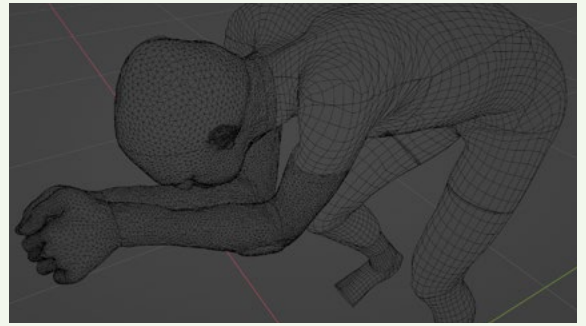


Figure 4.47: Digital rider model of the mannequin.

Figure 4.48: Mannequin limb segments.

Figure 4.49: Attachment interfaces on all limbs.

Figure 4.50: Hand interface from flexible material.

Figure 4.51: Segments from different materials.

Figure 4.52: Full-scale mannequin prototype.

3D Digital Model
The rider is 3D scanned and processed identically to the Generic Model, but several features are applied to it after. Segment faces are rounded with bevels and attachments slots are placed to attach the interfaces (Figure 4.47).

Interaction Segmentation
The mannequin requires segmentation to apply all cycling gear and to mount effectively to the bicycle. Considerations are made to achieve the best user interaction with the required product performance (Figure 4.48).

Attachment Interfaces
The segmented limbs must be easily attachable and stay in place at all times. Each limb is analysed and several prototypes are made to develop the attachment interface (Figure 4.49). This includes testing with 3D printing and application of magnets.

Bicycle Mounts
The assembled mannequin mounts to the bicycle at three points and requires appropriate design features. The bicycle is analysed and three mounting interfaces are developed, focussing on attaching hands to the handlebar (Figure 4.50).

Materials & Production
An ultra-personalized product with the size this mannequin is challenging to manufacture, so a study is conducted into materials & production. Experts are consulted and several materials are tested to design this feature (Figure 4.51).

Full-Scale Prototype
A full-scale prototype of the mannequin is produced in order to validate the designed features. Manufacturing a personalized mannequin is complex and the process is described in detail Figure 4.52).

Cyclist Mannequin - Siward Vloemans

4.4.1 3D Digital Model

The procedure to capture and process the digital model is identical to the workflow of the Generic Model. The 3D scanning participants posed naturally to capture a realistic model. The mannequin is modelled minimally to look as realistic as possible, but a few modifications improve user interaction and make this a better product. The modifications include the mesh applied to correspond the model, bevels near sharp edges and slots for the attachment interfaces.

Specifications

- Natural cycling position
- High drag leg position
- Separated hands

- Standardized hands, feet & face
- Shoes replaced by feet
- Bicycle attachments removed
- 50K Uniform, triangle mesh

Mesh

A 50K resolution, uniform, triangle mesh corresponds the processed model. The mesh is smoothened to hide individual facets (Figure 4.53). Hands, face and feet are standardizations of the 3D scan data to improve their quality. Shoes are replaced removed to show bare feet. The model is scaled and oriented correctly and is otherwise left untouched.

Figure 4.53: Original mesh (left), 50K vertex resolution mesh (middle) and 50K smoothened mesh (right).

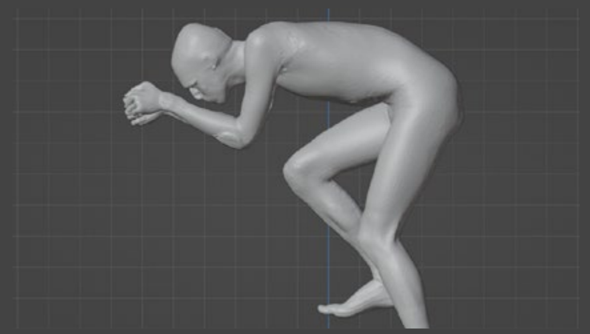


Figure 4.54: A rider model in high drag leg position.

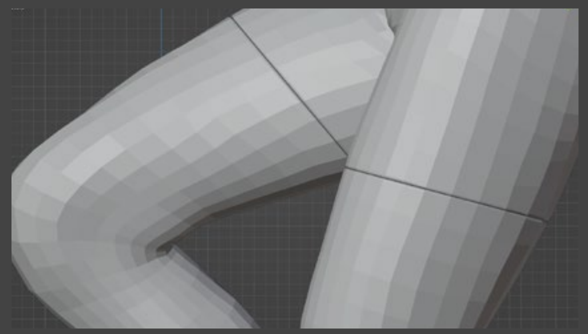


Figure 4.55: Bevels applied to the segment faces of the upper legs.

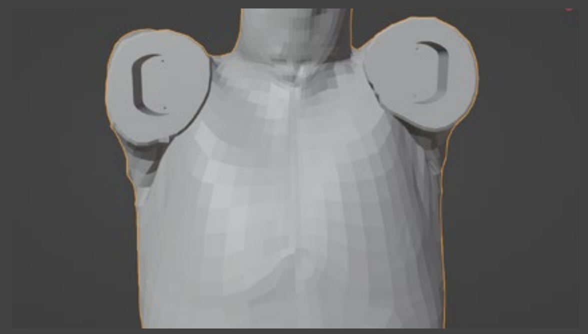


Figure 4.56: Recessed attachment slots in the upper arms of the torso.

Pose

The participating rider is holding his natural cycling pose in high drag position, with the left leg stretched and the right leg retracted (Figure 4.54). Unlike many riders' personal preference, the hands are separate and do not cover each other. This ensures better attachment to the bicycle. The rider is wearing a head cap to hide his hair.

Bevels

The model is segmented for interaction and rounded bevels are added to the segment faces (Figure 4.55). A fillet of 2.5 mm ensures tight cycling suits can smoothly slide over the edges without catching. Bevelled segment seams are hidden below the suit when the mannequin is dressed. A straight-edge bevel is used for the prototype to FDM 3D print without requiring support structures.

Attachment Slots

Recessed attachment slots are added to the segment faces (Figure 4.56). The slots include screw socket holes. The attachment interfaces are added during assembly of the product and can be replaced in this manner. Slots are included for both male and female side of the attachment interface for correct positioning.

4.4.2 Interaction Segmentation

The mannequin is segmented for user interaction with separate legs, arms and hands (Figure 4.57). The leading requirement is that a cycling suit must be applied to the mannequin, so legs and arms are detachable. The wrists are segmented for easy mounting to the handlebar and better repetition of the mannequin's position on the bicycle. The amount of separate limbs is kept to a minimum for ease of use and optimal product performance.

Arms
Orientation: Horizontal
Position: Protrusion of 55 mm
Interface: Recessed in torso

Legs
Orientation: Perpendicular to limb direction
Position: Halfway between crotch & knee
Interface: Recessed in torso

Hands
Orientation: Vertical
Position: Wrist
Interface: Recessed in arm

Overall
Bevel of 2.5 mm on segment edges

Figure 4.57: Segmentation of the mannequin in time trial pose.

Analysis

Interaction

The segmentation of the mannequin is based primarily on the cycling kit it is required to wear. The defining garment is the cycling suit, consisting of a connected pair of shorts and jersey. The suit is impossible to apply to a one-piece mannequin and requires segmentation of the legs and arms. Protrusion of the legs and arms from the torso must be minimized for easy application of the suit and optimized for easy attachment of the limbs.

A long-sleeve time trial suit (Figure 4.60) is the most challenging garment to apply. Regulations in professional cycling are defined by the International Cyclist Union. According to Article 1.3.026 of Clarification Guide Of The UCI Technical Regulation:

"When competing, all riders shall wear a jersey with sleeves and a pair of shorts, possibly in the form of a one-piece skinsuit. By shorts it is understood that these are shorts that come above the knee. Sleeveless jerseys shall be forbidden."

Performance

The segmentation is also based on the loads applied to the mannequin during use. The defining elements are connections points to the bicycle and the mannequin's centre of mass. Air resistance is of negligible influence in relation to the other forces on the mannequin, despite it being the product's research purpose.

Contact area and attachment plane angle must be optimized for reliable attachment of the limbs. Free-body diagrams of the time trial (Figure 4.58) and the road pose (Figure 4.59) show the difference between the two.

Most of the mannequin's weight is supported by the saddle, which is balanced by the mounts to the pedals. The road pose has only one support point for each arm, which is distanced far from the mannequin's centre of mass. This means a longer Moment Arm, resulting in a larger Moment of Inertia. The road pose therefore requires the appropriate design features near the arms and hands to support the loads.

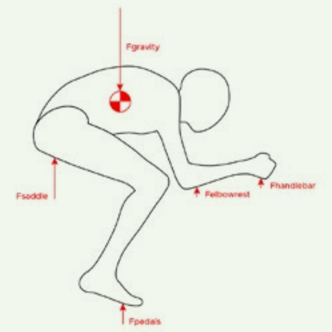


Figure 4.58: Free-body diagram of the mannequin in time trial position.

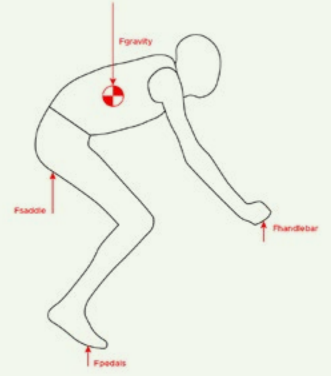


Figure 4.59: Free-body diagram of the mannequin in road position.

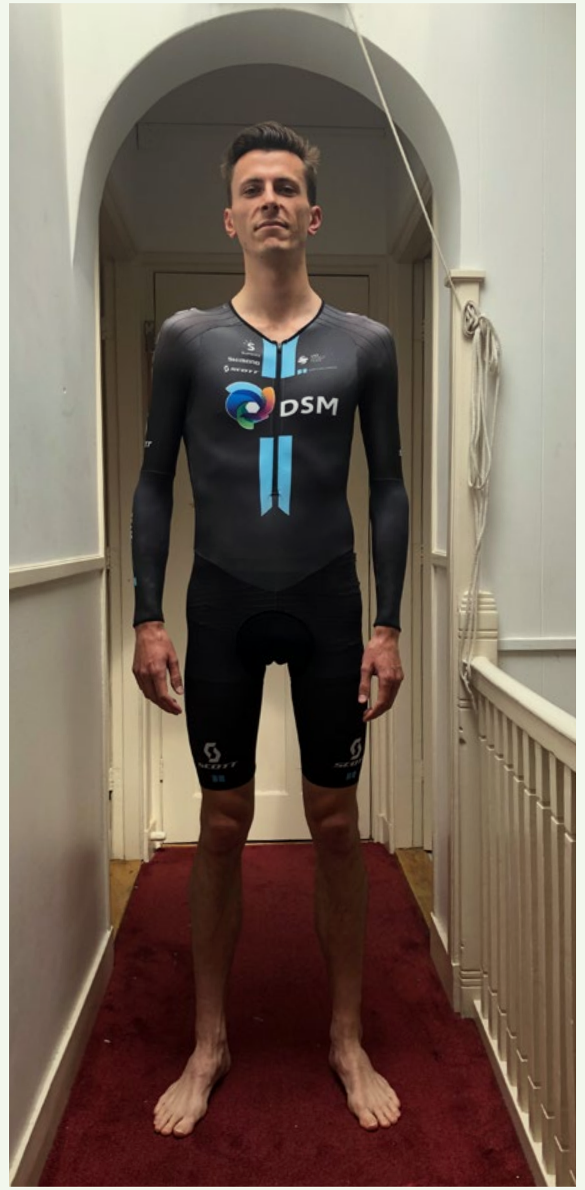


Figure 4.60: A time trial cycling suit with long sleeves.

Concept

A concept visualization shows limb segmentation of the mannequin (Figure 4.61). The image only shows the road pose, but segmentation applied to the time trial pose is almost identical.

An essential design element is the limb protrusion from the torso used to roll the garment's sleeves. There must be sufficient space to clear the attachment interface for easy interaction.

The legs itself are not segmented and they remain mounted to the pedals during any interaction, unless the socks or shoes are changed. That involves their placement on the ground upon detachment of the torso.

The arms, on the other hand, are segmented from the hands. The reason being that the hands are the only mounting point to the bicycle that are significantly different for a mannequin than for a human subject (they involve hand muscle force). The hands can be mounted firmly with the first interaction, making the mannequin's position more easily repeated in the following interactions.

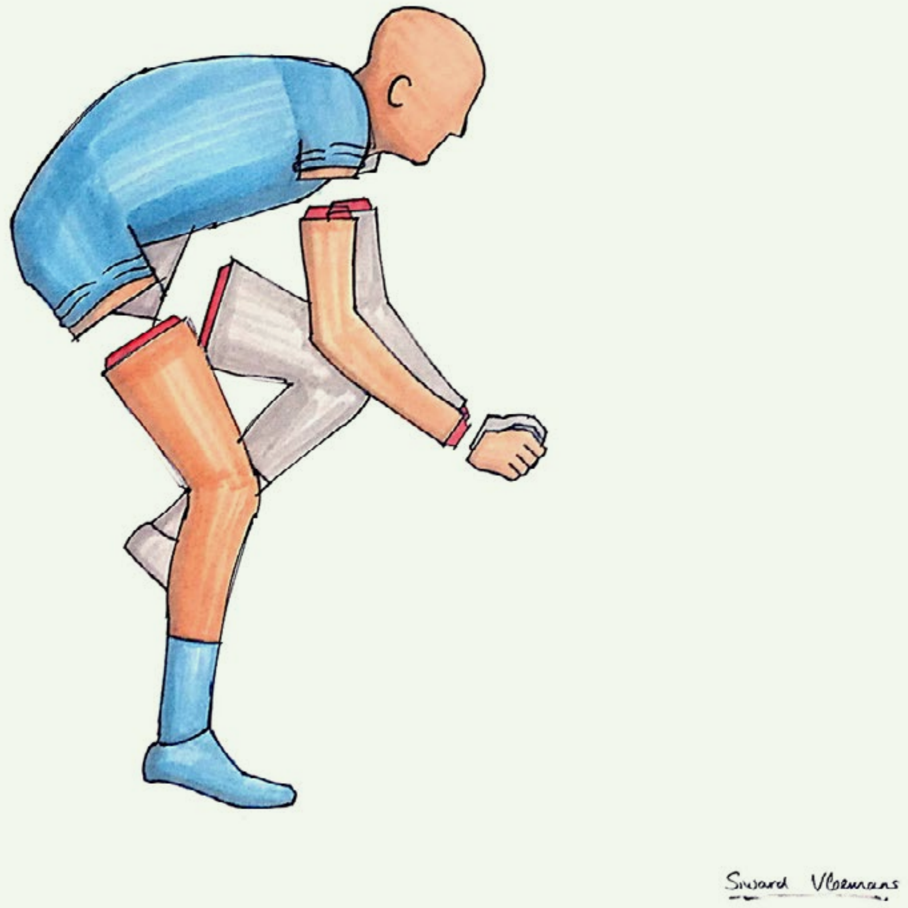


Figure 4.61: Segmentation of the mannequin in road pose.

Interaction

To research how much limb protrusion from the torso is required for a proper fit of the suit, a simple test is performed. A representative subject (length 194 cm, mass 70 kg) is dressed in a time trial suit (size M) and rolled back the sleeves as far as possible.

Orientation

As is apparent in Figure 4.64, the arm and leg sleeve edges sit perpendicular to the protruding limb. From the clothing perspective it is therefore effective to segment as such.

Bevel

Evaluation of the Dumoulin Mannequin has indicated that sharp segment edges catch the cycling suit during application of the garment (Figure 4.62). A bevel is therefore applied to round the edges. The downside is the inaccurate depiction of the human body, but the interactive upside is preferred in this situation. A bevel of 2.5 mm is applied to the segment edges for easy garment application, minimizing geometry manipulation while maximizing contact area between limbs.

Figure 4.62: Sharp edges of the Dumoulin mannequin's torso catch the suit.

Legs

As for the position of the segmentations, there must be a margin between sleeve end and segment edge. The legs are less critical limbs as the suit is more easily applied there. Extra protrusion is preferred here, as the bib may interfere between the legs. Segmentation is therefore applied halfway between the crotch and the knee. The attachment interface is recessed on the side of the torso.

Arms

The arm are more critical limbs as the suit is most challenging applied here. The shoulders are the last body part covered and the suit has become tighter as a result. Evaluation of the Dumoulin mannequin has indicated that his arms protrude too much (Figure 4.63). Based on the test and by digitally measuring the dimensions, an arm protrusion of 55 mm is determined. The attachment interface is recessed on the side of the torso.

Figure 4.63: Long arm protrusions make the suit challenging to apply around the shoulders.

Hands

The hands are less critical limbs as it comes to applying the suit as it is only influenced by the sleeve end. The UCI states that:

"By jersey with sleeves it is understood a jersey that leaves hands not covered. Consequently, integrated gloves in a jersey or a skinsuit are prohibited."

Therefore, it is most optimal to segment the arm at the wrist joint. This limits the size of the hand interface and the attachment interface is therefore extended on this end of the limb.

Figure 4.64: Representation of a cycling pose with the suit's sleeves rolled far back.

Performance
From the performance perspective a different segmentation approach is apparent. It may be used to adjust decisions made based on user interaction alone.

As only vertical loads affect the mannequin, horizontal segmentation is most effective. This avoids any different loads from forming.

Legs
For the legs, this differs significantly from the perpendicular segmentation determined previously. However, the legs are used mostly to balance the mannequin rather than to carry its weight as that is mostly carried by the saddle. Therefore performance quality is less important than interaction quality in this case. The legs remain segmented perpendicularly to their limb direction.

Arms
For the arms, this differs less from the perpendicular segmentation determined previously. It was also identified as a critical area in the free-body diagrams. Therefore performance quality is more important than interaction quality in this case. The arms are segmented horizontally.

Hands
For the hands, this differs significantly from the perpendicular segmentation determined previously. As horizontal segmentation would influence the interaction so significantly, a vertical segmentation is applied to the hands. This requires a strong attachment interface, but avoids any sliding if designed appropriately.

Figure 4.65: Standing pose with the suit's sleeves rolled back as far as possible.

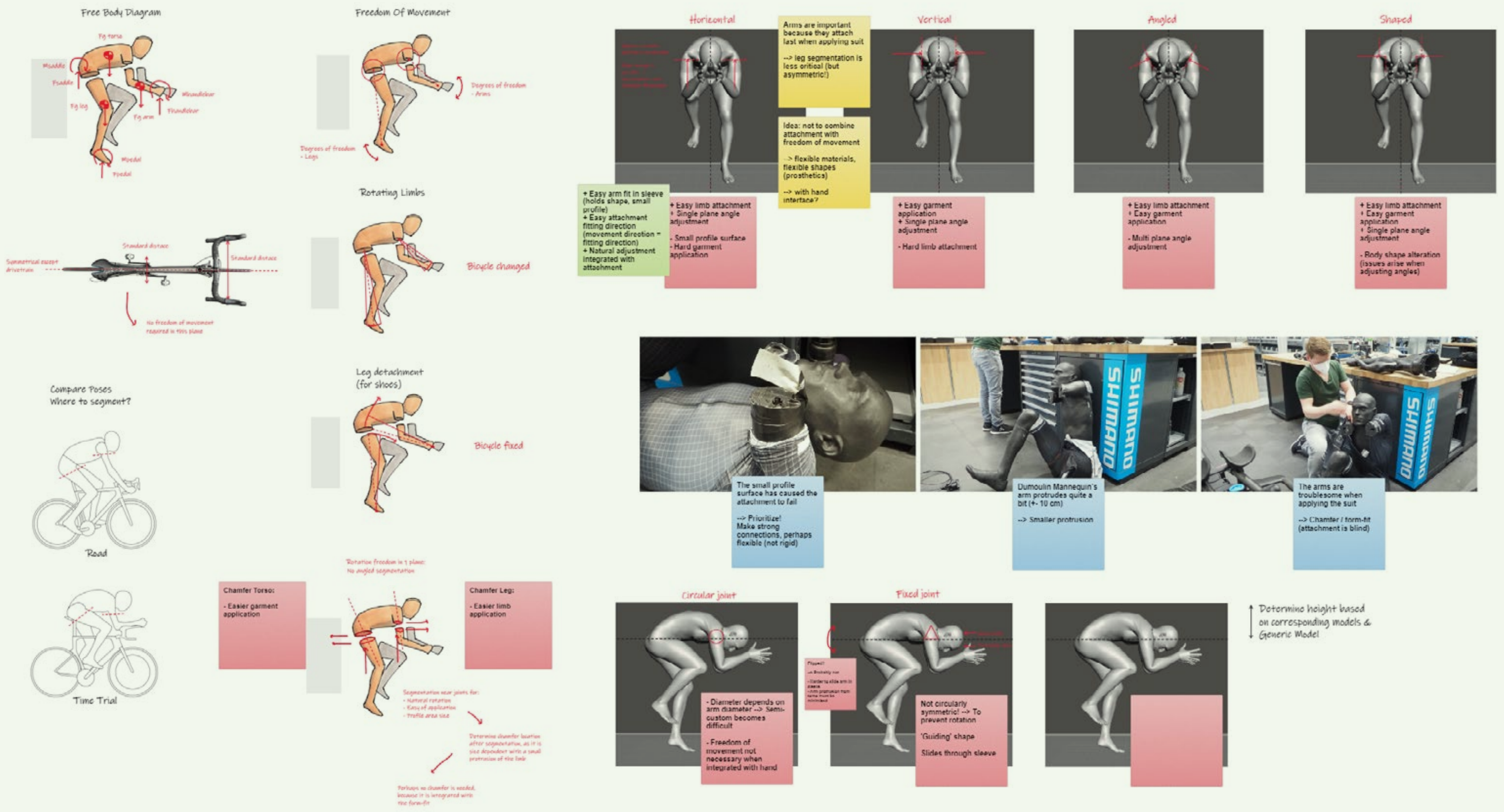


Figure 4.66: Visualization of the analysis and design process of the interaction Segmentation

4.4.3 Attachment Interfaces

The mannequin has magnetic, form-fitting attachment interfaces to easily assemble and disassemble the limbs (Figure 4.67). A pair of interfaces consists of a male & female side, identical for each Personalized Mannequin. The interfaces are fitted with a pair of N35 Neodymium magnets with alternating positive & negative poles for a guided attachment.

The attachment interfaces come in three sizes optimized for the legs, arms and hands. The shape is based on the cross-section profile of each one, maximizing surface contact area. All interfaces have a rounded shape to fit the CNC milled attachment slot. This also guides the interface form during attachment, just like the chamfered wall.

Screw sockets are included in the interfaces for fastening to and removing from the limbs. Colour coding is applied to distinguish left and right limbs. The attachment interfaces are SLS 3D printed from PA12 for high strength material properties. The limbs have recessed attachment slots to place the attachment interfaces.

Specifications

Wall thickness:	1 mm
Corner radius:	Ø 5 mm
Screw offset:	5 mm
Screw socket:	Ø 8 mm
Screw hole:	Ø 4 mm
Magnet socket:	Ø 21 mm
Magnet depth:	3 mm

Figure 4.67: Design of the arm attachment interface on various limbs.

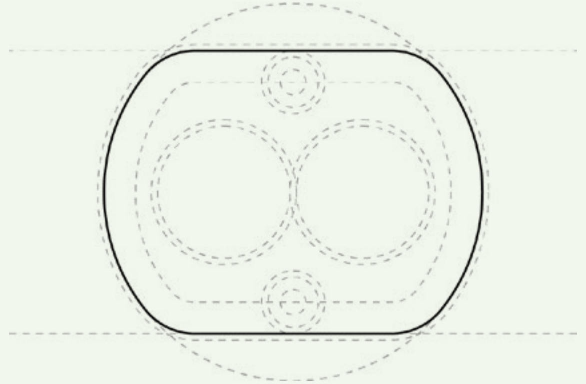


Figure 4.68: Cross section of the arm interface.

Attachment Slot Arm

The arm attachment interface (Figure 4.71) has two magnet slots (Figure 4.68). Alternating poles allow for a fit in only one orientation. Two screw slots fit exactly in available space between the magnets. As the cross section is relatively small, it is enough to hold the interface in place.

Length:	60 mm
Width:	45 mm
Height:	20 mm

Figure 4.71: Arm interface during attachment.

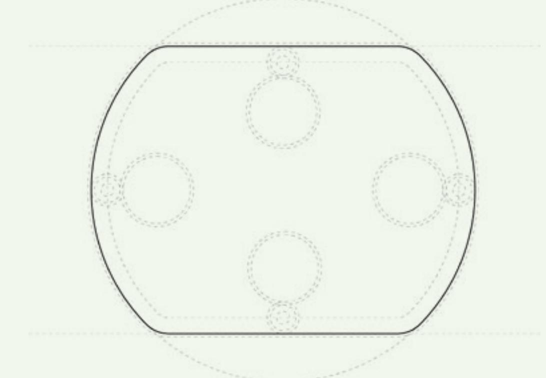


Figure 4.69: Cross section of the leg interface.

Attachment Slot Leg

The leg attachment interface (Figure 4.72)has four magnet slots, because the extra space available (Figure 4.69). The magnets are maximally spaced to utilize the magnetic force during attachment. Alternating poles allow for a fit in only one orientation. Due to its large size, the leg interface is somewhat flexible. Four screw slots hold the interface effectively in place.

Length:	120 mm
Width:	90 mm
Height:	20 mm

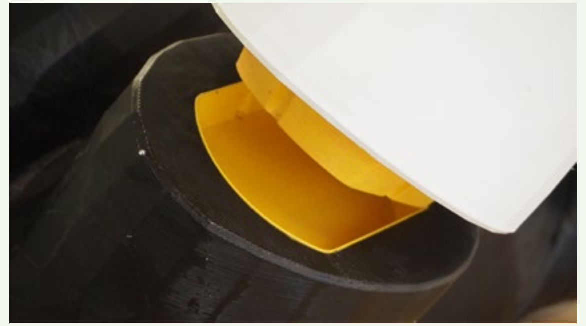


Figure 4.72: Leg interface during attachment.

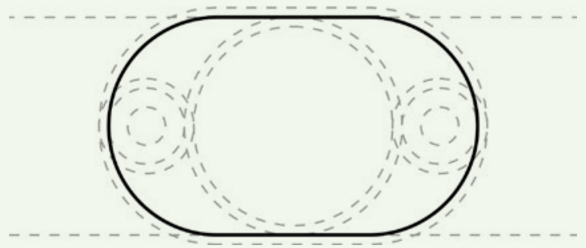


Figure 4.70: Cross section of the wrist interface.

Attachment Slot Wrist

The wrist attachment interface (Figure 4.73) only has one magnet slot (Figure 4.70). Subsequently, the interface has no alternating poles. Two screw slots fit exactly next to the magnet. The cross section of the wrist is so small that this interface uses all the available space.

Length:	39 mm
Width:	23 mm
Height:	20 mm

Figure 4.73: Wrist interface during attachment.

Prototyping

Modelling

The development process of the attachment interfaces focussed on the arm as most force is applied to it. The interfaces of the leg and wrist are based on this design. The three differ primarily in the available contact surface between the limbs. Legs have a large cross section and are easy to work with, while wrists have a small cross section and are more challenging.

Figure 4.74: Male side of the interface modelled in SolidWorks.

The attachment interfaces are digitally modelled in SolidWorks to their exact dimensions (Figure 4.74). The mod-els are exported as STL files. The exported files are loaded in Ultimaker Cura. The Support and Adhesion boxes to generate a brim on the print bed and support structures for overhanging features (Figure 4.75). The models are exported as G-code files.

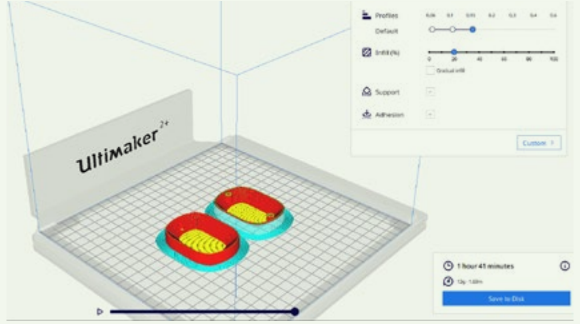


Figure 4.75: Slice the model and adjust settings to automatically generate a 3D print command.

Fabrication

Cura 3D print settings.

- Material: PolyLactic Acid filament
- Machine: Ultimaker 2+
- Nozzle: Ø 0.4 mm
- Layer height: 0.15 mm
- Time: 2-3 hours

Figure 4.76: The object is FDM 3D printed layer by layer.

The brim and supports are easily removed with a pair of pliers. Rough edges or filament remains are quickly finished with sanding paper (Figure 4.77).

Figure 4.77: After removing the brim and support, the result needs little finish.

Assembly

Adhesive neodymium magnets with N35 strength.

- Square: 20 x 20 x 1 mm
- Round: Ø 18 x 2 mm
- Round: Ø 20 x 2 mm

The magnets are easily applied to the inside of the attachment interfaces (Figure 4.78). The adhesive works effectively to keep the magnet in place. They also keep themselves in place due to the magnetic field. They are out of the way of any direct attachment mechanism. The round magnet is significantly stronger, because it is twice as thick.

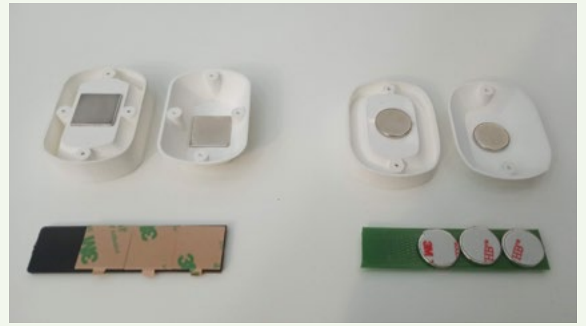


Figure 4.78: N35 neodymium magnets applied to the attachment interfaces.

Figure 4.79: The first attachment prototype.

Prototype #1

Height: 10 mm
Chamfer: 10 mm
Wall angle: 45 °

The first prototype (Figure 4.79) is a successful start. The interface has a good form-fit, but it is quite shallow. It therefore easily detaches.

The interface has right angles near the top which must be removed in order to fit a milled limb. The right angles of the attachment surface are effective however.

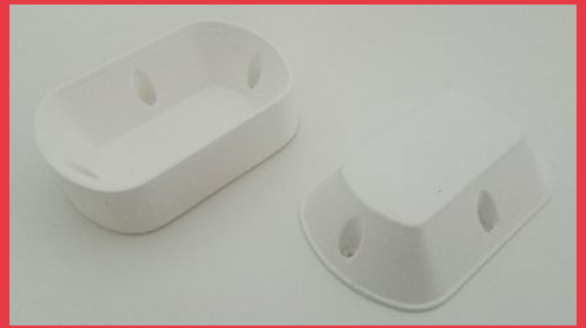


Figure 4.80: The second attachment prototype.

Prototype #2

Height: 15 mm
Chamfer: 9 mm
Wall angle: 60 °

The second prototype (Figure 4.80) is a significant improvement over the first. Its steep walls give the attachment a firm fit. It also finds and retains its position well.

Its four screw sockets may be effective, but not so efficient. It would be interesting to find if even steeper walls perform better.

Figure 4.81: One of the screw sockets broke off while removing support of the third prototype.

Prototype #3

Height: 20 mm
Chamfer: 5 mm
Wall angle: 75 °

The third prototype (Figure 4.81) has large screw sockets. These structures require support during 3D printing which are hard to remove afterwards. One of the sockets broke as a result. When positioned towards the edge of the interface, it is supported better and can decrease in size.

The walls of this prototype are so steep that attaching becomes difficult. The extra attachment surface does not seem to provide a better fit.

Figure 4.82: Fourth design attached to a block of wood.

Prototype #4
Height: 20 mm
Chamfer: 10 mm
Wall angle: 63 °

The fourth prototype (Figure 4.82) falls within outer dimensions 60 x 40 mm with a 2 mm brim. It has only two screw sockets, but they have increased in size. They are also more effectively embedded in the wall's shape. The interface's corners have a larger rounding than before for a better form-fit.

Screws insert successfully into the sockets. The interface attaches firmly to the wooden blocks. The shapes find their fit well and release by pull or rotation. A single magnet works, but a set of magnets works even better. It limits rotational movement and only attaches in one orientation. The magnets could use a dedicated slot to increase contact area between the attachment and parent object.

Figure 4.83: Fifth attachment interface attached to a block of wood.

Prototype #5
Height: 20 mm
Chamfer: 5 mm
Wall angle: 75 °

The fifth prototype (Figure 4.83) has steep walls once again, but with integrated screw sockets. The sockets are positioned on the long edge as opposed to the shorts edge previously, optimizing space left by the pair of magnets. The interface also has dedicated slots for the magnet pairs. A large variant for leg attachment is also fabricated with the same design (Figure 4.87).

Changes to the screw sockets and magnet slots prove to be significant improvements. The interface still attaches well to the parent object, despite the screws being moved. The magnet slots may be a little deeper, because the magnets still protrude from the interface. The large variant for leg attachment turned out well too, but is a lot more flexible. This may be resolved by attaching it to the parent object or by adding supporting elements.

Figure 4.84: Sixth attachment interface attached to a block of wood.

Prototype #6
Height: 20 mm
Chamfer: 5 mm
Straight edge: 10 mm

The sixth prototype (Figure 4.84) has both a chamfer and a straight edge. This is designed to have the same ease of use with better performance. The magnet slots are deeper and fully enclosed. The interface has an improved base plate with more contact area to the intended attachment slot. It is both FDM and SLS 3D printed to study difference in performance (Figure 4.88).

The straight edges of the interfaces make attachment firmer, but they are still easy to apply. A significant difference is noticeable between the FDM and SLS 3D printed parts, where the latter is more accurately fabricated and fits better. The base plate is an improvement as the magnets are properly recessed.

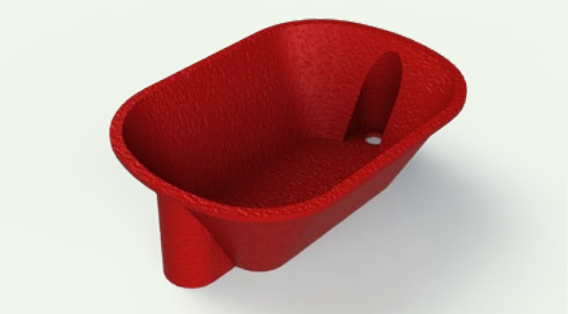


Figure 4.85: Fourth attachment interface, female half.

Figure 4.86: Fourth attachment interface, male half.

Figure 4.87: Large variant of the fifth attachment interface.

Figure 4.88: Sixth attachment interface FDM (yellow) and SLS 3D printed (black).

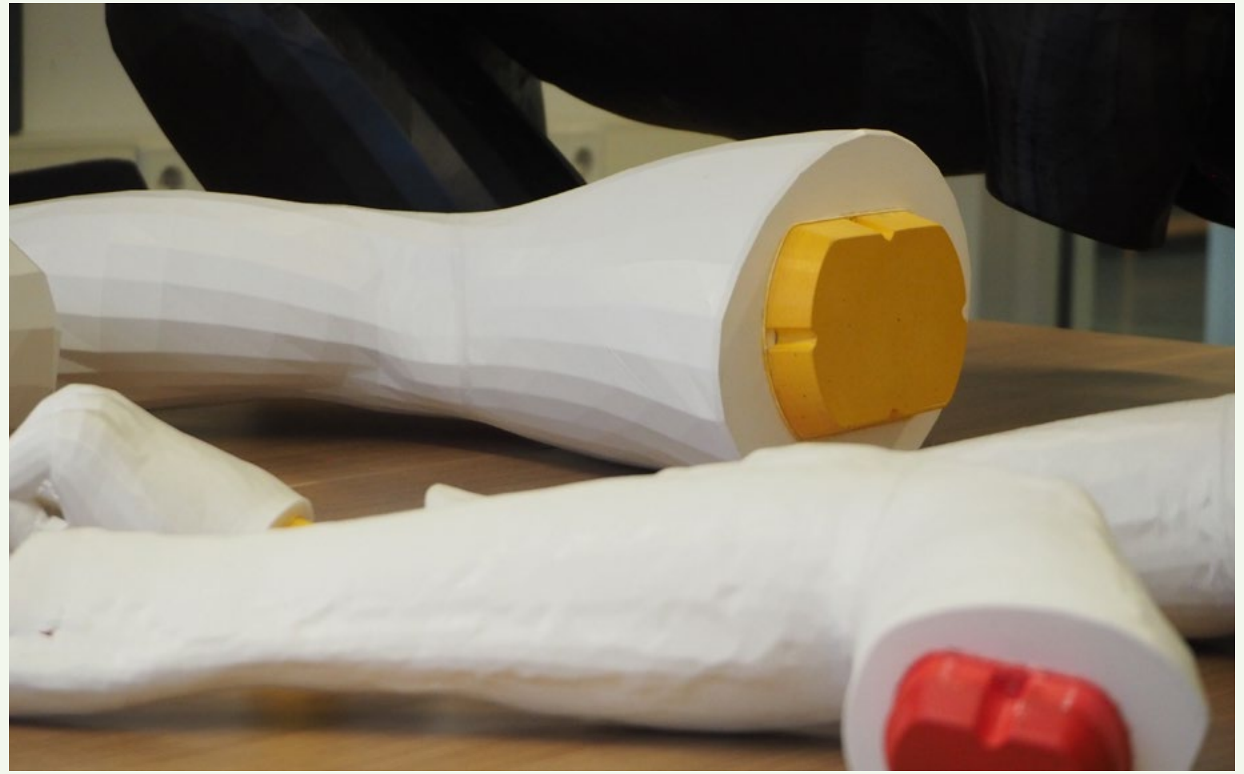
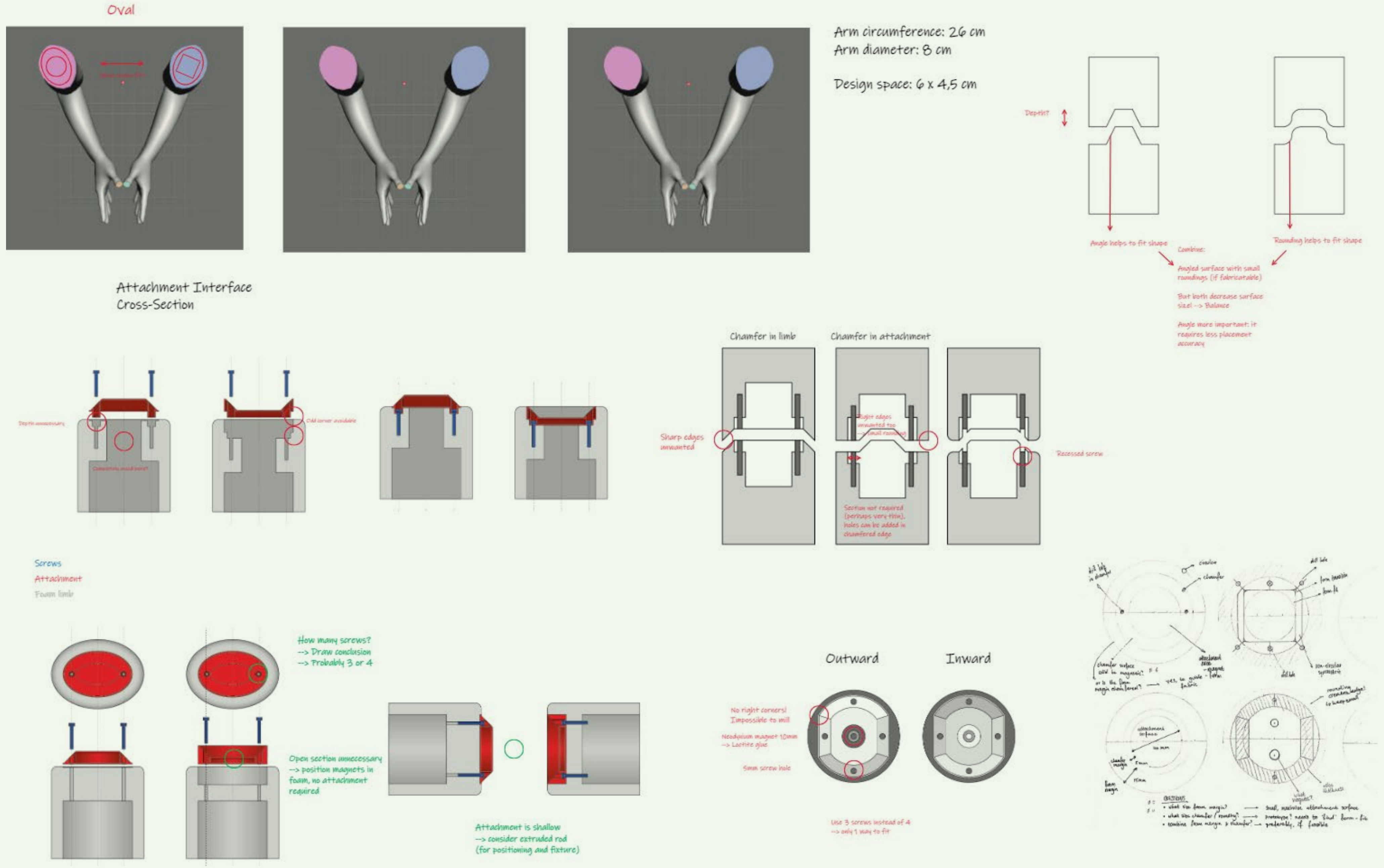


Figure 4.89: Design of the arm attachment interface on various limbs.



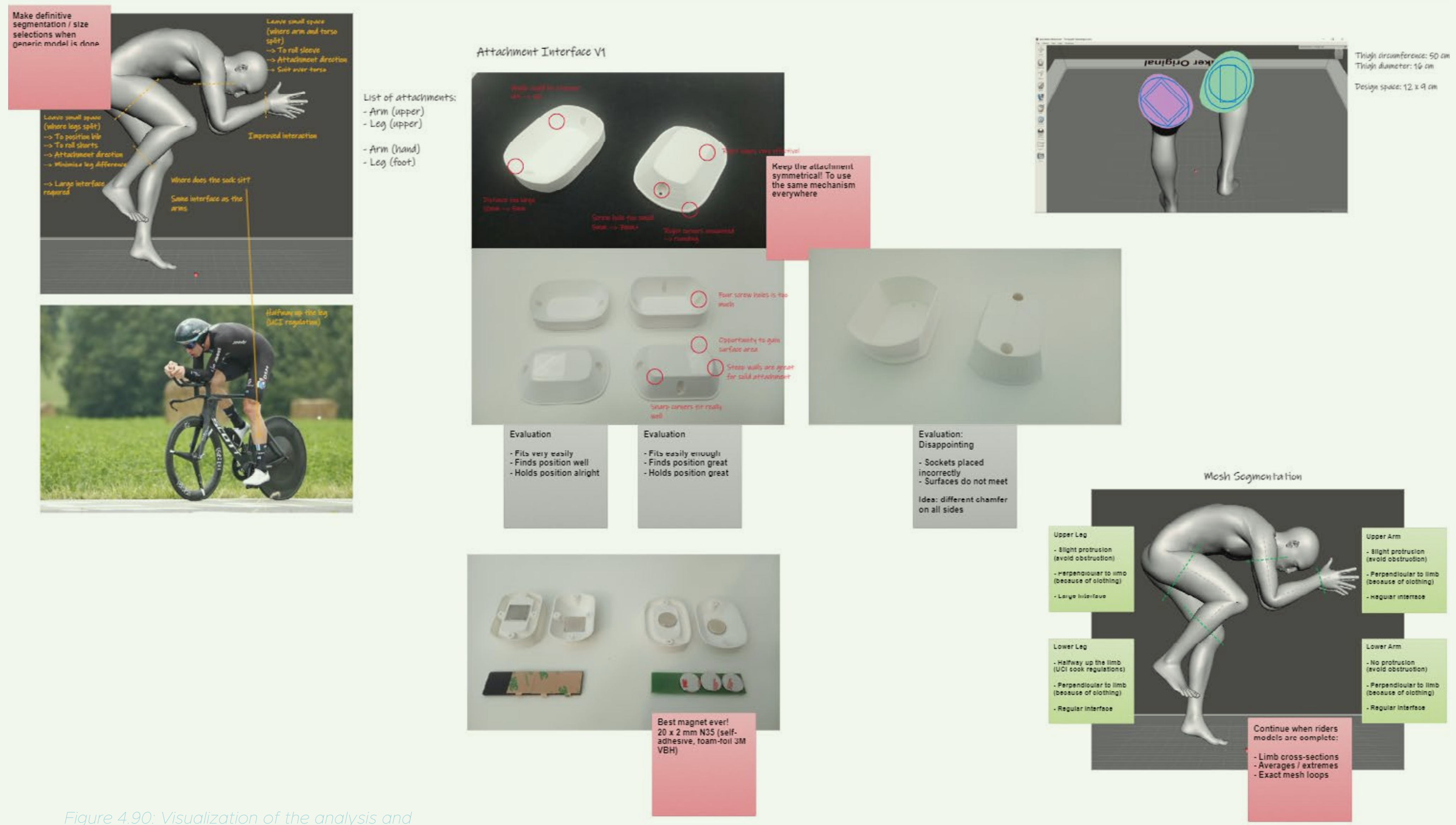


Figure 4.90: Visualization of the analysis and design process of the Attachment Interfaces

4.4 Personalized Mannequin: Design Features

4.4.4 Bicycle Mounts

The mannequin is mounted to a bicycle without any modifications. That means it utilizes identical contact point a live rider does: the saddle, the pedals and the handlebars.

Saddle
No design features are applied to the bottom of the mannequin, so it simply rests on the saddle (Figure 4.91). This mounting point carries most weight of the mannequin, but is stabilized by the arms and mostly the legs. Evaluation of the Dumoulin Mannequin indicates this design functions well and it is consequently applied to Rupert.

Pedals
The function of the mannequin is to wear cycling gear, shoes included (Figure 4.92). Cycling shoes use a clipping mechanism to mount to pedals that firmly attaches, but easily detaches. Such shoes are made to fit the rider's feet and are consequently the perfect method to mount the mannequin to the pedals. Several competitors apply the same design successfully. Rupert's feet are therefore shaped and sized accordingly.

Handlebar
The most critical bicycle mounting point is the handlebar, as live riders grip it with the force of their hand muscles. It therefore has the most challenging mounting interface out of the three. Two design directions are explored in this project: an adjustable mechanism with a hand-shaped cover (Figure 4.94) and a hand shape from flexible TPU material (Figure 4.95).

Figure 4.91: The bottom of the mannequin simply rests on the saddle.

Figure 4.92: Cycling shoes are used to mount the feet to the pedals.

Figure 4.93: Flexible hands fold around the handlebar and attach to the arm.

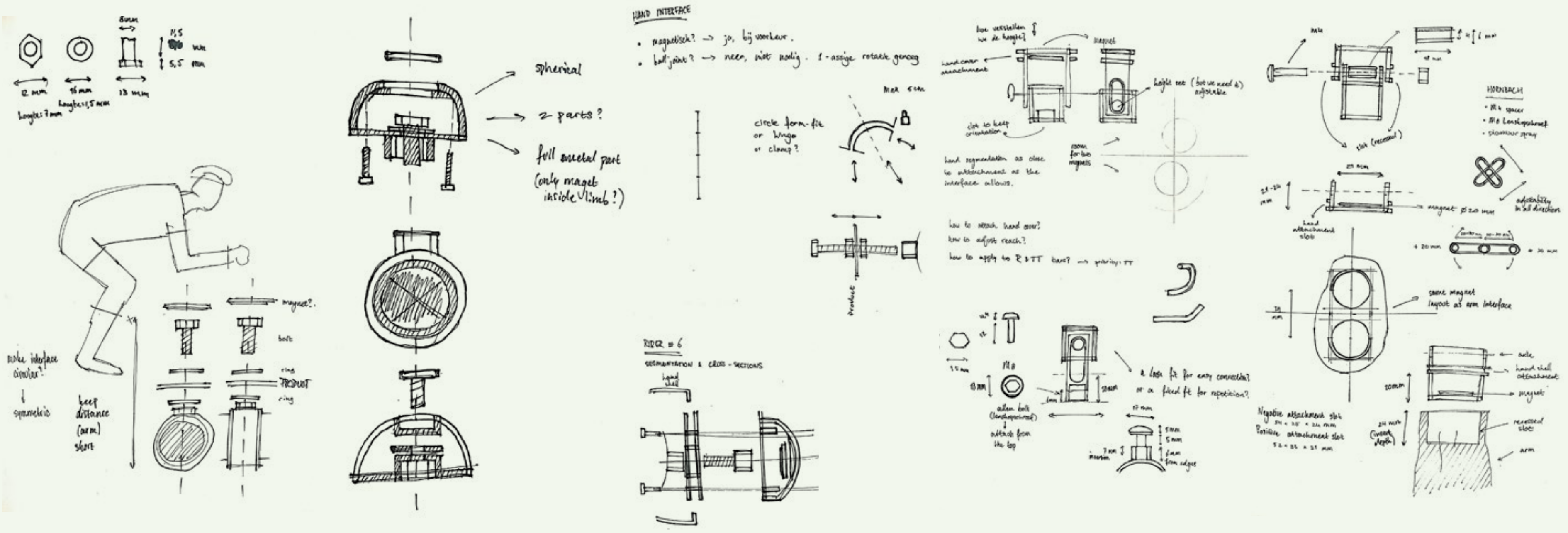


Figure 4.94: Technical sketches of the mechanical hand interface.

Mechanical
This design direction uses rubber-coated pipe clamps with an adjustable hinge mechanism for accurate positioning and repetition of the hand interface. The mechanism is covered by hand-shapes shell to take the right form.

The mechanical mounting mechanism is developed with sketches and by reviewing hardware, but the design direction is ultimately dropped as it is deemed too complex. Large forces rest on the handlebar and such a refined mechanism therefore requires a sophisticated and strong design. A simplified design direction is researched instead.

Figure 4.95: A hand made of flexible TPU.

Flexible
This design direction uses SLS 3D printed, flexible TPU to grip the handlebar with a hand-shape only. This rubber-like material has high elasticity and fatigue resistance (Oceanz, n.d.). The hand interfaces has a wall thickness of 4 mm, making it flexible enough to grab the handlebar and stiff enough to hold it.

The hand interface is originally 3D printed without holes, meaning all TPU powder remains between the walls of the object. This makes the hand less flexible than desired. The powder is removed by drilling a hole in the segmented face. Other properties such as wall thickness or internal structures influence the flexibility of the hand and may be optimized as such.

4.4.5 Materials & Production

The mannequin is CNC milled from high density polyurethane tooling board (Figure 4.96). This material lends itself excellently to subtractive manufacturing, because it can be produced in a variety of specifications and it has great material properties.

High density polyurethane is a heavy, closed-cell foam (Figure 4.95), unlike the soft, open-cell foam that is often used in packaging. Comparable to wood, it is hard to the touch. Unlike wood its material properties can be greatly manipulated, making it suitable for design studies, prototyping & wind tunnel models.

Specifications

Fabrication: CNC Milling 5-axis (1-3 mm margin rough cut & ball-end mill fine cut).
Material: High density polyurethane, closed-cell tooling board 470 kg/m3.
Bonding: Polyurethane room-temperature cure adhesive.
Finish: Light sanding.
Coating: Foam surface sanding sealant, surface primer & matte black paint.

"High-density polyurethane foam is a popular choice in the tooling industry because it does not outgas during heating, is dimensionally stable, has a predictable coefficient of thermal expansion (CTE), and has a fine/smooth surface finish." (General Plastics, 2018).

Figure 4.95: Three CNC milled and one 3D printed lower arm segments.

Figure 4.96: Two arm segments are CNC milled.

Expert Recommendations

About a dozen companies are contacted for advice about fabrication and material selection. Three of them (VIBA, Scabro & Jules Dock) respond with recommendations about high density polyurethane tooling boards. All three recommend similar foam densities for the mannequin.

VIBA:	500 kg/m3
Scabro:	350 – 470 kg/m3
Jules Dock:	450 kg/m3

VIBA and Scabro supplied samples of the recommended materials. Lower arm segments are CNC milled from RAKU-TOOL 0240, 0351 & 0470. Following the advice combined with experiencing one of the tooling boards, the high density polyurethane 470 kg/m3 is selected for the mannequin.

Prototyping

Three polyurethane hard foam samples are ordered from Scabro, Dutch producer and supplier of industrial model-making materials. Scabro employee Franz Klotz recommends RAKU-TOOL PU foam in densities of 240, 351 and 470 kg/m3 (Figure 4.97). The samples have dimensions of 290 x 180 x 50 mm, precisely enough to CNC mill a lower arm from. The arm is segmented in length (Figure 4.98) to fabricate on a 3-axis CNC mill without orientation adjustments.

Material:	Polyurethane foam 351 kg/m3
Machine:	Roland 3-axis CNC mill
End Mill Cutter:	Ø 10 mm, 50 mm length
Detail:	1.1 mm
Layer height:	5 mm
Time:	2-3 hours

Figure 4.97: RAKU-TOOL PU foam samples.

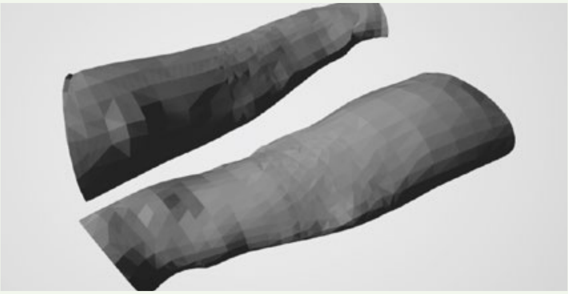


Figure 4.98: An arm segmented to fit the foam.

The arm segments come out nicely after CNC milling (Figure 4.99). The high density foam is hardly grainy and shows fine surface details. Any excess foam is easily removed. The segments are joined by applying Bison Spray Glue. Sanding works effectively to finish the seams. The limb feels strong and stiff, but the milling paths clearly show on the surface (Figure 4.100).

Following the first arm segment, two more arms are CNC milled from the remaining polyurethane foam. Layer height settings in DeskProto are adjusted slightly to accommodate the differences in material density. These arm segments also come out nicely and make a good comparison between the foam types in the right context (Figure 4.95).

Figure 4.99: Removing segments from milling bed.

Figure 4.100: Milling marks on the arm segment.

Three more polyurethane hard foam samples are ordered from VIBA, Dutch specialist in fasteners and bonding. VIBA employee Ritish Raghoebier recommends PU foam by Obomodulan and RenShape in densities of 500, 650 and 720 kg/m3 (Figure 4.101). The samples have dimensions of 120 x 50 x 10 mm, too small to CNC mill from. However, the samples are a useful tool to experience the differences between foam types.

Figure 4.101: Obomodulan & RenShape samples.

4.4 Personalized Mannequin: Design Features

4.4.6 Full-Scale Prototype

The full-scale prototype of the Personalized Mannequin takes two weeks to create from first 3D prints to final assembly. The FDM 3D printing process takes 261 hours including retried prints on two Ultimaker Extended 2+ with large nozzles on extreme settings. The process involves fabricating all parts, treating the surfaces for inaccuracies, joining the segments, filling any seams, painting the parts and assembling the product.

Parts of the mannequin are produced differently with the purpose of comparing results and managing time. The production process is prepared by fabricating separate limb segments. Consultation with Joris van Tubergen and PMB staff is invaluable in the production of this prototype. The full-scale prototype is used to validate the design of the mannequin on a bicycle (Figure 4.102).

Figure 4.102: The full-scale prototype assembled on a time trial bicycle.

Consult Wiebe Draijer
3D Printing expert Wiebe Draijer from the Model Making Machine Lab of the TU Delft is consulted. He mentions that most time can be saved by using a large nozzle, limiting the amount of wall layers and by experimenting with infill settings.

Wiebe Draijer's advice it to use the latest Cura 5.0 (beta) software as its algorithm optimizes printing speeds locally. Advanced settings can be accessed in the 'Settings Visibility' menu. Despite there being too many settings to study, a few relevant ones may prove valuable.

Lastly infill settings greatly affect fabrication time and product performance. A standard, 10% square infill already performs well enough. However, the Gyroid infill pattern supports loads from all directions. By applying Gradual Infill Steps, supports are maximized near surfaces and minimized near the object core.

Cura 3D print settings.

- Nozzle size: 0.8 mm
- Layer height: 0.2 – 0.4 mm
- Wall thickness: 1 – 2 mm
- Infill: gradual infill steps

Before the entire mannequin is fabricated full-scale, several separate limbs are fabricated individually. These are used to experiment with 3D printer settings and finishing methods, as well as functional analysis such as attaching to other limbs and mounting to the bicycle.

All limbs are initially fabricated on Ultimaker 2+ FDM 3D printers with standard 0.4 mm nozzles and white PLA filament.

Testing
All initial Digital Fabrication is performed with standard Ultimaker 2+ 3D printers.

Arms
Cura 3D print settings.

- Layer height: 0.15 mm
- Infill: 10 %
- Support: no
- Adhesion: no

To fabricate a full-scale arm with an Ultimaker 2+, it is segmented in three sections (one for the upper arm, two for the lower arm). By segmenting the limb cleverly it requires minimal support, minimizing fabrication time. The limb utilizes most of the Ultimaker 2+'s building volume (Figure 4.103).

With the 3D print settings, the arm is fabricated in about 33 hours. Cura gives warnings where support would be required and this results in small failures (Figure 4.104). Overall the models turned out well with little manual post-processing required. All limbs are preferably 3D printed without support or brim if their shape allows it.

The limb segments are attached using plastic model glue (Figure 4.105). The surfaces are lightly sanded for optimal adhesion. The segments are easily oriented because of the arm's shape. A form-fit would be a valuable addition to the model glue to enforce the connection.

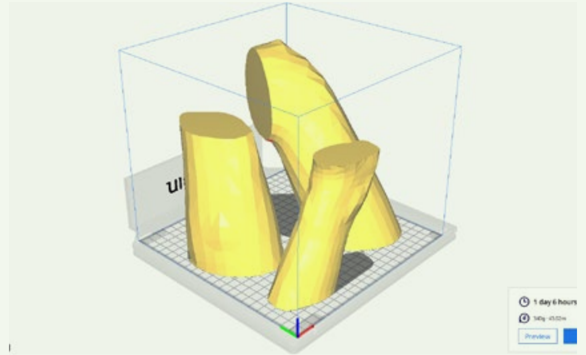


Figure 4.103: Three arm sections exactly fit the build volume of the Ultimaker 2+.

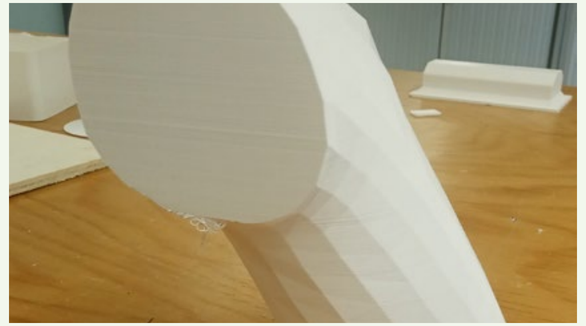


Figure 4.104: A small failure in the upper arm where support is required.

Figure 4.105: Upper, middle and lower arm segments glued together.

Figure 4.106: Remains of the supports are clearly visible near the fingers.

Hands

Cura 3D print settings.

- Layer height: 0.15 mm
- Infill: 20 %
- Support: yes
- Adhesion: yes

Lots of support was added to the hands in Cura to 3D print the overhanging shapes. This requires a lot of finishing post-fabrication. Even after the necessary processing, lots of support remains between the fingers (Figure 4.106). These areas are so hard to reach that correct removal becomes impossible. This significantly affects the performance of the limb as the palm of the hand is required for connection to the handlebar. An alternative fabrication method is desired for this limb.

Figure 4.107: A rough surface remains after removing all supports.

Foot 1

Cura 3D print settings.

- Layer height: 0.2 mm
- Infill: 10 %
- Support: yes
- Adhesion: yes

A size 40 foot exactly fits the 3D printing volume of the Ultimaker 2+. It is printed in the natural orientation with supports below the sole (Figure 4.110). Because of the shape's complexity, the supports cover the entire sole. Removing it is not too much work, but leaves a rough surface (Figure 4.107). Such a finish is not desired and requires too much work to finish properly. Alternatively, the foot may be segmented horizontally and joined afterwards to improve this workflow.

Figure 4.109: A left foot 3D printed vertically.

Figure 4.108: Holes appear near flat sections because of the layer height setting.

Foot 2

Cura 3D print settings.

- Layer height: 0.4 mm
- Infill: 10% gyroid
- Support: no
- Adhesion: no

The foot is segmented horizontally for this prototype, allowing the models to be 3D printed without support. The sole requires less finish this way. Time efficient printing settings are used, such as 10% gyroid infill (Figure 4.110). The layer height turns out too high for this nozzle. Holes appear near flat sections of the model (Figure 4.108). A layer height of 0.3 mm is about the maximum for a 0.4 mm nozzle, where a layer height of 0.4 mm could be used with a 0.8 mm nozzle.

Figure 4.110: Gyroid infill of 10%.

Modelling

All modelling tasks for the full-scale prototype are performed in Blender as recommended by Joris van Tubergen.

Model Transformation

The rider model is scaled and oriented incorrectly after corresponding in Wrap. A transformation is applied to correct the model before editing.

- Object > Transform
- Apply > All Transforms

Segmentation - Interaction

Apply planes to the model where segmentation is required (Figure 4.111). Split the model into segments and separate into parts.

- Add > Mesh > Plane
- Modifier > Solidify
- Modifier > Boolean Difference
- Edit > Mesh > Separate > By Loose Parts

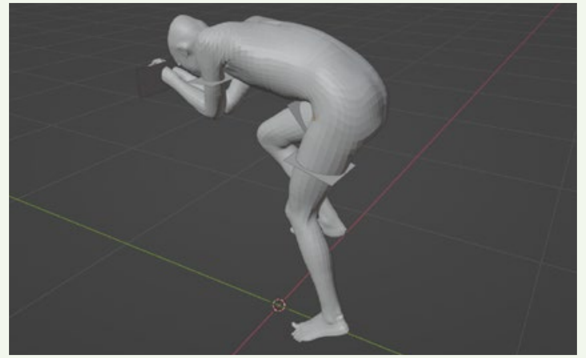


Figure 4.111: Segmentation planes positioned through the model.

Round Edges

Select the segmentation surfaces for each limb segment and apply bevels (Figure 4.112).

- Object Data > Add Vertex Group
- Modifier > Bevel Edge

Amount:	0.0025
Segments:	1
Limit Method:	Vertex Group
Clamp Overlap:	No
Loop Slide:	No
Harden Normals:	No

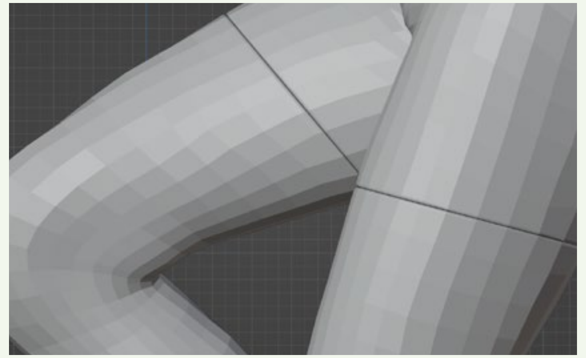


Figure 4.112: Bevels applied to the segment edges.

Attachment Slots

Load and position SVG files of the attachment interfaces (Figure 4.113).

- File > Import > SVG
- Object > Convert > Mesh
- Object > Join
- Transform > Move > Snap To Surface

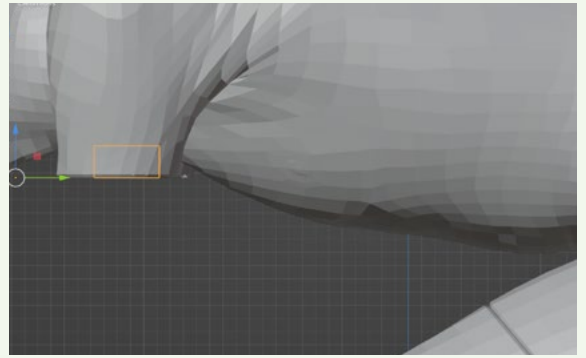


Figure 4.113: Sizing a placed attachment slot.

Size the interface and cut the attachment slot from the model (Figure 4.114).

- Transform
- Duplicate Collection
- Modify > Solidify
- Boolean > Difference

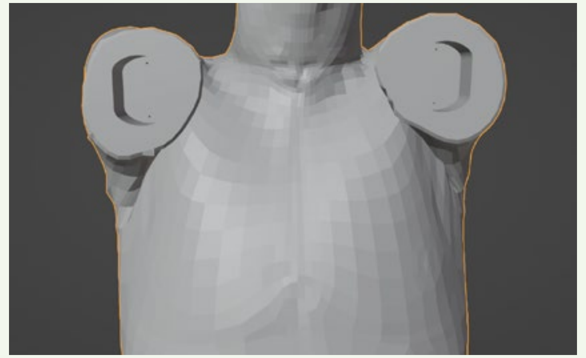


Figure 4.114: Attachment slots applied to the torso.

Cyclist Mannequin - Siward Vloemans

Segmentation - Fabrication

Add the volumes of available 3D printers to use for segmentation (Figure 4.115).

- Add > Mesh > Cube
- Object > Transform

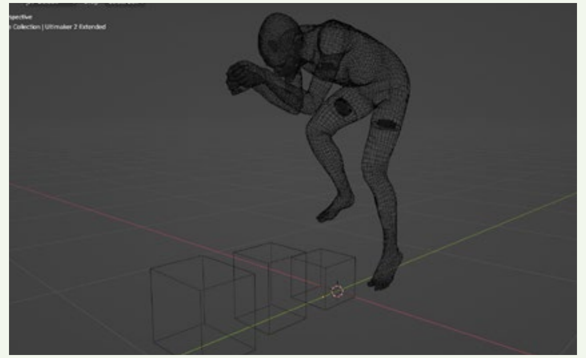


Figure 4.115: Rider model and box representations of the Ultimaker 2+, 2 Extended and S5.

Choose segmentation planes and position 3D printer volumes to segment the entire model (Figure 4.116).

- Modify > Boolean Intersect

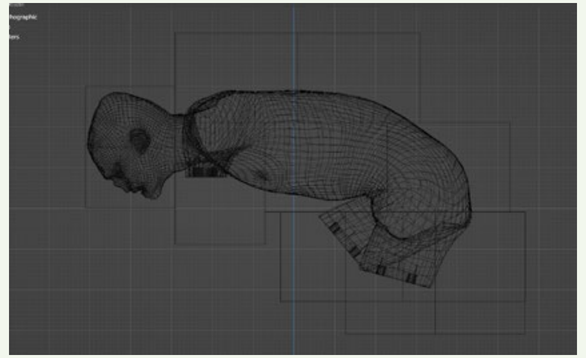


Figure 4.116: Torso box segments.

Detailed Mesh

As soon as an improved version of the model is ready, it can replace remaining limbs of the original model. The detailed mesh model is used for fabrication of the head and arms in this project (Figure 4.117).

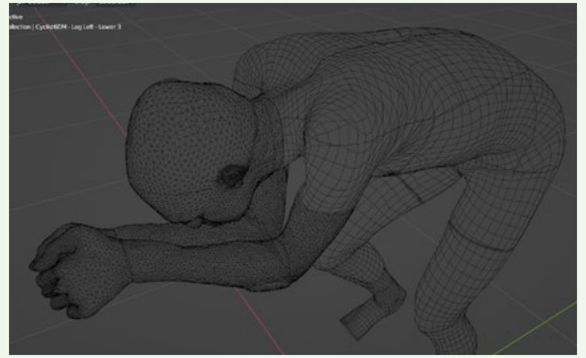


Figure 4.117: The model's head and arms have a more detailed mesh.

Consult Joris van Tubergen

Joris van Tubergen is the co-creator of the Dumoulin mannequin and specializes in FDM 3D printing on large scale. He uses inverted Ultimakers to fabricate to infinite length and has a large 3D printer that can fabricate up to 60 x 60 x 100 cm.

Joris van Tubergen's advice is to reduce 3D printing time of individual parts to a maximum of 1.5 to 2 days. This is to reduce risks with the chances of failure during fabrication.

One way to reduce fabrication time is to increase fabrication speed. The best method is to increase nozzle size and layer height. This creates a rougher surface finish, but favourable material strength. Different sections of the same part may be 3D printed with different speeds, depending on the complexity of each section.

Another way to reduce fabrication time is to reduce fabrication volume. The best method is to minimize infill and to avoid supports. The latter has the added advantage that little to no surface finish is required without supports. They can be avoided by 3D printing in multiple segments. Alternatively, they can be optimized by using tree-supports from Meshmixer.

Cura 3D print settings.

- Nozzle size: 0.8 – 1 mm
- Layer height: 0.4 mm
- Wall thickness: 2 layers
- Infill: minimal
- Support: minimal to none

Digital Fabrication

Digital Fabrication of the full-scale prototype is performed with a variety of Ultimaker 3D printers.

Materials

Ultimaker 2+
223 mm × 223 mm × 205 mm

Ultimaker 2 Extended+
223 mm × 223 mm × 305 mm

Ultimaker S5
330 mm x 240 mm x 300 mm

Legs

Any available 3D printers in the Model Making Machine Lab are used to fabricate the pair of legs. (Figure 4.118). Because of the varying build volumes, limbs are individually segmented for each Ultimaker.

Cura 3D print settings.

- Nozzle size: 0.4 mm
- Layer height: 0.3 mm
- Wall thickness: 2 layers
- Infill: 10% gyroid
- Speed: 60 mm/s
- Support: no
- Adhesion: raft

Total printing time: 76 hours. Two segments failed and are fabricated again. The legs came out nicely overall, because the 0.4 mm nozzle is accurate even with time efficient settings. However, 3D printing settings are still too slow to fabricate the torso. Therefore, dedicated Ultimakers are assigned with a larger nozzle.

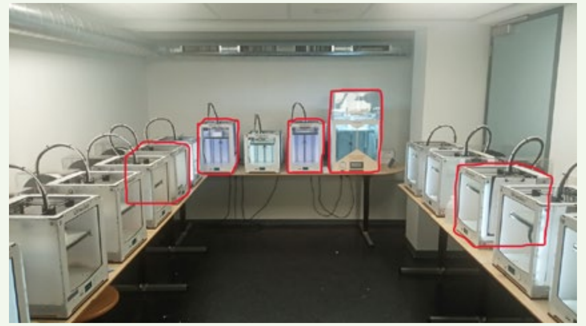


Figure 4.118: Five Ultimakers (2+, 2 Extended + and S5) 3D printing a pair of legs.

Figure 4.119: An upper and lower leg segment completed by the Ultimaker S5.

Torso
Two dedicated Ultimaker 2 Extended+ 3D printers are used to fabricate the torso (Figure 4.120). The standard 0.4 mm nozzle is replaced with an 0.8 mm nozzle to increase speed. Other settings in Cura are changed to increase speed as well. The first 3D prints serve as a test to ensure the quality still suffices.

Cura 3D print settings.
- Nozzle size: 0.8 mm
- Layer height: 0.4 mm
- Wall thickness: 2 layers
- Infill: 5% gyroid
- Speed: 80 mm/s
- Support: from build plate
- Adhesion: skirt

One of the torso segments has a rough surface finish on two sides (Figure 4.121). Nozzle vibrations were caused by play in the axle bearings. The bearings are replaced before the next 3D print. Print speed is decreased slightly as a test to prevent surface deformations.

- Speed: 70 mm/s

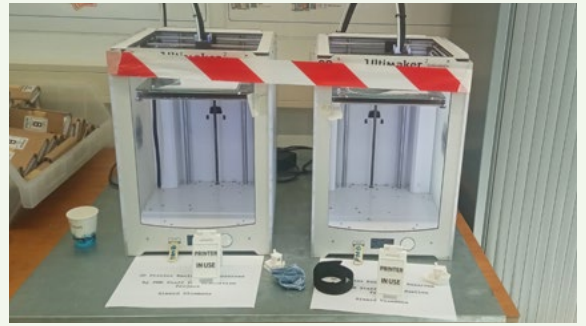


Figure 4.120: Two dedicated Ultimaker 2 Extended+ with large nozzles.


Figure 4.121: First torso segments suffer from surface errors.

Attachment Interfaces
As the interfaces not only have an aesthetic function, 3D print settings were adjusted to gain higher quality results. All attachment interfaces fit the print bed of the Ultimaker 2 Extended + (Figure 4.122).

Cura 3D print settings.
- Nozzle size: 0.8 mm
- Layer height: 0.3 mm
- Wall thickness: 2 layers
- Infill: 10% grid
- Speed: 60 mm/s
- Support: from build plate
- Adhesion: raft

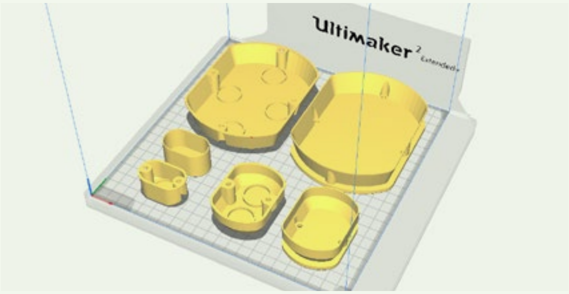


Figure 4.122: All attachment interfaces on the print bed of the Ultimaker 2+ Extended.

FDM 3D Printing Process			**(Hours)**
Legs	Left	*Upper*	31
		Lower	-
		Foot	8.5
	Right	*Upper*	16
		Middle	10.75
		Lower	7.5
		Foot	2.5
Arms	Left	*Upper*	8,5
		Lower	-
		Hand	-
	Right	*Upper*	8
		Lower	-
		Hand	-
Torso	Head	*Upper*	5
		Lower	3.75
	Back	*Left*	3.75
		Right	3.25
	Shoulder	*Left*	6
		Right	5.25
	Arm	*Left*	7
		Right	7
	Chest	*Left*	12.25
		Right	11
	Hip	*Left*	7.25
		Right	7
	Leg Left	*Crotch*	5.75
		Bottom	4
	Leg Right	*Crotch*	8
		Bottom	2.5
	Neck	*Neck*	1
Interface	Leg (2x)	*Male*	3.25
		Female	3.25
	Arm (2x)	*Male*	-
		Female	-
	Wrist (2x)	*Male*	-
		Female	-
Total			**217.25**

Consult Roland van der Velden
Production expert Roland van der Velden from the Model Making Machine Lab of the TU Delft is also consulted. He advises to use a quick-curing, budget adhesive to attach the torso segments due to the large connection surfaces. A PVC kit adhesive is available in the workshop. Roland recommends using weights and clamps to keep the segments in place as more parts are attached.

Furthermore, he mentions that seams will appear between segments of the torso. Wall filler is a user-friendly, budget solution to make the torso seamless. Applying a small amount of moisture lets the filler flow fluidly between the seams. After an hour of curing excess wall filler is simply removed by sanding.

After assembly, the torso must be finished and the rough surface requires some treatment. Roland recommends using spray putty to both prime the surface and to smoothen it. A light sanding must be applied between each layer and multiple layers are preferred. The torso may then be finished with two layers of paint and a transparent finish.

Production
All Production of the full-scale mannequin is performed in the Model Making Machine Lab.

Assembly
The mannequin is ready for assembly after 3D printing. Because of the high 3D printing speeds, all parts require surface and edge sanding before assembly. Tools used during assembly (Figure 4.123):

- Pattex PVC kit adhesive
- Alabastine wall filler
- A variety of sanding paper
- Weights & clamps

Every flat surface is sanded before applying kit. It is applied around the edges and near the centre of only one part (Figure 4.124).

The segmentation lines and base mesh give a visual indication of how to align all parts and assembly of the torso (Figure 4.125) is relatively simple. Seam lines are still clearly visible.


Figure 4.123: Supplies used to assemble the torso.


Figure 4.124: Applying kit to one of the surfaces.


Figure 4.125: The torso completely assembled.

Wall filler is applied generously to all seams (Figure 4.126) of the model and left to dry for about an hour.

Figure 4.126: Filled seams after light sanding.

After the wall filler has dried, all seams are sanded to remove any excess material (Figure 4.127). Wall filler now only remains inside seams.

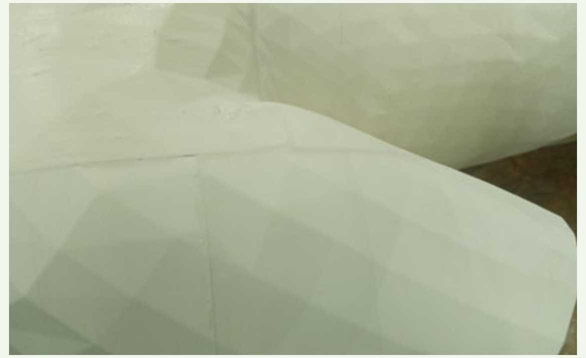


Figure 4.127: Filled seams after complete sanding.

Finish

The mannequin is finished using three types of spray (Figure 4.128). Each spray is applied in layers with at least an hour of curing in between. Two layers of spray putty, three layers of matte black paint and one layer of transparent finish are applied. The spraying cabin in the Model Making Machine Lab is used to apply the spray (Figure 4.129). The interface slots are masked while applying the spray putty.

Figure 4.128: Spray putty, matte black paint & transparent finish.

- Alabastine spray putty
- OK matte black paint
- OK transparent finish
- Masking tape

Figure 4.129: The torso in the spray cabin.

Figure 4.130: The torso after applying a layer of spray putty.

Figure 4.131: The torso after applying a layer of matte black paint.

Figure 4.132: Close-up of the torso after applying all layers of matte black paint.

The attachment interfaces are painted to indicate use cues. Interfaces for the left limbs are painted yellow, while interfaces for the right limbs are painted red (Figure 4.134). The interfaces are not primed, but a layer of transparent finish is applied.

Figure 4.133: The attachment interfaces before applying a layer of paint.

Figure 4.134: The attachment interfaces after applying a layer of paint.

Assembly

The mannequin is assembled after all parts are finished (Figure 4.135), meaning limbs segments are joined, seams are filled and the surface is sanded or painted. First, magnets are applied to the attachment interfaces (Figure 4.136).

The interfaces are designed to screw into dedicated slots integrated with the limbs. However, this is not possible due to multiple reasons. First, the interface slots of the legs are scaled incorrectly due to a modelling error. Second, the arm interface slots have the old screw positions by mistake. Lastly, some of the screw sockets broke off during support removal, because the supports are much larger with a 0.8 mm nozzle. Consequently, the interfaces are attached using plastic model glue and become non-removable. The slots are used to position the interfaces correctly (Figure 4.137).

After assembly is completed, the full-scale mannequin is finally finished (Figure 4.138).

Figure 4.135: All separate parts of the mannequin to assemble.

Figure 4.136: Magnets are placed in dedicated slots of the attachment interfaces.

Figure 4.137: The interfaces are placed in the torso slots inversed to align them to the leg.

Figure 4.138: Fully assembled limbs of the full-scale mannequin.

4. Personalized Mannequin

4.5 Validation

Validation session conducted on Monday 20-06-2022 with Wouter Terra & Harm Ubbens.

Introduction
This experiment aims to validate the design of the Personalized. Functionalities from the Function Analysis and desires from the List of Requirements are used to evaluate the desirability of the mannequin. The goal is to use the results to make recommendations about the development of the product. The research question is:

"How is the Personalized Mannequin experienced by users?"

Method
Participants
The research involves the participation of project clients and end-users Wouter Terra and Harm Ubbens.

Apparatus
- Personalized Mannequin prototype
- Time trial bicycle (rider-specific)
- Cycling kit
- Bicycle trainer stand

Stimuli
The participants are given tasks to perform based on the Function Analysis of the Personalized Mannequin. The tasks are:

- Apply cycling gear (suit, shoes & helmet)
- Connect limbs (hands, arms & legs)
- Mount to bicycle (saddle, pedals, bars)

The participants perform the tasks together and are asked to think out loud. Comments are noted by the researcher. The interactions are recorded with a photo camera.

Procedure
Location: Faculty of Industrial Design Engineering.
Time: 13:00-14:00.

Preparation
The bicycle is installed in the trainer stand. The setup is positioned with room to walk around it (Figure 4.139). Limbs of the mannequin and the cycling kit are placed on a table separately.


Figure 4.139: Bicycle and mannequin positioned with room to walk around.

Introduction
The participants are introduced to the purpose of the research. They are instructed about the activities to perform with the mannequin. The participants are asked to think out loud and are asked for permission to photograph the session.

Activities
The participants conduct the activities with the mannequin together (Figure 4.140). Comments are noted by the researcher and photos of the activities are also taken by the researcher.

Processing
The participants are asked about their first impression. They are also asked about the mannequin's best features and about features to be improved. Lastly, the participants are asked to rate the desirability of the mannequin.


Figure 4.140: Participants mounting the mannequin to the bicycle.

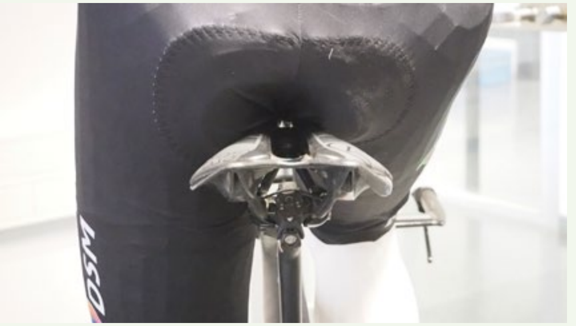


Figure 4.141: Not enough space between the legs.

Data Collection
The participants answer open questions directly after the activities. The questions are:

How did you experience applying cycling gear?
How did you experience connecting limbs?
How did you experience mounting to the bicycle?

The participants rate several criteria on a Likert Scale from one (strongly disagree) to five (strongly agree). The criteria are desires from the List of Requirements.

The mannequin's pose is accurately repeatable.
The mannequin's pose is accurately adjustable.
The mannequin's shape is accurately realistic.
The mannequin is quickly (un)mounted.
The mannequin's limbs are quickly (dis)assembled.

Data Analysis
The ratings are analysed to validate desirability of the Personalized Mannequin. The ratings itself identify strengths and weaknesses of the design and are plotted in a histogram. Answers to the open questions are processed manually used to substantiate the quantitative data.


Figure 4.142: The feet do not reach the pedals.

Results
Answers to the open questions are summed up for each of the activities in this research.

Apply cycling gear
The perpendicular segmentation plane of the legs is a preferable choice.
The bib of the suit is more challenging to apply than the sleeves, because the area between the legs is limited.
Arm protrusion is perfect. Short enough to apply the suit and long enough to roll the sleeves.
The bevel of the segment faces make clothes easy to apply. They are unobtrusive when the clothes are applied, but could be smaller.
The head is too large for the helmet and it sits awkwardly because of the head's odd shape.

Connect limbs
All limbs connect easily, but are not connected well enough.
The arms are able to move and the legs require duct tape to stay connected.
The limbs do not connect seamlessly, which is an important desire.
The magnets could be more powerful, near the legs in particular.

Mount to bicycle
The saddle does not fit well between the legs, because they are too close together (Figure 4.141).
The feet are too wide to fit a shoe and cannot be mounted to the pedals consequently (Figure 4.142).
The hands are not modelled correctly, so the shape does not follow the handlebar well enough.
The mounting system is easy to use, but needs some refinement.

Likert Scale
Ratings of the desirability criteria are plotted in a histogram (Figure 4.143). Repeatability and realism are rated neutral (3) by both participants. Adjustability is rated negatively (2), while mounting and assembling are rated positively (4 & 5) by the participants. Participant 2 is most favourable about the last two criteria.

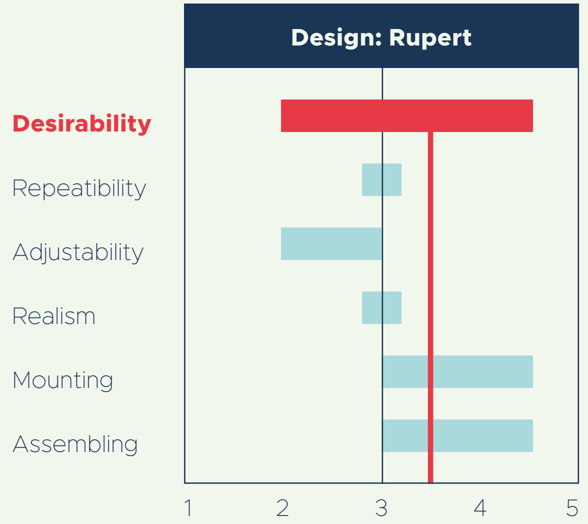


Figure 4.143: Ratings of the desirability criteria.

Interaction Scenario Rupert #2

Harm Ubbens & Wouter Terra dress, assemble and mount Rupert to a time trial bicycle. Noteworthy and unintended interactions are described here.

Figure 4.144: A participants sits on the torso to apply the suit easier.

Figure 4.145: Duct tape is applied to connect the legs more firmly.

Figure 4.146: The cycling suit sleeves have stretched during application.

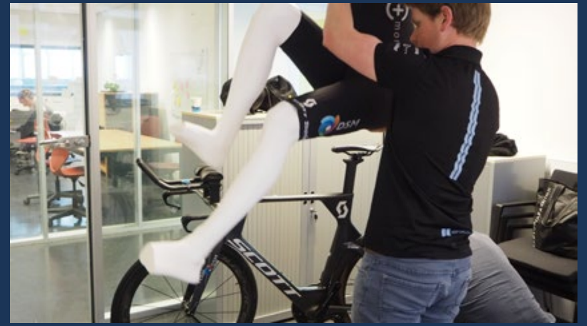


Figure 4.147: The assembled mannequin has to be lifted over the bicycle.

Figure 4.148: The arms are asymmetric and the hands do not connect with the bar-ends.

Figure 4.149: The feet are too large to fit a cycling shoe.

Figure 4.150: The head is oddly sized and the helmet does not fit properly.

Figure 4.151: The attachment interfaces have slack, causing the arms to move.

Discussion

Discussion open questions

Applying cycling gear is experienced positively, but flawed. The participants applied the suit to the legs first, but the limited area between the legs made it challenging. The right leg was dressed before the left leg. Once applied to the legs, the suit was easily applied to the rest of the torso. The smooth surface, edge bevels and segmentation of the arms was perceived positively. However, the mannequin creaked under force and the suit stretched out around the sleeves during application. A participant mentioned that was also due to the quality of the garment. Applying the helmet gave more trouble as it did not fit the head correctly. The issue was caused by the large size and odd shape of the head.

Connecting limbs is experienced well, but performed poorly. The legs had to be fastened with duct tape as they did not hold together. That is also due to the lacking support of the pedals, which would normally help. The arms held in place, but caused slack and felt fragile. The hands connected best. Overall, the attachment system worked well for the participants, but they desired better performance. The participants suggested stronger magnets, a firmer form-fit and a stronger structure. The attachments must also connect seamlessly.

Mounting to bicycle is experienced user-friendly, but flawed. The participants applied the bottom of the mannequin to the saddle first, but the saddle was too wide. The mannequin was moved forward and tilted incorrectly on the bicycle as a result. The feet did not reach the pedals consequently, and they were too large to fit a shoe. However, the arms did reach the elbow rests and handlebars and the mannequin was stable overall. The flexible handlebar mount is experienced positively, though the participants mention the hands could follow the shape of the handlebar better. This caused worry about repeatability of the position. The participants mention flexibility would be preferable near the knee as well.

Discussion Likert Scale

Ratings from the Likert Scale confirm most of the aforementioned statements. Repeatability is rated neutral because the mannequin did not seamlessly connect to the bike. Adjustability is rated poorly, because space around the saddle was too tight and the feet did not connect to the pedals. Realism is rated neutral, because the mannequin had a clearly visible, low resolution polygonal mesh surface, but a good surface finish. Mounting and assembling are rated positively, because the mannequin was easy to use. It mostly suffered from performance issues. The participants mentioned several possible improvements.

Conclusion

The research questions is: "How is the Personalized Mannequin experienced by users?". The answer is that the mannequin is experienced desirable overall, but suffers from practical flaws.

The mannequin model is oddly shaped near the bottom, head and feet, making cycling gear challenging to apply and tilting the mannequin on the bike. Attaching limbs is easy but the attachment interfaces itself are weak, disconnecting or moving during use. Limb flexibility is experienced positively and may be applied more to benefit mounting to the bicycle if modelled correctly. Performance, quality and adjustability are the weaknesses of the mannequin model and improvements to it will benefit the experience by users and increase desirability of the product.

Figure 4.152: The Personalized Mannequin with annotations of conclusions from validation.

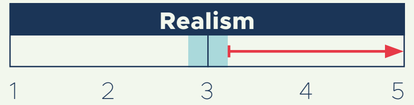
5. Conclusion

5. Conclusion

5.1 Recommendations

Improvements to the Personalized Mannequin become apparent after validation with Rupert. Recommendations are presented on how to improve the product, as another iteration falls out of the scope of this project. The recommendations are structured identically to how the product features are presented in this report. The goal is to increase the desirability ratings for all desired criteria: Repeatability, Adjustability, Realism, Mounting & Assembly to make Rupert hit the Innovation Sweet Spot.

3D Digital Model
Realism of the mannequin is rated sufficient with room for improvement. Recommendations regard the resolution of the base mesh and the shape and size of the head.

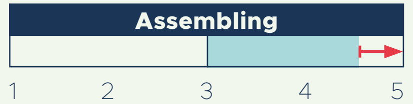


Base Mesh Resolution
First and foremost, the base mesh resolution of the digital model must be improved. However, this is already performed in this project. The improved model was simply not ready when fabricating the full-scale prototype. The recommendation is to use the smoothened, uniform, triangle 50K base mesh presented in this report (Figure 5.1).

Head Shape & Size
The second recommendation regarding the digital model is to improve the head shape and size. The head shape is replaced with data from the 3D scan in A-pose as the quality is superior. The resulting model is manipulated to achieve a head circumference of the desired size. Practical helmet sizes is a leading requirement. Studying the international population from the DINED 1D database, the mean male head circumference is 570 mm. This corresponds to a medium size helmet for many brands (Evo Cycles, n.d.).

Figure 5.1: Difference between the original (left) and the final mesh (right).

Interaction Segmentation
Assembling of the mannequin is rated positively with opportunities to perfect it. Recommendations regard the segmentation of the legs and the bevels on the segment edges.



Leg Segmentation
Validation shows functional limb segmentation, but applying the suit caused fabric to stretch near the legs. The recommendation is to shorten leg protrusion from the torso. The length of the protruding limb is shortened to a third of the upper leg length (Figure 5.2). A study with the cycling suit shows the sleeve is able to fold back far enough. This not only prevents the fabric from stretching, but makes the suit easier to apply overall.

Bevels
All segmented surfaces have a straight bevel of 2.5 mm at the edge. The recommendation is to decrease bevel size to 1.0 mm and to make it rounded instead of straight (Figure 5.3). Participants experienced the feature positively, but mentioned it could be smaller. A smaller bevel also more closely represents a realistic body shape. The bevel was originally straight because it requires no support during FDM 3D printing. This is no longer a requirement when the Personalized Mannequin is CNC milled. The suit slides over a rounded bevel easier than over a straight bevel.

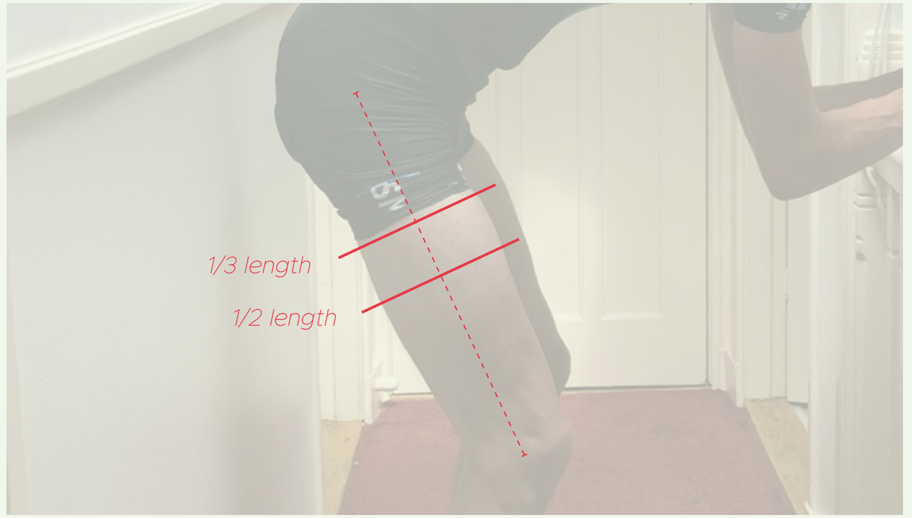


Figure 5.2: Leg protrusion from the torso is decreased from 1/2 to 1/3 of the upper leg length.

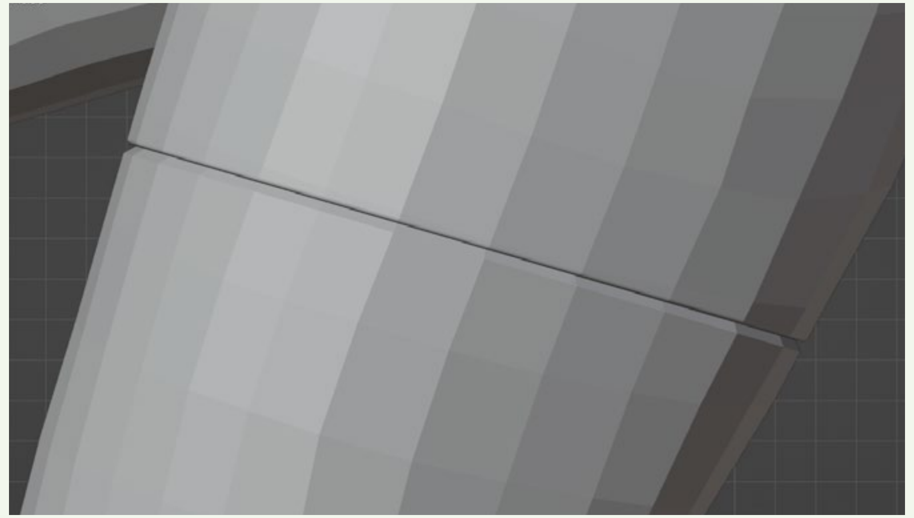
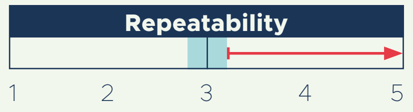


Figure 5.3: A small, rounded bevel (above) is recommended over a large, straight bevel (below).

Attachment Interfaces

Repeatability of the mannequin is rated sufficiently with room for improvement. Recommendations for a redesign of the Attachment Interface regard its shape, the magnets and integrated with the limbs.

The Attachment Interfaces are redesigned following validation (Figure 5.4). The performance did not meet requirements and several recommendations are therefore presented.



Shape

First, the shape of the interfaces is changed to improve the performance and to reduce slack. The recommendation is to recess the interfaces deeper, increasing their effective moment arm. It is also recommended to give the interfaces taller straight (albeit drafted) faces, so the male side does not slide out of the female slot. The bevel size remains identical to its original design.

Magnets

Second, it is recommended to increase magnetic force. This is possible by multiple methods. One is to use a stronger magnet. The Neodymium N50 magnet is recommended over the common N35 for its higher maximum strength (MagnetPartner, n.d.). Magnetic force is also defined by volume, so another method is to use larger magnets. Mostly thickness can be increased as the interfaces have a limited surface area. The area can be used more effectively by installing the magnets on the surface so they make direct contact. Appropriate adhesive is essential to keep the magnets in place.

Integration

Third, the Attachment Interface is recommended to be integrated with the polyurethane limb instead of being attached as a separate, SLS 3D printed part. The design that results from iterations in this project does not require complex features that can be realized through SLS 3D printing. Integration with the CNC milled limbs eliminates unnecessary manufacturing. Attachment with screws becomes unnecessary and the intended sockets are redesigned as an extra attachment measure preventing slack.

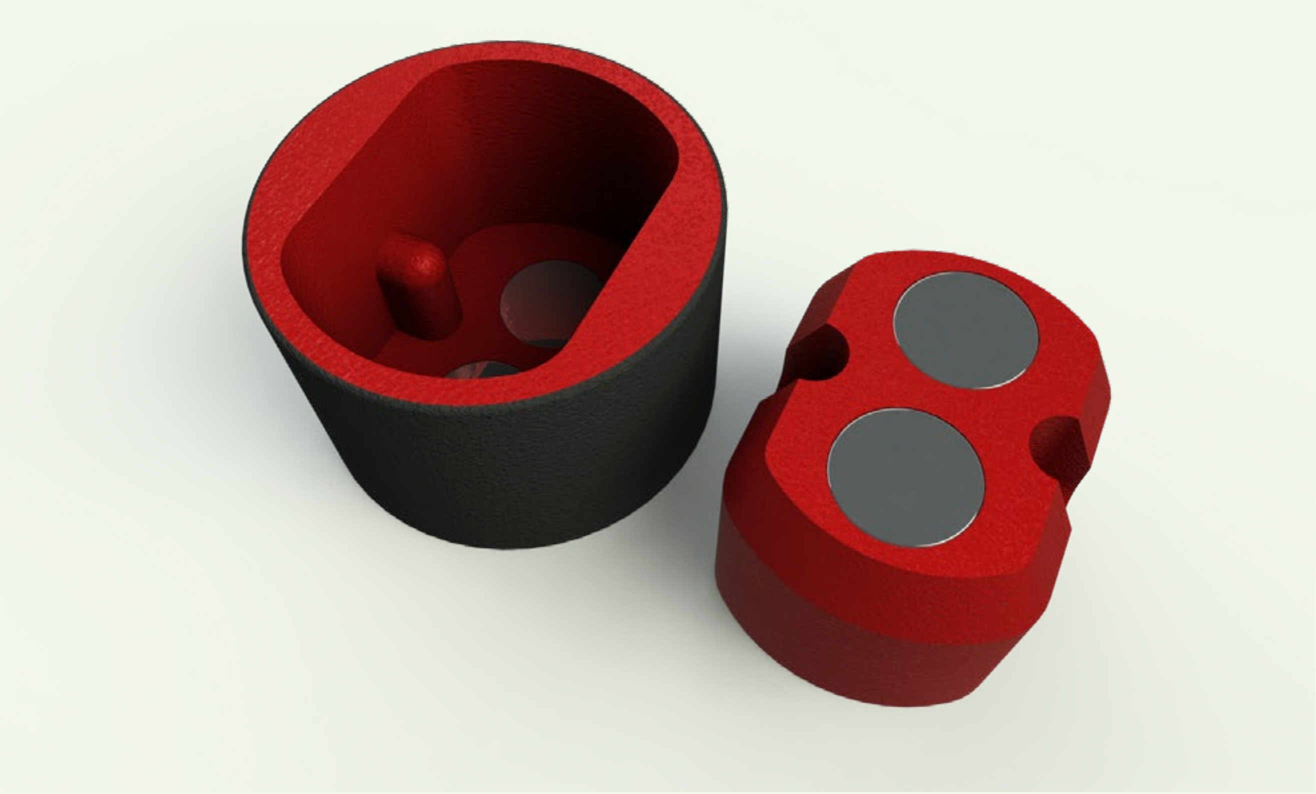
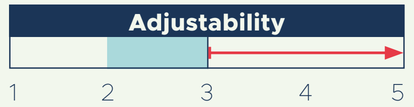


Figure 5.4: The recommended Attachment Interface of the arm integrated with a cylinder.

Bicycle Mounts

Adjustability of the mannequin is rated poorly with a need for improvement. Recommendations regard the shape and size of each mount and flexibility of the joints to mount them correctly.



Shape & Size

Similar to the head of the mannequin, its hands, feet and bottom did not have the intended shape and size. The recommendation is to manipulate the shape and size of each limb to their desired specification.

First, the hands must follow the shape of the handlebars more closely. This is achieved by modelling the fingers around a digital model of the handlebar (Figure 5.5). Road handlebars have a diameter of 23.8 mm without handlebar tape (Novoviç, 2021) and following that number allows the tape to put pressure on the fingers.

Second, the feet must be shaped and sized correctly to fit a cycling shoe. This challenge is similar to that of the head and helmet. Mean shoe size of the participants is 44.5, but a more practical size may the selected too. The recommendation is to model the foot slightly smaller than intended to apply the shoe easier and give the mannequin slight adjustability (Figure 5.6).

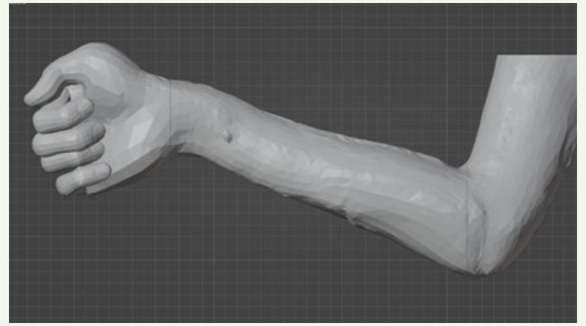


Figure 5.5: The hands must follow the shape of the handlebar.

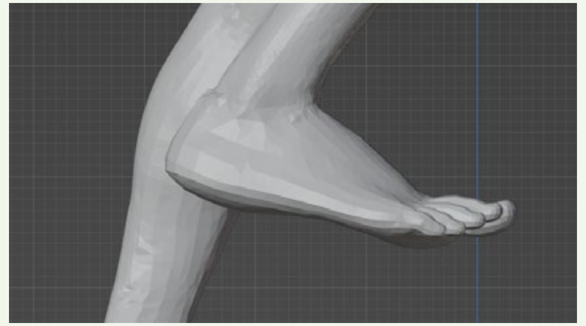


Figure 5.6: The feet must be sized slightly smaller than the desired shoe size.

Figure 5.7: The bottom must leave enough space for any saddle.

Third, the bottom of the mannequin must allow more space for the saddle. The recommendation is to enlarge the area between the leg, specifically towards the back as the saddle is widest there (Figure 5.7). "Common bike saddle sizes range from 135 mm to 160 mm" (Hincapie, 2021) so the mannequin must be modelled accordingly.

Flexible Joints

The feet of the mannequin did not reach the bicycle pedals during validation. As discussed with the participants, the recommendation is to apply a flexible joint at the knees for adjustability (Figure 5.8). A joint in this position allows for natural movement. Using SLS 3D printed flexible TPU the joint's flexibility can be manipulated, allowing for both adjustability and repeatability. Overall size, wall thickness and internal structures can be optimized to improve the joint's performance. A similar joint can be applied at the elbows, but validation in this research did not identify such a requirement.

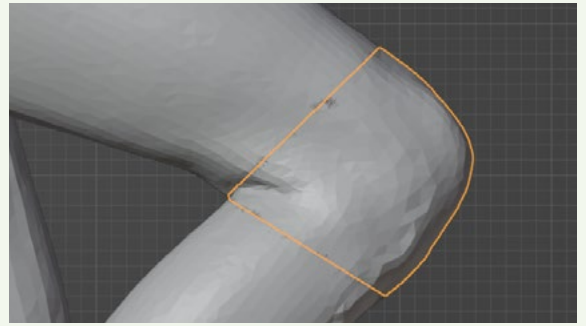


Figure 5.8: A flexible knee segment allows for accurate adjustability.

5.2 Overall Conclusion

The aim of this research is to increase the speed of cyclists by reducing aerodynamic drag. Common research methods are digital and physical simulations. The goal is this project is to develop an anthropometric model for each method based on professional cyclists from Team DSM.

Digital Model (Generic)
The first goal of this research is to create a generic cyclist model for research organisations around the world. The Generic Model is an average of ten male, professional cyclists in both road and time trial pose (Figure 5.9). The DINED Mannequin approach is used to divide the method into four steps: Capture, Process, Correspond & Average.

The 3D scanning process in this project is challenging as the participants are captured in a representative context: on-site, on a bicycle in cycling gear. This affects the quality of the 3D scan and influences any processing of the models. The models are corrected for movements, missing sections and unwanted noise. Design of the base mesh also influences the result as it determines surface quality and level of detail. It is preferred to stay true to the original anthropometric data, but manipulation is essential for the desired result.

The Digital Human Modelling knowledge generated in this project may be relevant in future anthropometric research. The workflow provides insights into capturing a human body in the context of cycling, but it may be applied in a different context too. The rest of the workflow similarly describes how to process the anthropometric data to specific desires. Aerodynamic research is not the only context where this knowledge is relevant and applicable.

The Generic Model is going to be published on the 4TU Repository to perform comparable aerodynamic research around the world. The Generic Model provides a benefit to the industry by increasing knowledge about and application of cycling aerodynamics. A limitation of the model is its limited dataset. The model is based on ten riders, but the number may increase in the future. The model lacks quality in some places, but is an improvement over what is available.

Figure 5.9: Generic Model of ten male, professional cyclists in time trial pose.

Physical Mannequin (Personalized)
The second goal of this research is to design a personalized cyclist mannequin for aerodynamics researchers. The Personalized Mannequin is the physical representation of an individual cyclist's anthropometry in time trial pose (Figure 5.10). The Centre of Design for Advanced Manufacturing Approach is used to divide the process into four steps: Digitalization, Design Automation, Digital Fabrication & Production.

The Advanced Manufacturing process of Rupert is challenging as the Personalized Mannequin is such a large, Ultra-Personalized Product. Possibilities are limited as every version of the product is different and requires advanced materials and fabrication. CNC Milling rigid polyurethane foam provides the accessibility, product performance and design features Rupert requires. The design has segmented limbs to apply cycling gear, magnetic interfaces to attach limbs and flexible interfaces to mount to a bicycle. The mannequin stays true to the original anthropometric data, but has design features to provide the desired user interaction.

The Advanced Manufacturing knowledge generated in this project may be relevant in future Ultra-Personalized Products of this scale. The design process provides insights into the application of additive and subtractive manufacturing. Advanced Manufacturing at this scale is uncommon, especially with the level of detail a mannequin requires. The project elaborates on the selection of fabrication methods and materials which is highly relevant in this context. The knowledge may be applicable in other prototype or product design projects.

This project only results in one version of the Personalized Mannequin. The workflow is partially automated and accurately described in this report so it can be repeated. Rupert's design may be of use to other organisations with a different anthropometric model, perhaps in a different context than cycling. A limitation of the design is that it is specifically designed for the context of aerodynamic research. Design features may not function as intended with a different application. The design of Rupert also has its flaws, so recommendations are presented in this report. If the Personalized Mannequin is further developed, I believe it is a well designed and valuable product.

Figure 5.10: Personalized Mannequin of an individual male, professional cyclist in time trial pose.

6. Sources

This list contains all the sources referenced throughout this report in alphabetical order.

Artec 3D. (2017). *Professional 3D scanners.* Retrieved from: *https://www.artec3d.com/*

Artec 3D. (2017). *Data Processing documentation.* Retrieved from: *http://docs.artec-group.com/as/13/en/process.html*

Autodesk Meshmixer. (2020). *Free software for making awesome stuff.* Retrieved from: *https://www.meshmixer.com/*

Autodesk Meshmixer. (2020). *Sculpt Tool.* Retrieved from: *https://help.autodesk.com/view/MSHMXR/2019/ENU/?guid=GUID-6D77C4D0-0E73-411F-B00F-F71508D00DEA*

Ayachit, U. (2015). *paraview.simple. LoopSubdivision.* Kitware. Retrieved from: *https://kitware.github.io/paraview-docs/latest/python/paraview.simple.LoopSubdivision.html*

Ayachit, U. (2015). *The ParaView Guide: A Parallel Visualization Application.* Kitware. Retrieved from: *https://www.paraview.org/*

Blender Foundation. (2018). *Blender - a 3D modelling and rendering package.* Retrieved from: *http://www.blender.org*

Centre of Design for Advanced Manufacturing. (n.d.) *About.* TU Delft. Retrieved from: *https://www.tudelft.nl/io/onderzoek/research-labs/center-of-design-for-advanced-manufacturing/about*

Cycling Weekly. (April 28th, 2017). *What's it really like inside a state-of-the-art cycling wind tunnel?* Retrieved from: *https://www.cyclingweekly.com/news/product-news/inside-state-art-cycling-wind-tunnel-327535*

Evo Cycles. (n.d.). *Helmet Size Guide.* Retrieved from: *https://www.evocycles.co.nz/helmet-size-guide*

Formlabs. (n.d.). *3D Printing Technology Comparison: FDM vs. SLA vs. SLS.* Retrieved from: *https://formlabs.com/blog/fdm-vs-sla-vs-sls-how-to-choose-the-right-3d-printing-technology/*

García-López, J., Rodríguez-Marroyo, J.A., Juneau, C.-E., Peleteiro, J., Martínez, A.C. & Villa, J.G. (May, 2008). *Reference values and improvement of aerodynamic drag in professional cyclists.* J. Sports Sci., 26 (2008), pp. 277-286

Garimella, R., Moens, S., Vleugels, J., Huysmans, T., Beyers, K., & Verwulgen, S. (2020). *Development of an Articulating Cycling Mannequin for Wind Tunnel Testing.* In Proceedings of 3DBODY.TECH 2020 : 11th Int. Conference and Exhibition on 3D Body Scanning and Processing Technologies.

General Plastics. (n.d.). *Machining vs cast molding: Choosing the best manufacturing method to process polyurethane foam.* Retrieved from: *https://www.generalplastics.com/technical-papers/machining-vs-cast-molding-choosing-the-best-manufacturing-method-to-process-polyurethane-foam*

General Plastics. (July 30th 2018). *Tooling & Molds User Guide.*

Giant Bicycles. (n.d.). *Performance Benefits.* Retrieved from: *https://www.giant-bicycles.com/int/technology/detail/117*

Grappe, F., Candau, R., Belli, A. & Rouillon, J. D. (December 1st 1997). *Aerodynamic drag in field cycling with special reference to the Obree's position.* Ergonomics, 40. Issue 12, Pages 1299 – 1311.

Guimond, A., Meunier, J. & Thirion, J.-P. *Average brain models: a convergence study.* Comput. Vis. Image Understand., 77 (2) (2000), pp. 192-210

Hincapie, D. (November 23rd, 2021). *How To Measure Sit Bone Width For Bike Saddle Size.* Retrieved from: *https://hincapie.com/ride-with-us/stories-from-the-saddle/how-to-measure-sit-bone-width-for-bike-saddle-size/*

Huysmans, T. (July 16th 2020). *AFHE2020 Tutorial on 1D to 4D Anthropometry with the Open Platform DINED.* Retrieved from: https://www.youtube.com/watch?v=kmJpvRmiLLk&ab_channel=ToonHuysmans

Huysmans, T., Goto, L., Molenbroek, J., & Goossens, R. (2020). *DINED Mannequin.* Tijdschr. Voor Hum. Factors, 45, 4-7.

Huysmans, T. (2019). *Statistical Shape Modelling: Computational Design for Digital Fabrication.* TU Delft.

iGoldenCNC. (May 26th 2021). *CNC foam milling and engraving – foam cutting.* Retrieved from: https://www.igolden-cnc.com/cnc-foam-milling-and-engraving-foam-cutting/

MagnetPartner. (n.d.). *What Is the Difference Between n35 and n50 Magnets?* Retrieved from: https://magnetpartner.com/difference-between-n35-and-n50#:~:text=So%20what%20is%20the%20difference,strongest%20of%20the%20neodymium%20magnets.

Malizia, M. & Blocken, B. (July, 2021). *Cyclist aerodynamics through time: Better, faster, stronger.* Journal of Wind Engineering and Industrial Aerodynamics, 214.

McLeod, S. (2013). *Kolb's Learning Styles and Experiential Learning Cycle.* Retrieved from: https://www.simplypsychology.org/learning-kolb.html

Minnoye, A.L.M., Doubrovski , E.L., Huysmans, T., Wu, J., Kwa, F. S. S. & Song, Y. (2022). *Personalized product design through digital fabrication.* Center of Design for Advanced Manufacturing, TU Delft.

Molenbroek, J. *DINED 1D Database.* Retrieved from: https://dined.io.tudelft.nl/en/database/tool

Norwegian SciTech News. (March 17th, 2017). *Team Sky partners with NTNU on ultra-fast time trial suit.* Retrieved from: https://norwegianscitechnews.com/2017/03/team-sky-partners-ntnu-ultra-fast-bicycle-suit/

Novoviç, R. (September 2nd, 2021). *Bicycle handlebar dimension standards.* BikeGremlin. Retrieved from: https://bike.bikegremlin.com/3784/bicycle-handlebar-dimension-standards/

Oceanz. (n.d.). *Oceanz Flexible TPU.* Retrieved from: https://www.oceanz.eu/en/materials/oceanz-flexible-tpu/

PermissionToPlay. (n.d.). *The three lenses of human centred design: desirability, feasibility, viability.* Retrieved from: https://www.permissiontoplay.co/fieldnotes/lenses-of-human-centred-design-desirability-feasibility-viability/

Russian 3D Scanner LLC. (2021). *About Wrap.* Retrieved from: https://www.russian3dscanner.com/

Russian 3D Scanner LLC. (2021). *Wrap Tutorials.* Retrieved from: https://www.russian3dscanner.com/wrap-tutorials/

Sargent, R. (2011). *Verification and Validation of Simulation Models. Syracuse University.*

Silverstone Sports Engineering Hub. (February 13th 2020). *3D Mannequin testing in a Cycling Wind Tunnel.* Retrieved from: https://silverstonesportshub.co.uk/2020/02/13/3d-mannequin-wind-tunnel-testing/

Team Jumbo-Visma. (June 15th, 2021). *Team Jumbo-Visma aims for time gain in wind tunnel.* Retrieved from: https://www.teamjumbovisma.com/interview/innovation/team-jumbo-visma-aims-for-time-gain-in-wind-tunnel/

Terra, W. (2021). *Informed Consent Form: Cyclist 3D Scanning.* TU Delft.

TU Delft. (2016). *A 3D printed mannequin of Tom Dumoulin in the TU Delft wind tunnel helps gain a competitive advantage.* Retrieved from: https://www.tudelft.nl/en/2016/tu-delft/a-3d-printed-mannequin-of-tom-dumoulin-in-the-tu-delft-wind-tunnel-helps-gain-a-competitive-advantage

TU Delft. (n.d.). *Open Jet Facility.* Retrieved from: https://www.tudelft.nl/lr/organisatie/afdelingen/aerodynamics-wind-energy-flight-performance-and-propulsion/facilities/low-speed-wind-tunnels/open-jet-facility

Th3rd. (n.d.). *Tom Dumoulin.* Retrieved from: https://th3rd.nl/portfolio_page/tom-dumoulin/

Union Cycliste International. (October 5th 2021). *Clarification Guide Of The UCI Technical Regulation.*

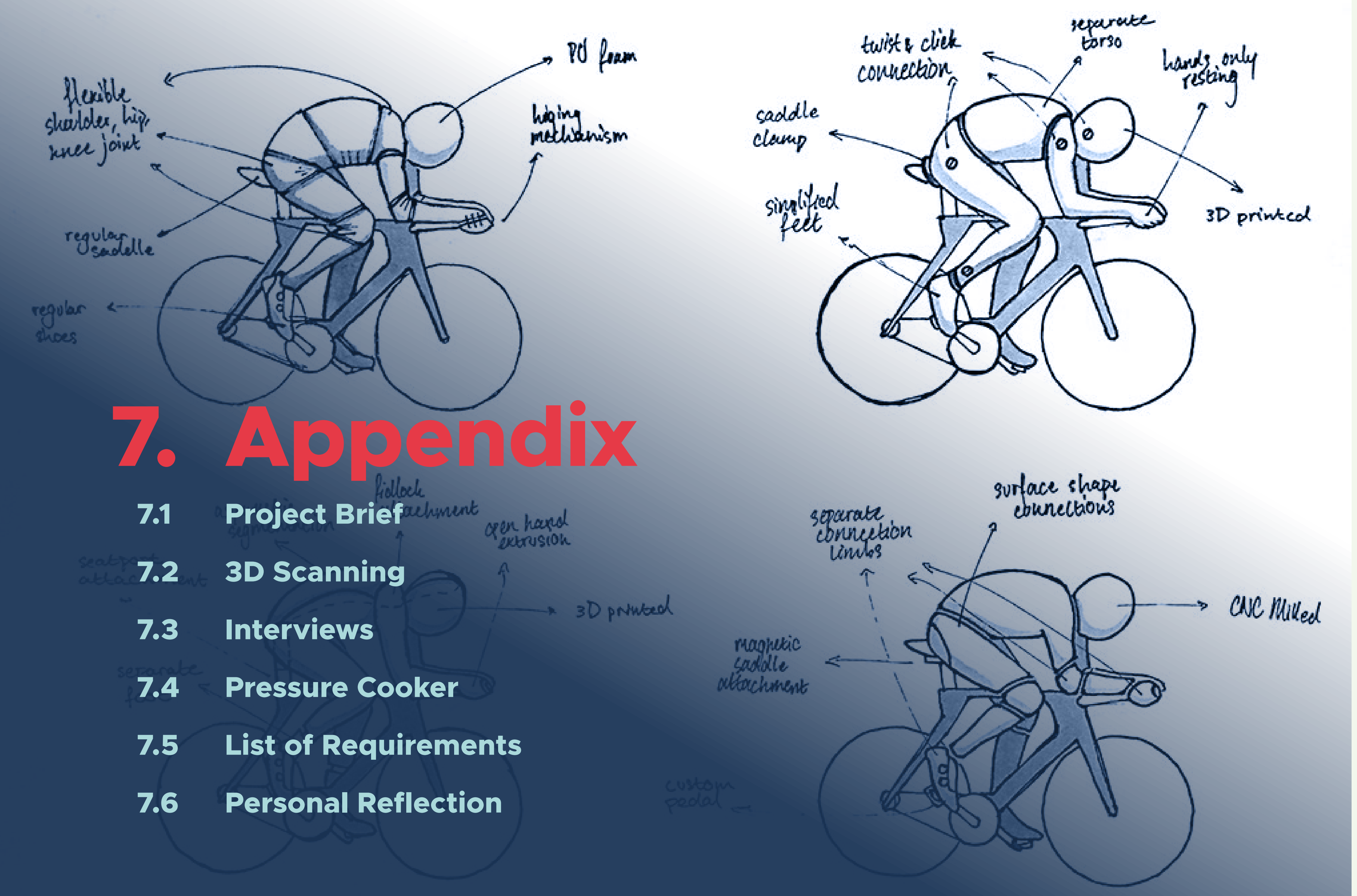
Valette, S., Gelas, A., Noll, M., Weigl, A., Sansom, K. & Dinckelacker, S. (n.d.). *ACVD: a program to perform fast simplification of 3D surface meshes.* Retrieved from: https://github.com/valette/ACVD

Van Boeijen, A., Daalhuijzen, J. & Zijlstra, J. (2020, Rev. Ed.). *Delft Design Guide: Perspectives-Models-Approaches-Methods.* Amsterdam: Bispublishers.

Vorteq. (n.d.). *3D Printed Mannequins.* Retrieved from: https://vorteqsports.co.uk/3d-printed-mannequins/

Wood, R. (December 2015). *Anthropometry and Cycling.* Topend Sports. Retrieved from: https://www.topendsports.com/sport/cycling/anthropometry.htm

3D Printing Industry. (July 30th 2021). *Artec Leo 3D scanning helps Vorteq create "world's fastest" cycling skinsuit for Olympic athletes.* Retrieved from: https://3dprintingindustry.com/news/artec-leo-3d-scanning-helps-vorteq-create-worlds-fastest-cycling-skinsuits-for-olympic-athletes-193736/

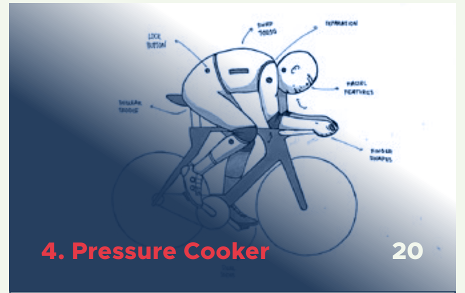


7. Appendix

7. Appendix

Table of Content

The Appendix of this report is referenced throughout and is included as a separate document. It contains six chapters including the Project Brief, 3D Scanning, Interviews, Pressure Cooker, List of Requirements and a Personal Reflection.



7. Appendix

1. Design Brief

The project brief is discussed during the project kick-off meeting on Wednesday 09-02-2022 and later finished completely.

DESIGN FOR our future

TU Delft

IDE Master Graduation

Project team, Procedural checks and personal Project brief

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

- The student defines the team, what he/she is going to do/deliver and how that will come about.
- SSC E&SA (Shared Service Center, Education & Student Affairs) reports on the student's registration and study progress.
- IDE's Board of Examiners confirms if the student is allowed to start the Graduation Project.

USE ADOBE ACROBAT READER TO OPEN, EDIT AND SAVE THIS DOCUMENT
Download again and reopen in case you tried other software, such as Preview (Mac) or a webbrowser.

STUDENT DATA & MASTER PROGRAMME
Save this form according the format "IDE Master Graduation Project Brief_familyname_firstname_studentnumber_dd-mm-yyyy".
Complete all blue parts of the form and include the approved Project Brief in your Graduation Report as Appendix 1 !

family name: Vloemans 5498
initials: S. J. J. given name: Siward
student number: 4456556
street & no.: [redacted]
zipcode & city: [redacted]
country: [redacted]
phone: [redacted]
email: [redacted]

Your master programme (only select the options that apply to you):
IDE master(s): ★ IPD / Dfl / SPD
2nd non-IDE master: N.A.
individual programme: - - (give date of approval)
honours programme: Honours Programme Master
specialisation / annotation: Medisign / Tech. in Sustainable Design / Entrepeneurship

SUPERVISORY TEAM **
Fill in the required data for the supervisory team members. Please check the instructions on the right !

** chair: Toon Huysmans — dept. / section: Ergonomics & Design
** mentor: Sander Minnoye — dept. / section: Materializing Futures
2nd mentor: Harm Ubbens
organisation: Team DSM
city: Deventer — country: The Netherlands

comments (optional): Wouter Terra is also involved in this project on behalf of TU Delft faculty of Aerospace Engineering.

Chair should request the IDE Board of Examiners for approval of a non-IDE mentor, including a motivation letter and c.v..

Second mentor only applies in case the assignment is hosted by an external organisation.

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

APPROVAL PROJECT BRIEF
To be filled in by the chair of the supervisory team.

chair: Toon Huysmans — date: 15 - 02 - 2022 — signature: Toon Huysmans (Digitally signed by Toon Huysmans Date: 2022.02.15 09:52:19 +01'00')

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

Master electives no. of EC accumulated in total: 27 EC
Of which, taking the conditional requirements into account, can be part of the exam programme: 27 EC
List of electives obtained before the third semester without approval of the BoE

★ YES — all 1st year master courses passed
NO — missing 1st year master courses are:

name: K. Veldman — date: 17 - 02 - 2022 — signature: Kristin Veldman (Digitally signed by Kristin Veldman Date: 2022.02.17 12:30:40 +01'00')

FORMAL APPROVAL GRADUATION PROJECT
To be filled in by the Board of Examiners of IDE TU Delft. Please check the supervisory team and study the parts of the brief marked **.
Next, please assess, (dis)approve and sign this Project Brief, by using the criteria below.

- Does the project fit within the (MSc)-programme of the student (taking into account, if described, the activities done next to the obligatory MSc specific courses)?
- Is the level of the project challenging enough for a MSc IDE graduating student?
- Is the project expected to be doable within 100 working days/20 weeks ?
- Does the composition of the supervisory team comply with the regulations and fit the assignment ?

Content: ★ APPROVED / NOT APPROVED
Procedure: ★ APPROVED / NOT APPROVED

comments

name: Monique von Morgen — date: 01 - 03 - 2022 — signature:

project title: Develop a cyclist mannequin from 3D scans for aerodynamics tests.

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

start date: 09 - 02 - 2022 — end date: 13 - 07 - 2022

INTRODUCTION **
Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

In professional cycling, rider mannequins are used to conduct extensive aerodynamic research in the wind tunnel. Mannequins are a great tool because they substitute the variable human subject with a constant factor, therefore generating more accurate results. They also avoid logistical and practical challenges with human subjects.

A generic rider model provides reference data for larger populations and comparable data for different institutions. It can be used to combine knowledge and results from different research. It can also be used in the automatic interpretation of 3D cyclist models.

Personalized mannequins provide rider-specific data. However, personalized mannequins require labour-heavy processing and manufacturing, while only providing relevant data for a single rider in limited positions. Processing includes interpretation and modulization of the 3D model, articulation of limbs, joints and user interaction points.

Cyclist mannequins have become a proven concept, but can be further developed into a refined product. Consider features for multiple rider positions and improved user interactions. It also involves an automated workflow, optimized material selection and production method.

The most important stakeholders involved in this project are aerodynamics, digital human modelling & agile manufacturing experts from IDE, Aerospace Engineering and Team DSM. Budget is supplied by TeamNL in agreement with the clients.

space available for images / figures on next page introduction (continued): space for images

image / figure 1: This thesis will be the successor to the Dumoulin mannequin from 2016.

TO PLACE YOUR IMAGE IN THIS AREA:
- SAVE THIS DOCUMENT TO YOUR COMPUTER AND OPEN IT IN ADOBE READER
- CLICK AREA TO PLACE IMAGE / FIGURE

PLEASE NOTE:
- IMAGE WILL SCALE TO FIT AUTOMATICALLY
- NATIVE IMAGE RATIO IS 16:10
- IF YOU EXPERIENCE PROBLEMS IN UPLOADING, COVERT IMAGE TO PDF AND TRY AGAIN

image / figure 2:

Personal Project Brief - IDE Master Graduation
TU Delft

PROBLEM DEFINITION **

Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

The challenge of this project is to develop personalized cyclist mannequins into a reproducible product. This is going to involve generating a generic cyclist model from multiple subjects. A generic model of the riders combined may be used to compare research data to that of other institutes such as the University of Melbourne.

The generic model will be used for the interpretation of individual 3D scans and automate the workflow of producing personalized mannequins. The life-size mannequin must be optimized for wind tunnel testing. It must be able to take multiple rider positions and feature interactions such as dressing, mounting and detaching. Intended users are Team DSM aerodynamics experts and staff.

Approximately 20 riders of professional cycling Team DSM are going to be 3D scanned and processed for this project. The project will entail challenges in 3D scanning, digital human modelling and digital fabrication. It will focus on aspects of the mannequin such as limbs, joints, user interaction points, materials and manufacturing method.

ASSIGNMENT **

State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in "problem definition". Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

Develop a personalized cyclist mannequin for aerodynamics research. The mannequin is digitally fabricated life-size with user interaction features. The workflow is automated using a generic 3D cyclist model.

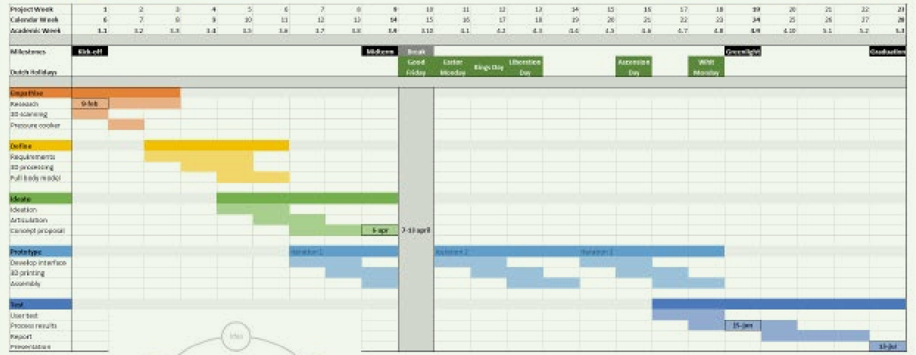
This project involves 3D scanning, digital human modelling, digital fabrication, aerodynamics and ergonomics. It therefore touches upon many elements of Integrated Product Design, but will require the knowledge of specific experts too. The development and automation of the design workflow will contribute to the feasibility of personalized cyclist mannequins. A generic model will assist in the automatic interpretation of individual 3D scans. It will also make collected data from subsequent research comparable. The mannequin itself will be valuable in the aerodynamics research of TU Delft Sports Engineering Institute in partnership with Team DSM.

Personal Project Brief - IDE Master Graduation
TU Delft

PLANNING AND APPROACH **

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any, for instance because of holidays or parallel activities.

start date 9 - 2 - 2022 13 - 7 - 2022 end date



Full-time graduation, five days a week for 22 weeks due to multiple holidays in Q4 and a 1-week break after the midterm. The thesis will start February 9th 2022 and end July 13th 2022 (estimated). During a 1-week pressure cooker at the start I will run through the entire project to identify bottlenecks and adjust the planning accordingly.

The planning contains three iterative design cycles, but that may vary depending on the project flow. I am going to apply the Lean Start-up approach by frequently building and evaluating prototypes early on (following the pressure cooker). As this project is a successor to the Dumoulin mannequin, it holds a baseline and can follow a structure like this. The final prototype will be a life-size mannequin to be validated in a wind tunnel aerodynamics test.

09-02-2022 Kick-off
06-04-2022 Midterm
07-04-2022 – 13-04-2022 Holiday break
15-06-2022 Greenlight
13-07-2022 Graduation

15-04-2022 Good Friday
18-04-2022 Easter Monday
27-04-2022 Kings Day
05-05-2022 Liberation Day
26-05-2022 – 27-05-2022 Ascension Day
06-06-2022 Whit Monday

Personal Project Brief - IDE Master Graduation
TU Delft

MOTIVATION AND PERSONAL AMBITIONS

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... Stick to no more than five ambitions.

My personal motivation for this project is my interest in bicycles and the connection with its rider. I started cycling at the start of the pandemic and I have worked on many bicycles since. Now, I am excited to take it a step further than a hobby and tackle a related challenge during my IPD master thesis. I find professional cycling intriguing and I wish to discover how I can be an addition to it as an industrial design engineer. During the thesis, I aim to learn about three ambitions.

• Experience the cycling industry
My first ambition comes from my passion which is cycling. In my thesis, I aim to become familiar with the cycling industry and its intricacies. What kind of people are involved, what current developments are and where I can make a difference. I also want to discover if the world of cycling is an interesting direction for my professional career.

• Learning about digital human modelling & fabrication
Secondly, I wish to learn about digital human modelling and fabrication During my time at IDE, I have had little experience in these fields. I realize that may pose a challenge, but I also see it as an opportunity to take. As there are many developments and opportunities in these fields, it would be great to contribute and find my passions here if there are any.

• Managing a design process
Lastly, I wish to build my confidence in managing a design process. As the master thesis is 100 days long and individual, it will require thorough management by the student himself. I believe I possess the necessary tools to succeed, but I will use this project to improve myself and gain confidence for the start of my professional career.

FINAL COMMENTS

In case your project brief needs final comments, please add any information you think is relevant.

2.1 Pilot

Pilot conducted on Wednesday 09-02-2022 at the faculty of Industrial Design Engineering, TU Delft with Bertus Naagen, Harm Ubbens & Wouter Terra.

Introduction

"A generic cyclist model is defined based on average cyclist anthropometric data. Therefore, the aim is to make body scans of a large group of elite riders to extract this average model. After having defined the generic cyclist model, the geometry is stored in the 4TU repository with open access to the general public. This allows for better comparison of cycling aerodynamic research among different research groups around the world and speed up the understanding of the flow around a rider and bike" (Terra, 2021).

Research goal

Establish a method to capture a cyclist's anthropometric data using 3D scanning.

Method

Participants

One participant is involved in the pilot.

- Gender: male
- Age: 23 years
- Length: 187 cm
- Weight: 80 kg
- Cycling type: recreational road cyclist

Apparatus

- Time trial bicycle
- Bicycle trainer stand
- Time trial cycling kit

- Artec Eva handheld 3D scanner (2x)
- Laptops with Artec Studio 16 software (2x)
- External hard drive
- Head cap
- Rotating platform

Stimuli

The participant is placed in position in cycling kit. The participant is instructed to remain still while being captured by the researchers for about 5 minutes. This research involves three poses:

- A-pose on rotating platform.
- A-pose on the floor (Figure 7.1).
- Time trial (TT) pose on the bicycle (Figure 7.2).

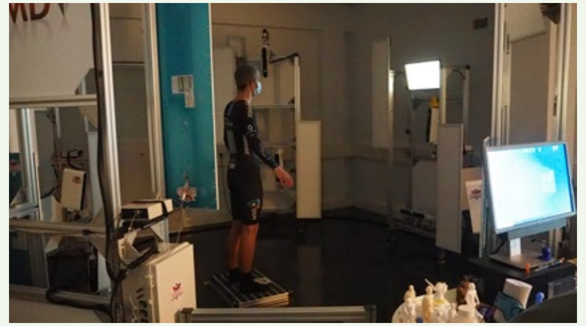


Figure 7.1: Participant positioned in A-pose with a full-body 3dMD scanner setup.

Figure 7.2: Participant positioned in time trial pose on the bicycle with a handheld scanner setup.

Procedure

Location: 3D Body Scanning Lab, TU Delft
Time: participant present from 10:30-12:30

Instruction

The participant is welcomed, introduced to the researchers and the research overall. The informed consent form is explained and signed.

Preparation

- The participant is asked to change into the cycling kit.
- The bicycle is installed in the trainer stand and positioned in an open space.
- The 3D scanners and laptops are connected and powered up (Figure 7.3).

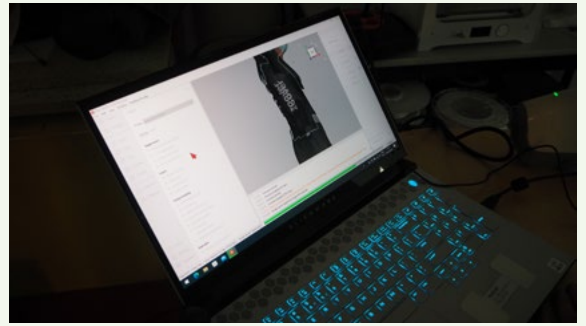


Figure 7.3: Digital model in 3D capturing software on a laptop.

3D Scanning

- The participant is placed in a selected pose.
- Two researchers capture the participant from left and right side of the body with handheld scanners.
- Captured results are confirmed for completeness in the software before ending scanning.
- Raw capture data is named and stored on an external hard drive.
- The scanning procedure is repeated for the other poses.

Data processing

The collected raw data is processed in Artec Studio 16 software. Each file is processed using the following steps:

- Editor – Eraser: unwanted elements.
- Tools – Rough serial registration.
- Tools – Fine registration.
- Tools – Global registration.
- Tools – Sharp fusion

After the initial steps, the file is saved in the OBJ format. The file is then combined with the corresponding second half of the scan. The halves are combined using the following steps:

- Align – New pair (3x)
- Align – Auto-alignment
- Align – Non-rigid
- Tools – Sharp fusion

A combined model is now created. Holes in the model may appear. These may be automatically filled by using settings in the 'Sharp fusion' tool. If holes are filled incorrectly, manually applying 'Bridges' may help. When too many holes appear to fill, the subject may have to be scanned again.

Results

A-pose

The most accurate scan is produced by the 3dMD full-body scanner (Figure 7.4). This scan is easiest and fastest to perform. However, this setup is not available during the actual research.

Figure 7.4: A-Pose model captured with full-body 3dMD scanner.

The handheld scanner produces significantly different results. It is more difficult and slower to operate. The models generated suffer from incompleteness. The A-pose recorded using the rotating platform is a combination of scans, because the scanner is unable to record continuously (Figure 7.5). The main issue is capturing the arms completely. This scan is performed by a single researcher.

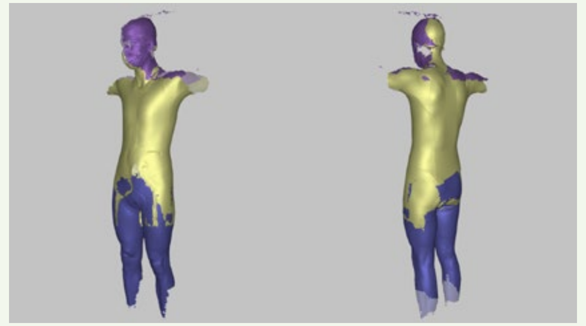


Figure 7.5: A-Pose model captured on a rotating platform with a single handheld scanner.

The A-pose recorded without rotating platform shows a more complete scan (Figure 7.6). This scan is performed by two researchers with handheld scanners and later combined with the software. It is easier to perform the scan without the rotating platform. The model shows some incompleteness in the hair, trousers and inside of the arms. This scan is performed on a different participant than the other scans.

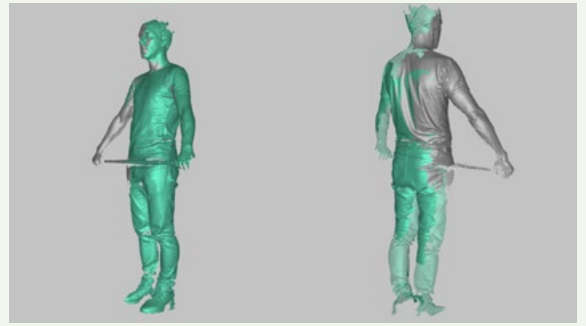


Figure 7.6: A-Pose model captured without a rotating platform with two handheld scanners.

Time trial pose

The time trial pose is recorded with one method only: by two researchers with handheld scanners. Combining both halves results in quite a complete model that mainly lacks its feet (Figure 7.7). There are some holes near the bottom, hands, elbows, upper arms, lower legs, neck and helmet (Figure 7.8).

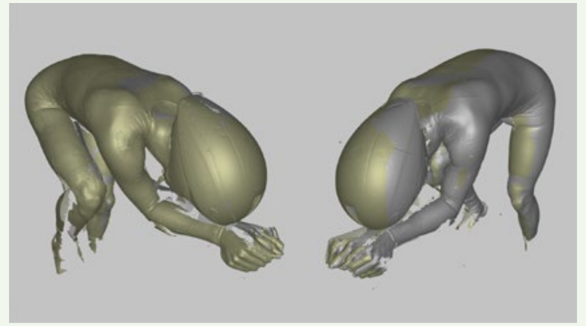


Figure 7.7: Captured TT pose in perspective.

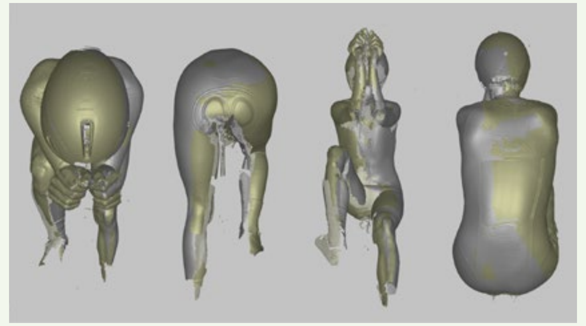


Figure 7.8: Captured TT pose from the sides.

After post-processing, all holes in the model are filled (Figure 7.9). Inaccuracies show near the head, arms and lower legs (Figure 7.10). The feet still lack as these cannot be borrowed from the A-pose model.

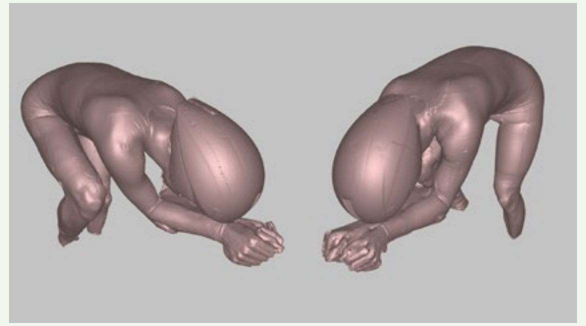


Figure 7.9: Processed TT pose in perspective.

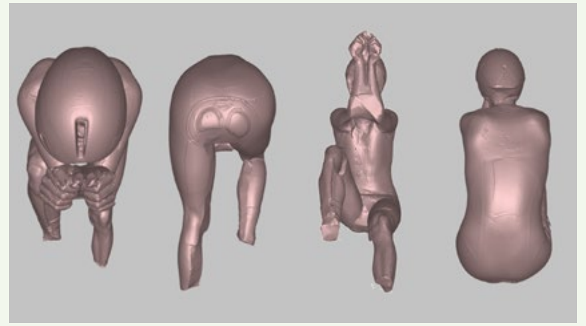


Figure 7.10: Processed TT pose from the sides.

Discussion

A-pose

As a full-body scanner will not be used in the research, two hand scanning methods are compared to capture the A-pose: with and without a rotating platform.

The automatic rotation causes the participant to move from the focal point of the hand scanner continuously. This causes errors with the capturing software and results in separate scans. The scans can be combined later, only requiring some manual effort. The arms and lower legs are not captured at all. The lower legs can be explained because the participant was wearing black socks. The arms are not captured at all as they protrude significantly from the body. The researcher is unable to move the focal point of the hand scanner fast enough. Therefore, the rotating platform is not the right tool for this job.

Capturing the participant without the rotating platform is more effective. However, this involves two researchers hand scanning each side of the subject. The results only show incompleteness in the hair, trousers and inside of the arms. The subject wore no head cap and had dark trousers, explaining these holes in the model. The inside of the arms was a human error as these areas are hard to reach. They require extra attention from the researchers.

Time trial pose

Capturing the participant with two researchers hand scanning each side of the subject is effective. The contours of the subject are captured completely and only some holes occurred in other areas.

Similar to the A-pose, this model lacks its feet because the participant wore black socks and shoes. The holes near the hands, elbows and bottom are due to contact points with the bicycle in these areas. They cannot be avoided. The holes near the helmet are due to the participant's hair that was not completely covered by the head cap. The holes near the upper arms, lower legs and neck are due to human error and scanner limitations. These areas a hard to reach, because they are partially obstructed by the bicycle and the participant himself. They require extra attention from the researchers and post-processing. The A-pose model may be used for these corrections.

Limitations

All scans were performed on the same participant, except the A-pose without rotating platform. This means the A-pose results cannot be directly compared. However, the researchers noted a preferred workflow without the rotating platform. Thus a conclusion can still be drawn and the platform will not be used in the future.

The participant was instructed to wear a helmet to strike the right pose during scanning, but this is not desired in the generic model. The helmet may be used to practice the pose prior, but will be removed during scanning.

The participant wore black socks and shoes during scanning. Those were not captured successfully due to their colour. However, the shoes are not desired in the generic model. They will either be removed during scanning or during post-processing in the following research.

Conclusion

The research goal of this report is:
Establish a method to capture a cyclist's anthropometric data using 3D scanning.

The pilot has been valuable in establishing the research method and it can be concluded as successful. A cyclist model is generated by 3D scanning a participant on a time trial bicycle. Repeating this process will produce enough data to generate a generic cyclist model.

Possible improvements for the research method are identified and will be implemented in the following research. The improvements concern the optimal apparatus, clear stimuli and a detailed procedure.

7. Appendix 2: 3D Scanning

2.2 Briefing

Introduction
The research goal is to create a generic cyclist model for the purpose of aerodynamic investigation. The generic cyclist model is defined based on the average cyclist anthropometric data. Therefore, the aim is to make body scans of a large group of elite riders to extract this average model. After having defined the generic cyclist model, the geometry will be stored in the 4TU repository with open access to the general public. This allows for better comparison of cycling aerodynamic research among different research groups around the world and speed up the understanding of the flow around a rider and bike.

Method
Procedure
The participants are introduced to the research. They are given an informed consent form they are asked to read and sign. The researchers ask demographic information about the participant and take manual body measurements.

The participant changes into cycling kit. The research involves 3D scanning each participant in several poses (Figure 7.11). The complete session takes about an hour for each participant.

- *A-pose (standing up, arms & legs spread).*
- *Riding pose on time trial bicycle.*
- *Riding pose on road bicycle.*

Figure 7.11: 3D Scanning a participant on a TT bicycle.

Data collection
Prior to scanning, demographic information is asked about the participants. Manual body measurements are also taken.

This research captures data using two handheld Artec Eva 3D scanners. Two researchers operate a device each and scan a side of the participant's body. The data is processed by computer software to create a 3D model of the participant. The average of the personal models is calculated to generate a generic cyclist model.

Data analysis
The data of the individual scans is not shared with anyone outside of the project team except the person of the corresponding cyclist team. TU Delft is the only institution involved. As such TU Delft will follow the Personal Research Data Workflow to ensure GDPR compliance about the collection and processing of human participants. The raw measurements, derived datasets, and finalized model will also be under TU Delft IP. The generic cyclist model (anonymized data) will be shared openly with the research and cyclist industry.

Participation
Responsible researchers
- *Harm Ubbens (Team DSM)*
- *Siward Vloemans (graduate student)*
- *Wouter Terra (aerodynamics)*
- *Bertus Naagen (3D scanning)*
- *Toon Huysmans (human modelling)*

Participants required
A variation of at least 20 professional cyclists (gender, length, weight, type of rider, etc.).

Advantages of participation
- *Experience participation in an academic anthropometric research.*
- *Learn about the process of 3D scanning human subjects.*
- *Helping student and researcher in the development of cyclist aerodynamics.*

Risks of participation
The risk is that the digital geometrical and anthropometric data of the participant on his/her bike is shared outside the project group and used for purposes, other than described in this document. This risk is mitigated by 1) keeping the amount of people involved in this project as small as possible, 2) only including TU Delft staff and 3) the data management plan that is in place and approved by the ethical committee of TU Delft.

The possibility exists that one of the researchers conducting the study infects the participant with the COVID-19 virus, despite the measures taken. The latter measures taken by the research team to mitigate the risk of infection are as prescribed by the RIVM at the time of the study (e.g. wearing facemasks, no physical contact, limited amount of people in one room).

Withdrawal from participation
The cyclists can withdraw from the study at any time by sending an email to the research team. The participants have the right to be forgotten at any time; they can exert this right by sending an email to the research team.

Contact
Location
Keep Challenging Center
Anemoonstraat, 6134 TH Sittard

Contact person
Harm Ubbens

2.3 Informed Consent

All participants involved in this project are briefed and asked to sign an informed consent form.

Informed consent form

Author : Wouter Terra (w.terra@tudelft.nl)

The information sheet, accompanying this informed consent form, describes the nature of the present study. Please read this carefully before filling out the present form.

Consent Form for Generation of a Generic Cyclist Model

Please tick the appropriate boxes — **Yes** **No**

Taking part in the study

I have read and understood the study information dated [DD/MM/YYYY], 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 the collection of my body geometry, standing and sitting on a bike, manually using measurement tape and by 3D body scanning. ○ ○

I understand that taking part in the study involves the following risks: ○ ○

Great care is taken to secure the personal body geometry data of the participants. Nevertheless, a small risk remains that this personal anthropometric data comes into the hands of others than the team of people involved in this study. Note, that this risk is mitigated by limiting the amount of people involved in this study, that all people in this study that will see this personal data are staff of the TU Delft and that latter are aware and should act as is described in the TU Delft data management plan as approved by the ethical committee of the university.

The possibility exists that one of the researchers conducting the study might infect me with the COVID-19 virus, despite the measures taken. The latter measures taken by the research team to mitigate the risk of infection are as prescribed by the RIVM at the time of the study (e.g. wearing facemasks, no physical contact, limited amount of people in one room). ○ ○

Use of the information in the study

I understand that information I provide will be used for the generation of a generic cyclist model by aggregating the geometries of all participants in this study. This generic model will be shared openly with the scientific community and cycling industry. The personal geometries, obtained by the body scanning, might be used anonymously (excluding large parts of the body, head among others) only to elucidate the procedure of processing the individual scans into the final generic model. Never will any data be shared outside the project group that can be traced back to individual participants. ○ ○

In addition to making the generic cyclist model freely available, the present research will be presented at conferences (e.g. ISEA conference) and published in scientific journals (e.g. journal of biomechanics, wind engineering & industrial aerodynamics).

I understand that personal information collected about me that can identify me, such as my personal geometry and anthropometric data, will not be shared beyond the study team. ○ ○

Future use and reuse of the information by others

I give permission for the geometry and anthropometric data that I provide to be archived in the TU Delft project repository so it can be used for future research and learning. The data will be deposited in the form of stl and ASCII files (defining the geometry) and Microsoft Excel files listing the participants anonymously including their length, weight, gender etc. ○ ○

Apart from the project team, only one of the people of the collaborating cycling team can access the data of the participants of his/her cycling team.

Signatures

________________ ________________ ________

Name of participant [printed]

and legal representative If applicable) Signature Date

For participants unable to sign their name, mark the box instead of sign

I have witnessed the accurate reading of the consent form with the potential participant and the individual has had the opportunity to ask questions. I confirm that the individual has given consent freely.

________________ ________________ ________

Name of witness [printed] Signature Date

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

Study contact details for further information: [*Name, phone number, email address*]

Cyclist Mannequin - Siward Vloemans

7. Appendix 3: Interviews

3.1 Advanced Manufacturing

Interview with TU Delft's advanced manufacturing expert Sander Minnoye on Monday 28-02-2022.

The following steps explain the process of Advanced Manufacturing from 3D scanning to finishing. Additional information was added from the 'Personalized product design through digital fabrication' booklet.

"Agile manufacturing refers to the ability for a company to adapt quickly to the customer's demand, to the technology evolution and more generally, to react positively to the variation of the market." (CDAM). The Centre of Design for Advanced Manufacturing lab identifies four directions: Digitalization, Design Automation, Digital Fabrication and Human-Robot Coproduction. Digital Fabrication is the direction used to realize a product.

Digital Fabrication
In ultra-personalization enabled by Industry 4.0, products are always digitally fabricated. Digital fabrication fits well with 3D scanning and both are embedded in the computational design process. "Designers need to create flexible and knowledge-based designs that can be seamlessly integrated in the design to manufacturing workflow."

Additive Manufacturing
3D Printing
Possibly the most discussed digital fabrication method in recent years is 3D printing. It is unique because it functions by adding material rather than subtracting it. Fused Deposition Modelling 3D printers have become commercially available for home use. However, FDM printing is no production method. The process requires manual operation and frequently fails. Advanced industrial 3D printers exist with variations of the FDM technique. These are often useful for fine product details.

Example: Oceanz is an example company that takes 3D printing to an industrial level. They deliver 3D printed products that are certified for food, medical and industrial. 3D Files can be uploaded online with the desired finish and Oceanz delivers the product to the customer's doorstep.

Subtractive Manufacturing
CNC Milling
Milling on 5-axis CNC is a fast digital fabrication method that can be used on a variety of materials. Creating shapes out of a block of material, CNC milling relies on subtracting amounts of material. It is fast and accurate, but sometimes limited by the access to complex shapes. Results often do not need a finish.

Polyurethane is a foam commonly used for CNC milling. It has dense variants that feel like a solid rather than a foam. Its rigid characteristics make it a viable option for a personalized mannequin.

Example: Haas Automation is an example company that produces CNC Milling machines requiring no manual labour. The machines can validate their own accuracy and results. Besides vertical, horizontal and 5-axis capabilities, their machines can be fully integrated with automation options.

Sheet Manufacturing
Laser cutting is an example of sheet manufacturing, by far the most common digital fabrication method. Sheet manufacturing has been applied for years and has proven to be extremely effective. The method involves cutting a shape from a 2D material sheet, often processed into a 3D product. That particular characteristic is also its most limiting one, complex 3D shapes are hard to create.

Example: 247TailorSteel is an example company that has completely automized their sheet manufacturing process. The website takes production jobs and is able to calculates costs directly. Manufacturing including assembly and painting is completely automated.

Combining & Automizing
In advanced manufacturing, fabrication techniques are often combined. Each one has its own strengths and weaknesses, so every product feature has its own optimal method. By making design decisions and effective fabrication combinations, manufacturing may become almost automized. Despite that posing a challenge, it is a great goal to work towards as well.

Finish
Digitally fabricated products often require finishing. 3D Prints in particular may have a rough surface that requires finishing. Various techniques exist and testing product sections with different ones can be effective to reach the desired finish. Thick automotive paint is an example that can directly finish a rough surface and provide the right colour. Spray cans are often thinner and fail to do so.

Mannequins
"Wout van Aert's mannequin is finished so smoothly, it was probably fabricated using a different method altogether. Using a negative cast and a gel coat layer, glass or carbon fibre sheets can enforce a shape on the inside with an incredibly smooth finish on the outside. This process is used to create the hull of small boats, for example."

3.2 Digital Human Modelling

Online interview with TU Delft's digital human modelling assistant professor Toon Huysmans on Tuesday 22-02-2022.

The following steps explain the process of digital human modelling from 3D scanning to mannequin design. Additional information was added from the '1D to 4D Anthropometry' tutorial lecture (Huysmans, 2020).

Capture 3D Model (Artec Studio 12)
Scan the participants without helmet and shoes preferably, or post-process using software. Take 3-5 relevant body measurements per participant for reference. Ask each participant for cycling kit size to make a representative 3D model. No hole-filling in Artec Studio, only basic editing such as section pairing and noise removal.

Edit Wrap Template (Blender)
Select wrap template from Wrap3D database in A-pose. Approximate cycling pose by making manual adjustments in Blender. This is the reference to interpret the 3D scans with. The reference may contain a bias, so the template may later be replaced by the generic model.

Apply Wrap Template (R3DS Wrap3)
A wrap template reference is applied to raw 3D scans to make the models corresponding in R3DS Wrap3. The models are now automatically interpretated, filling any holes if necessary and recognizing landmarks such as facial features and body parts. This is also called 'retopology'.

Scientific Visualization (Paraview plug-in)
Requires a population of corresponding 3D models for scientific visualization. Import custom filter in the Tools menu of Paraview. Align & Compute Average / Shape function to generate a generic 3D model. After this step, the generic model may be used as reference template to make an iteration of model correspondence. This will remove reference bias caused by the edited wrap template.

Articulate Limbs (Mixamo)
Apply an articulating skeleton to the 3D model in Mixamo. Stock movement animations can be directly applied from the library.

Geometric Operations (Rhino & Grasshopper)
Visual programming language to apply geometric operations to a 3D model. The operations can be repeatedly applied to different models because of the automated structure.

4.1 Ideation

The starting point of this pressure cooker is a preliminary list of requirements resulting from the initial research phase. The pressure cooker runs through the creative process of the project in a short time of three days. This method has the following goals:

- Identify assumptions & knowledge gaps.
- Identify opportunities & bottlenecks.
- Evaluate project planning & methods.

Ideation
Goal: Generate as many ideas as possible.
Method: How-To's & Design Drawing.

Design challenges in this project are defined as: body segmentation, limb attachment, mounting points and digital fabrication. These challenges are used to create How-Tos. Three How-Tos are created to ideate about mounting points more in-depth.

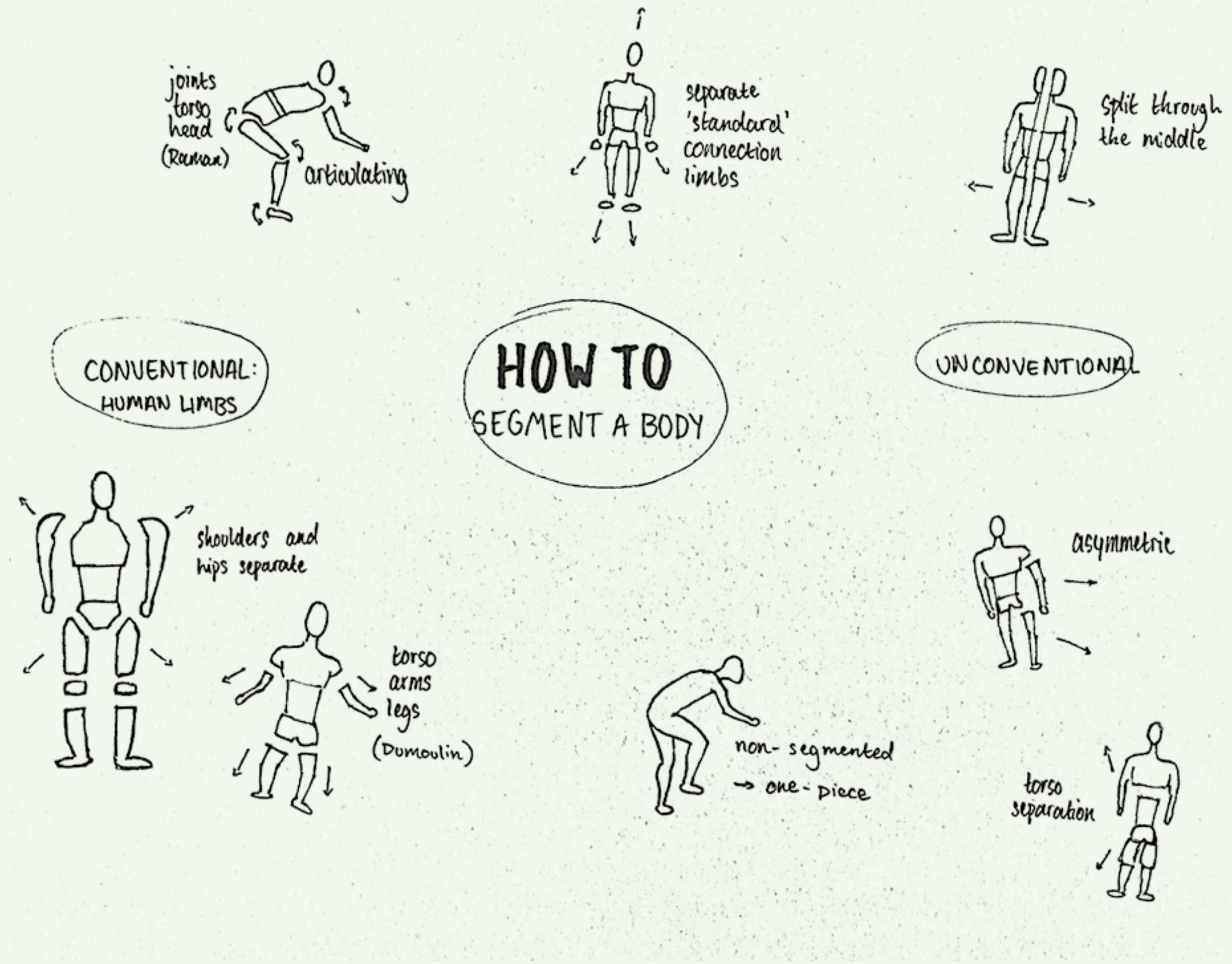


Figure 7.12: How-To segment a body

Figure 7.13: How-To attach limbs.

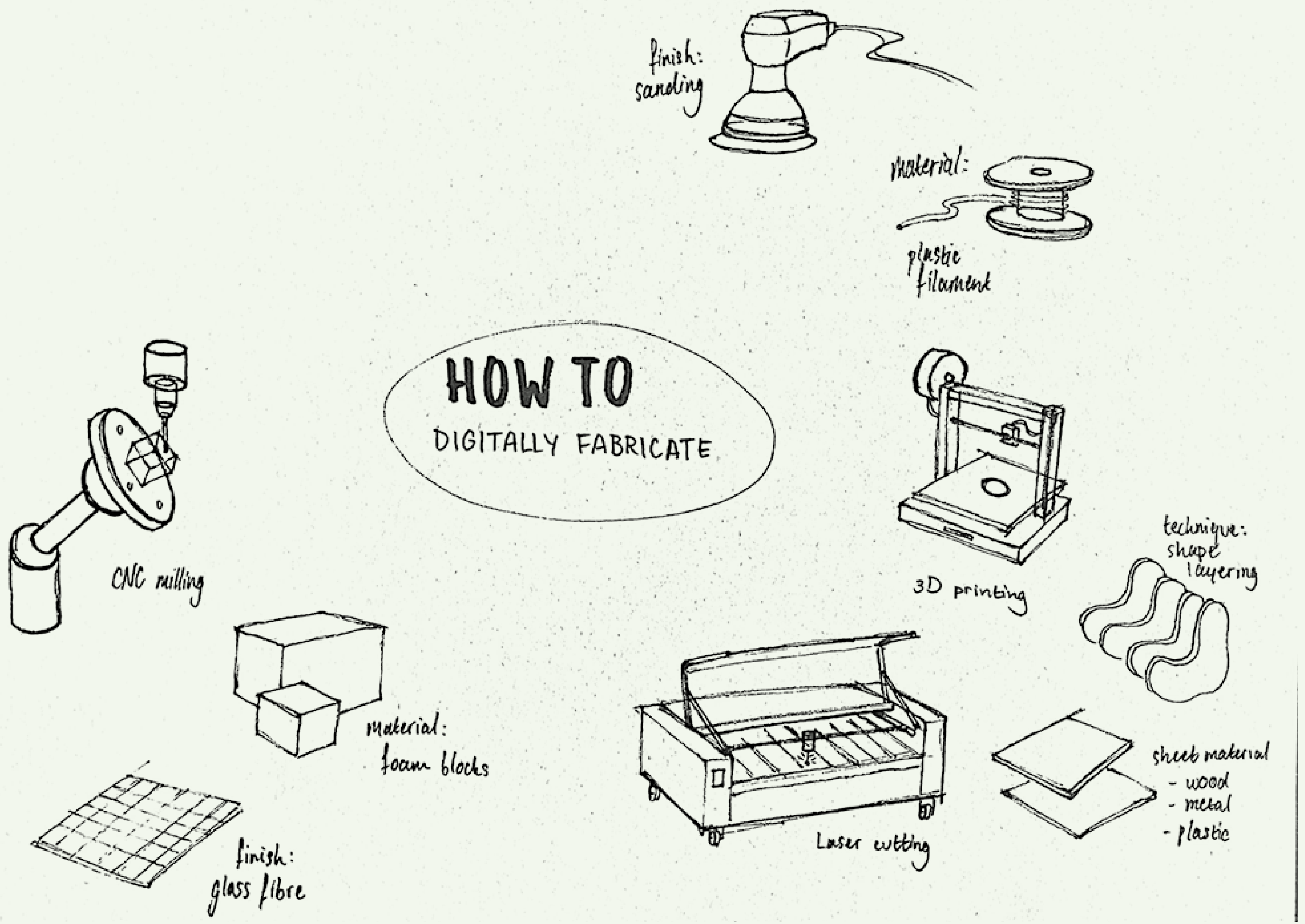


Figure 7.14: How-To digitally fabricate.

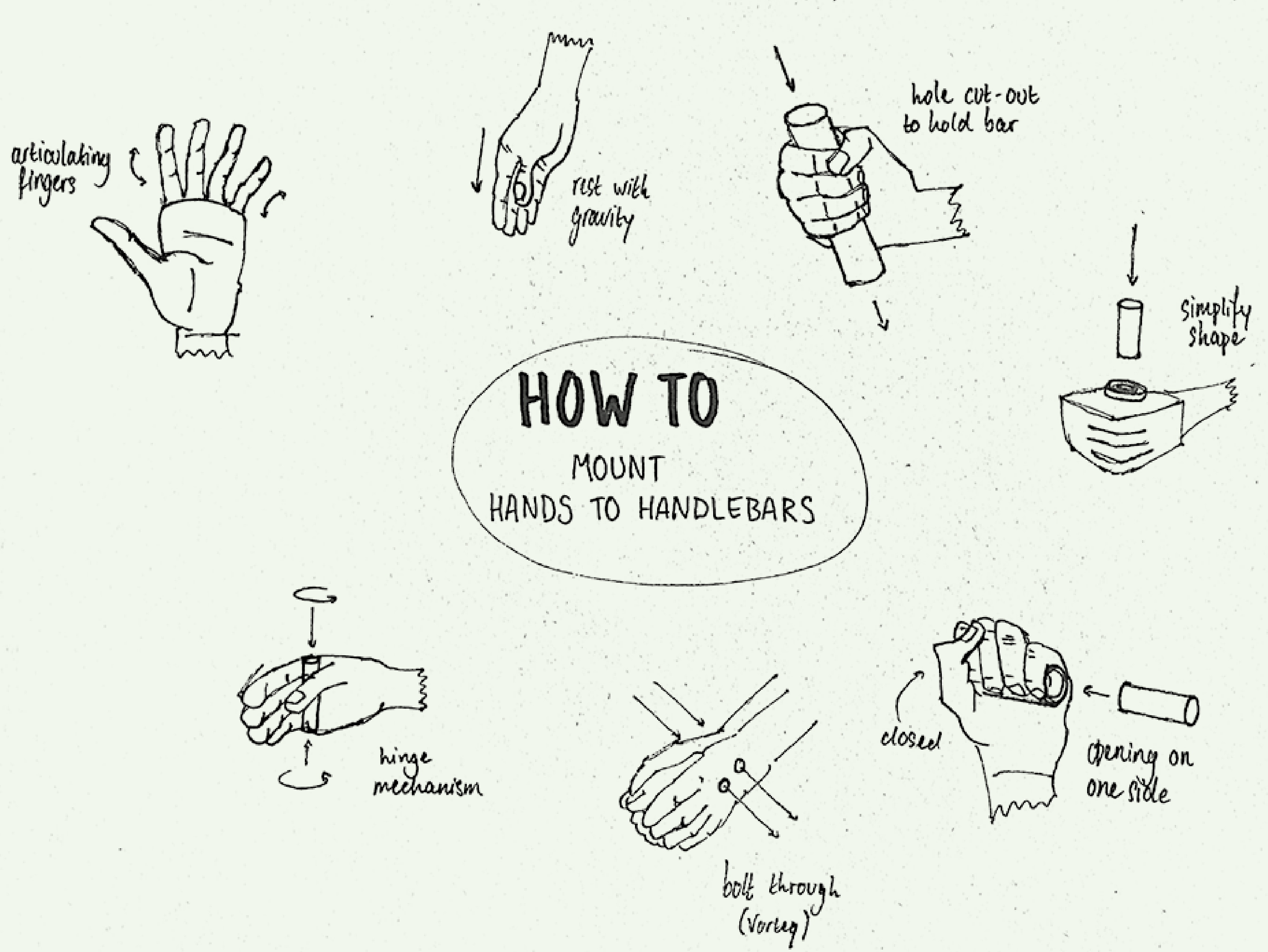


Figure 7.15: How-To mount hands to handlebar.

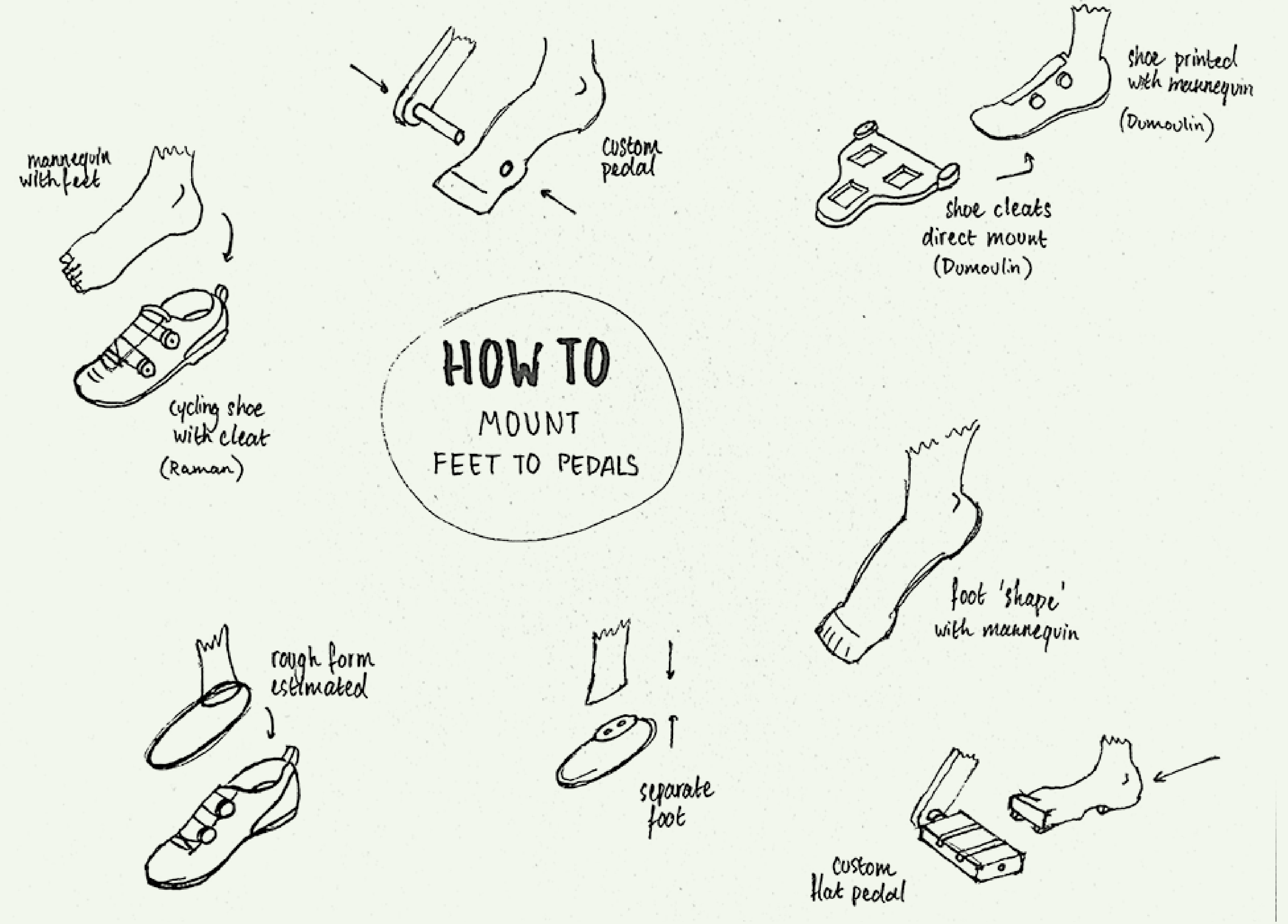


Figure 7.16: How-To mount feet to pedals.

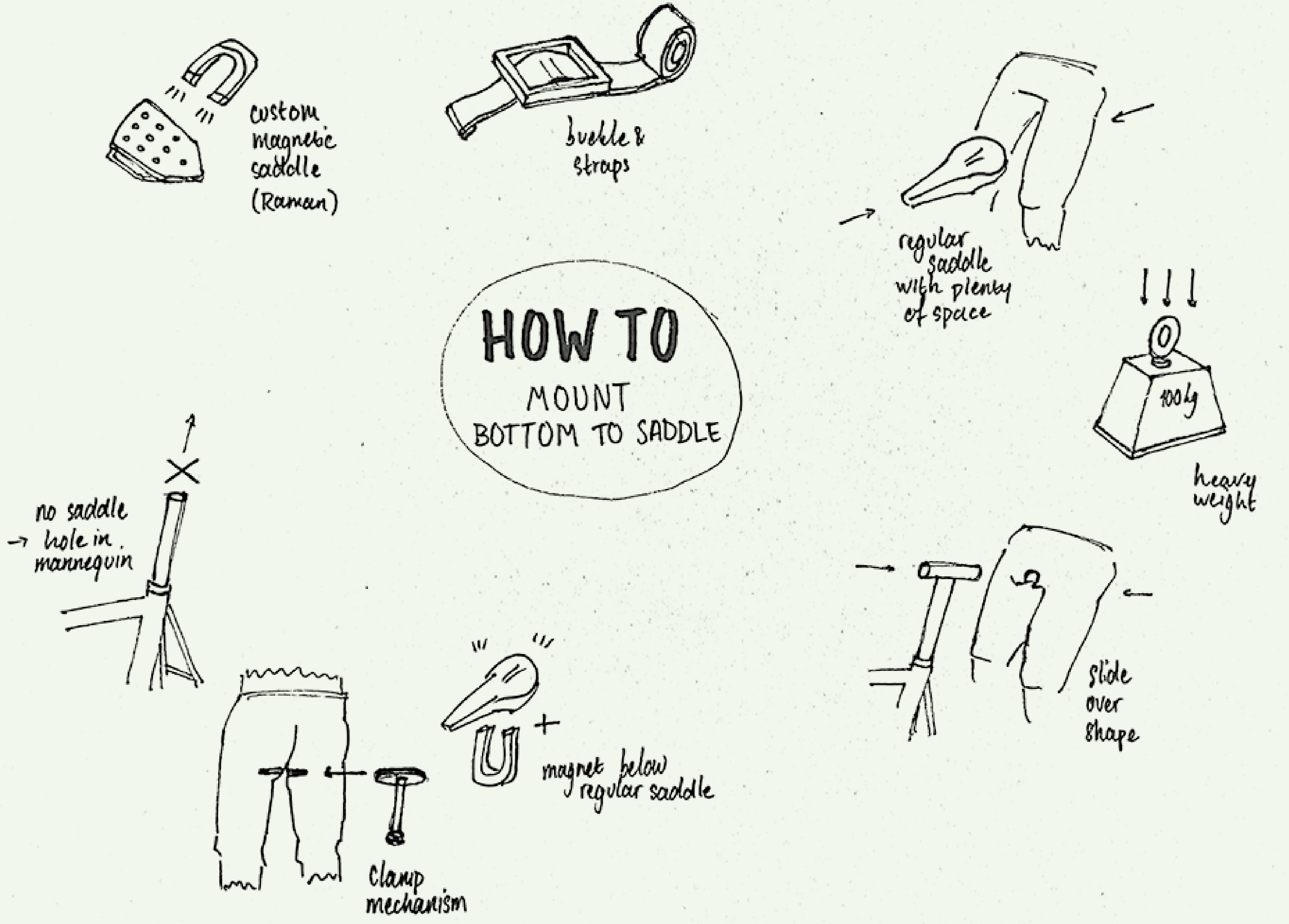


Figure 7.17: How-To mount bottom to saddle.

7. Appendix 4: Pressure Cooker

4.2 Conceptualization

Goal: Form detailed concepts based on ideas.
Method: Morphological Chart & Design Drawing.

After generating solutions for each design challenge using How-Tos, a Morphological Chart is used to structurally generate concepts. Each How-To forms a row in the chart and the ideas fill the columns. First, the Morphological Chart is used to identify where competitors sit in the solution space (Figure 7.18). Second, it is used to combine ideas in a new way (Figure 7.19). Four idea combinations are made, ranging from 'first thought' to 'weird' combos. The combinations are developed into complete concepts (Figure 7.20).

Before selection of a concept, the concepts are detailed further by force-fitting two pairs of concepts together (Figure 7.21 & Figure 7.22). This creates more refined products than direct results from the Morphological Chart. One of the concepts can be chosen using a selection method. However, a combination of the final two concepts is made instead (Figure 7.23).

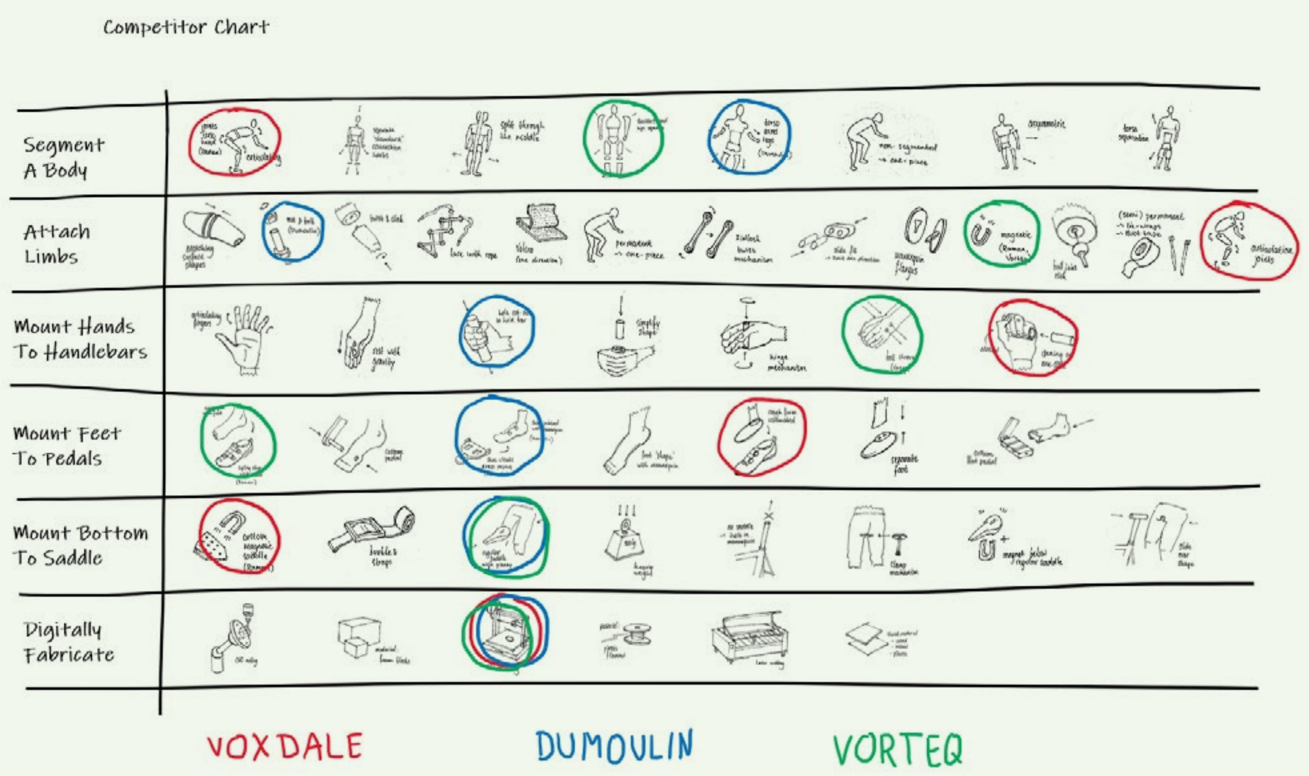


Figure 7.18: Morphological Chart of competitors.

Cyclist Mannequin - Siward Vloemans

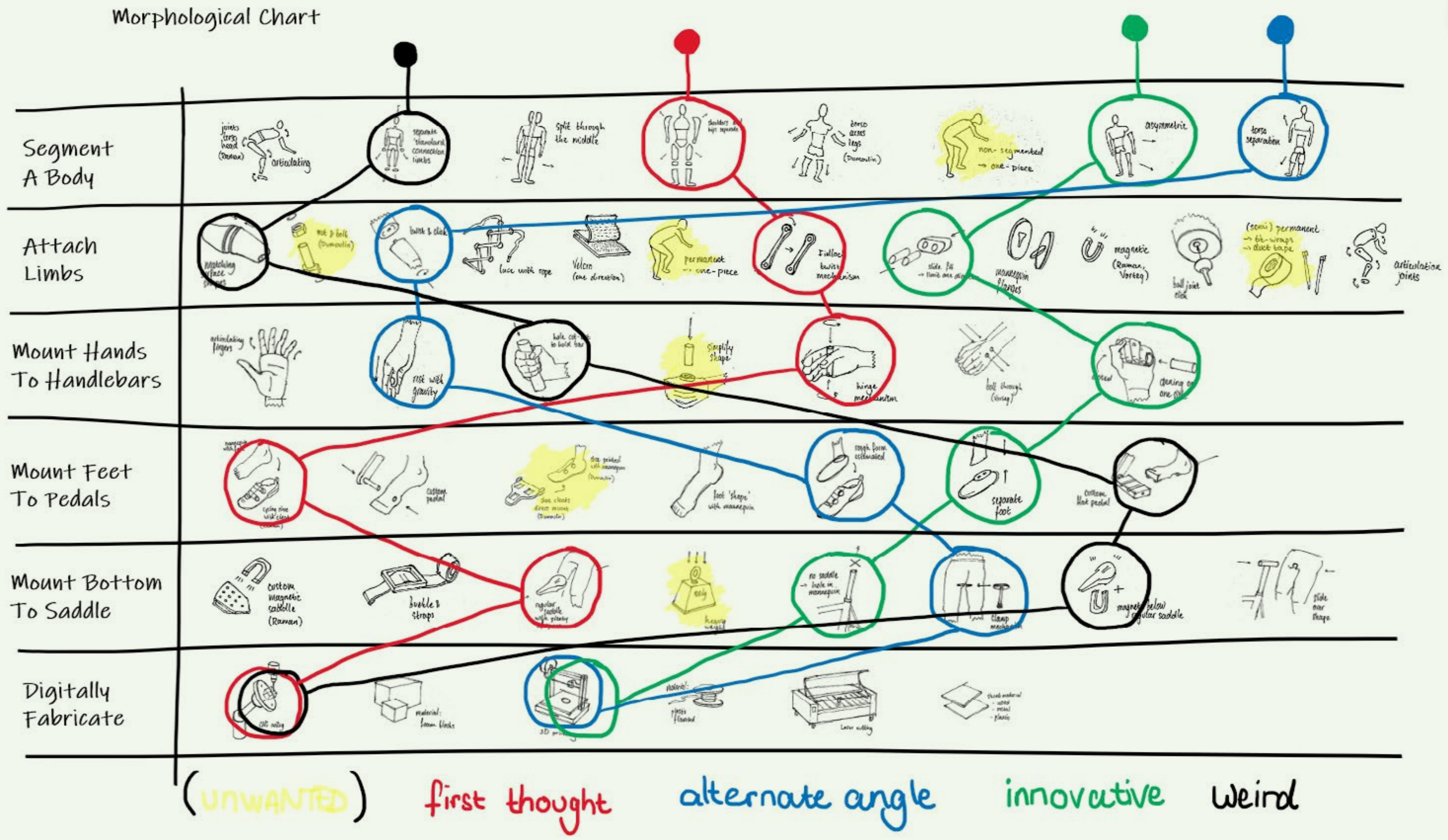


Figure 7.19: Morphological Chart of new idea combinations.

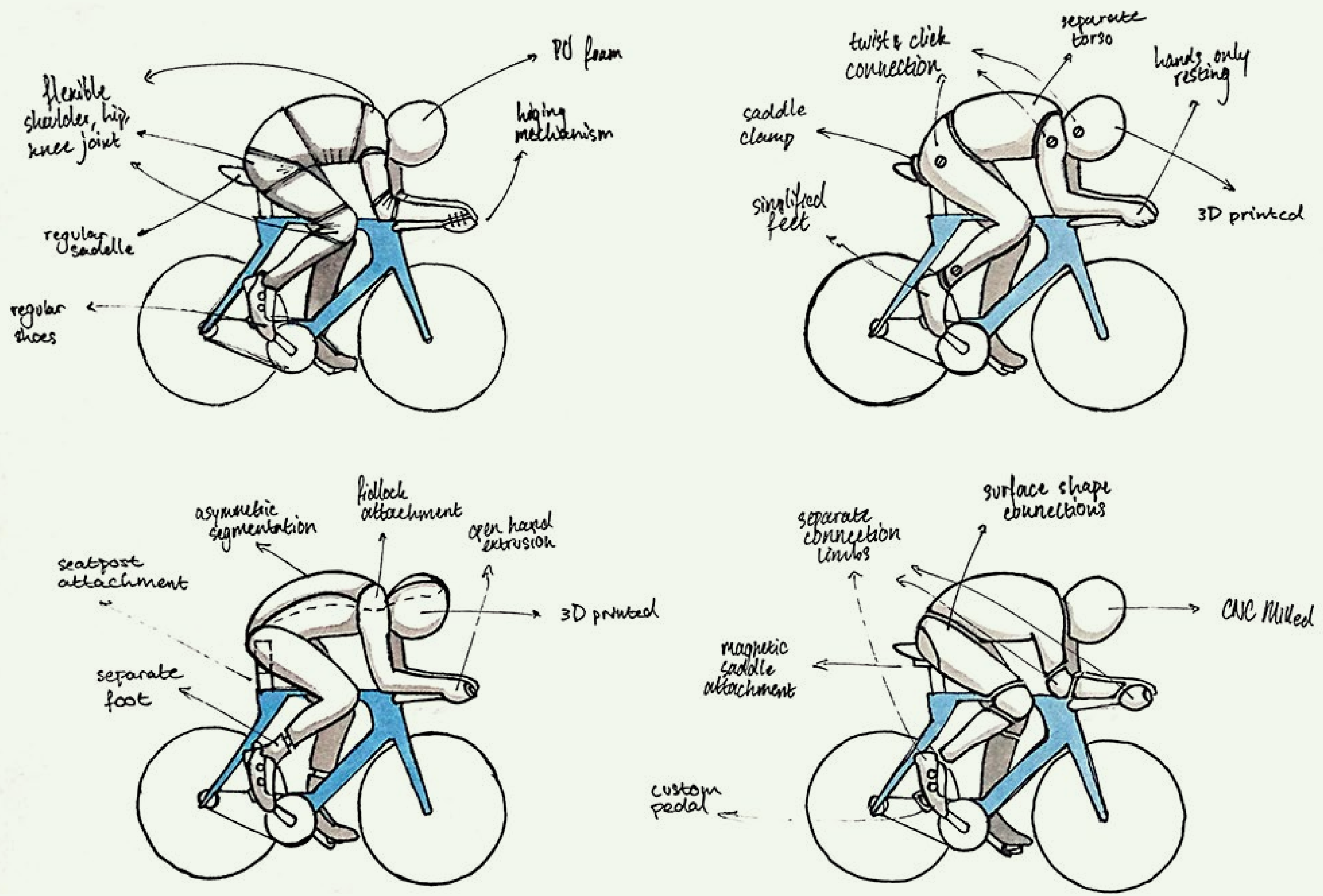


Figure 7.20: Four developed concepts.

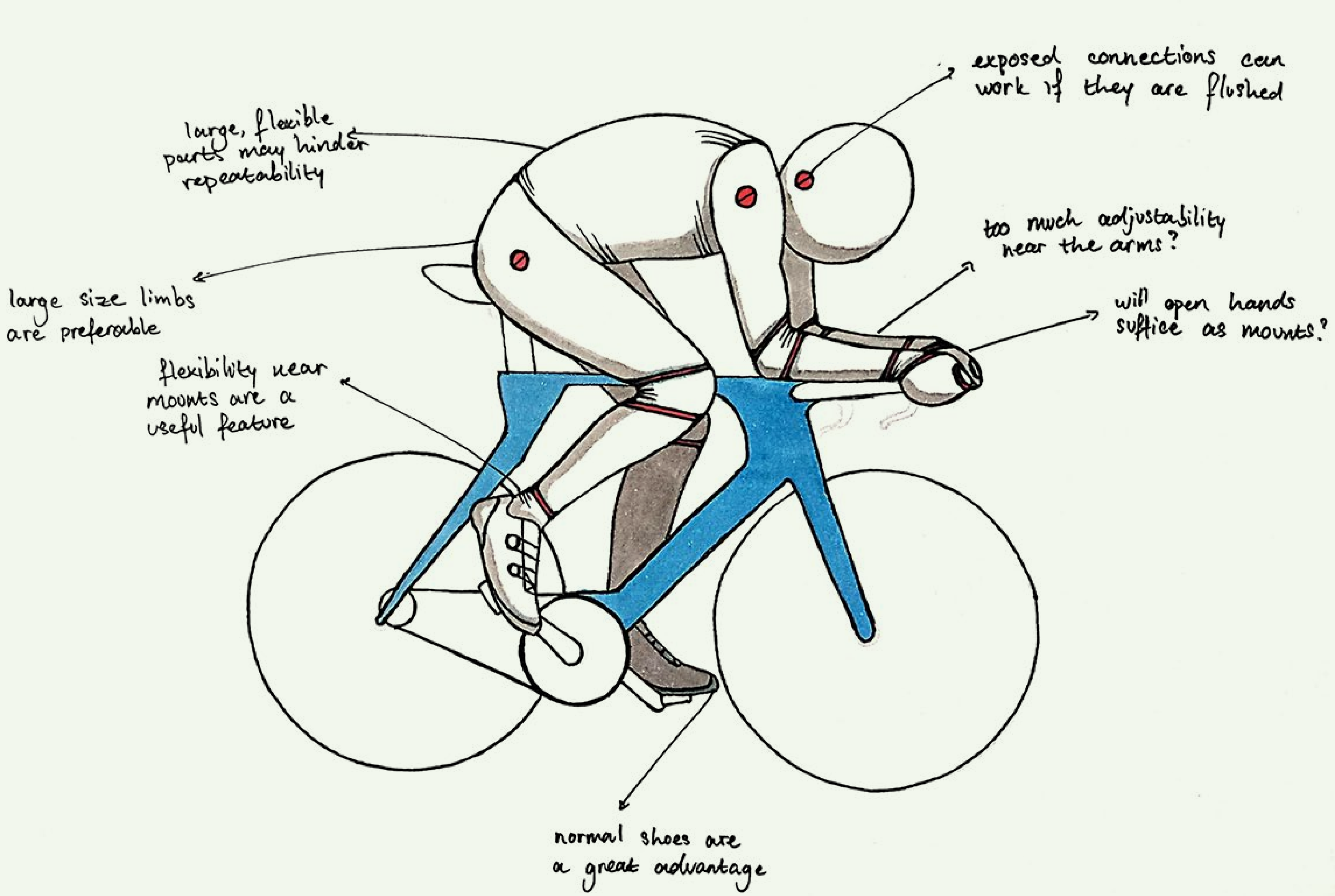


Figure 7.21: Force-fitted concept combination (1/2).

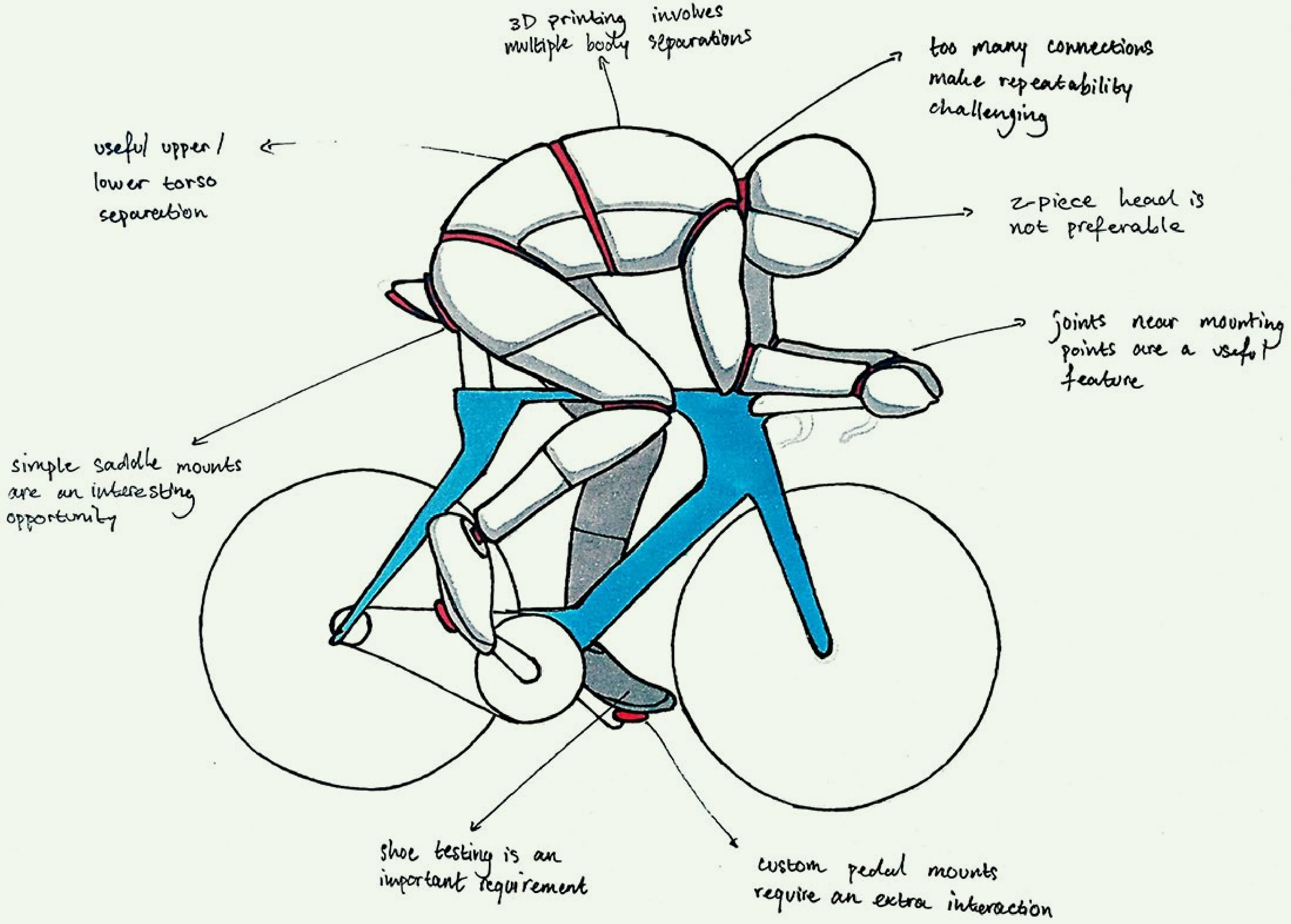


Figure 7.22: Force-fitted concept combination (2/2).

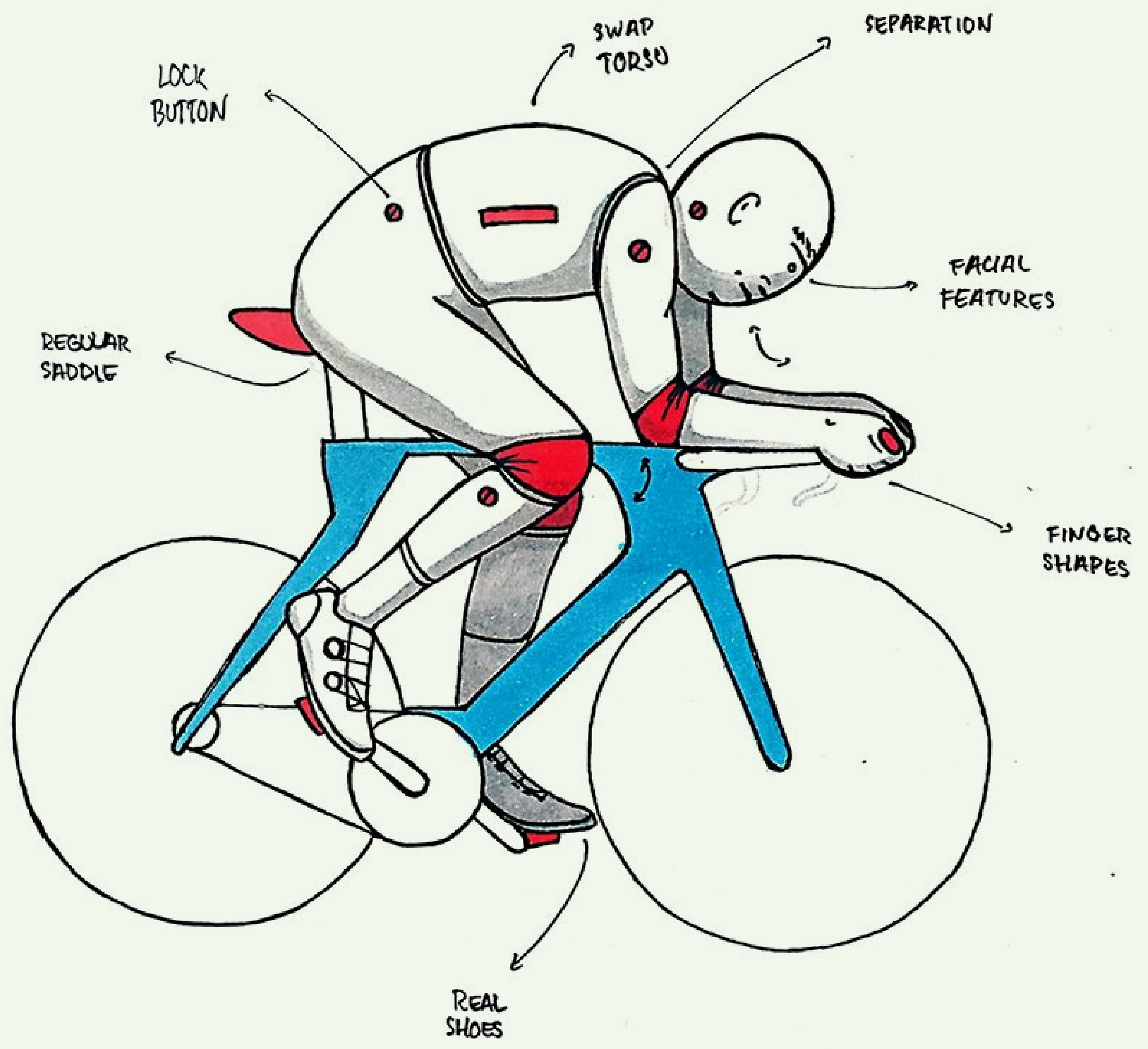


Figure 7.23: Final, combined product concept.

7. Appendix 4: Pressure Cooker

4.3 Development

Goal: Develop a chosen concept.
Method: Product Prototyping.

Introduction
Magnets as a method to attach limbs to the mannequin are frequently recurring in this pressure cooker. The goal of this test to learn more about the application of magnets in this context.

Research question
'How are magnets best applied as an attachment method?'

Method
Participants
No participants are involved in the research.

Apparatus
The prototypes used for this research are made at home using some simple tools (Figure 7.24).

- Wooden blocks (100 x 44 x 18 mm)
- Wooden rods (ø 8 x 20 mm)
- Neodymium ring magnets N50 (ø 10 x 3 mm)
- Steel screws (ø 2.5 x 12.5 mm)

- Drill & drill bits
- Screwdriver
- Sanding paper

Figure 7.24: Materials used to create the prototypes.

Stimuli
Seven magnet attachment interfaces are prototyped (Figure 7.25). Each interface consists of two corresponding blocks, resembling the limbs to be attached. Every interface has a different combination of magnets, pins & holes. All interface combinations of 1-3 different elements are prototyped.

Figure 7.25: Prototyped attachment interfaces numbered #1-7 from top-left to bottom-right.

Procedure
Each interface is attached & detached five times consecutively. The researcher rates the attachment on three criteria about freedom of movement: attachment force, rotation and sliding. A scale from 0-2 is used to indicate no performance at all to good performance.

Data analysis
As only limited data is collected in this research, no extensive analysis is conducted. Ratings of the different prototypes are directly compared and the results used to identify product feature characteristics.

Results
The performance ratings of the attachment interfaces can be found in Figure 7.26. It is clear that performance increases as more attachment points are included in the interface. Where interfaces #1 and #2 both only score points for one criteria, interfaces #3 and #4 score points for two criteria and interfaces #6 and #7 score points for all three. Interface #5 is an outlier, only scoring points for strength. Based on these results, interface #6 (Figure 7.27) is the best attachment method, scoring maximum points for each criterium except attachment force.

#	Force	Rotation	Sliding
1	0	0	2
2	1	0	0
3	1	1	0
4	0	2	2
5	2	0	0
6	1	2	2
7	2	1	2

Figure 7.26: Interfaces rated on attachment performance.

Figure 7.27: The best scoring interface #6.

Discussion

The performance ratings show a correlation with the amount of attachment points on the interface. One rod prevents sliding. Two rods also prevent rotation. One magnet provides force and two magnets provide twice as much, as explained below.

The ideal attachment interface limits movement on all axes. Magnets ensure the attachment position is not completely fixed: they will detach if enough force is applied. The amount of required force is equal to the strength of the magnets, adding up linearly. This is why interface #5 and #7 perform best with this criterium: they utilize two magnets to create double the force.

To apply magnets as an attachment method, movement along the other axes must be blocked. A rod only limits movement in a single direction as it can rotate in its slot. This is why interface #4 and #6 perform best with this criterium: they utilize two rods to block sliding and rotation.

Limitations

This research is limited by some inaccuracies in prototyping. All wooden objects are hand sawn, sanded and drilled. The magnets installed are not in direct contact, limiting their effectivity. Furthermore, only round pin connections are used. Follow-up research could include different shapes as well.

Conclusion

To conclude this research, the research question is repeated:

'How are magnets best applied as an attachment method?'

The answer to the research question is that magnets are best applied as an attachment method to non-permanently fix a position along one axis. Limiting freedom of movement along two axes by using shape-fit, magnets can be applied to set a force threshold for detachment.

5. List of Requirements

	Process		Sub-process		Sub-process		Requirement / Desire	Remarks
1	**Originate**	1.1	Select	1.1.1	Select human subject	1.1.1.1	The subject is informed about data collection & analysis.	
				1.1.2	Select bicycle	1.1.2.1	The subject's personal bicycle geometry is used.	
		1.2	Capture	1.2.1	3D scan human subject in A-pose	1.2.1.1	The subject positions feet below shoulders & arms separated.	
				1.2.2	3D scan human subject in road bicycle pose	1.2.2.1	The subject holds the handlebar deep in the drops.	
				1.2.3	3D scan human subject in time trial bicycle pose	1.2.3.1	The subject holds the handlebar ends with separate hands.	
		1.3	Process	1.3.1	Align model scans sections	1.3.1.1	The model scan sections overlap.	
				1.3.2	Correspond model with mesh template	-	-	
				1.3.3	Replace inaccurate model body parts	-	-	
		1.4	Automate design	1.4.1	Segment model	1.4.1.1	The mannequin's body segments are parametrically defined.	
				1.4.2	Apply model design features	1.4.2.1	The mannequin's design features are parametrically defined.	
		1.5	Source	1.5.1	Source raw materials	1.5.1.1	The mannequin's raw materials are commonly available.	
				1.5.2	Source stock components	1.5.2.1	The mannequin's stock components are commonly available.	
		1.6	Fabricate digitally	1.6.1	Digitally fabricate custom components	1.6.1.1	The mannequin's custom components are quickly fabricated.	
				1.6.2	Finish custom components	-	-	
		1.7	Produce	1.7.1	Assemble components	1.7.1.1	The mannequin's production method is commonly available.	
						1.7.1.2	The mannequin's production method is automated.	
						1.7.1.3	The mannequin's production method is accessible worldwide.	
						1.7.1.4	The mannequin is cost efficient.	
				1.7.2	Package	-	-	
2	**Distribute**	2.1	Contract	2.1.1	Data security	2.1.1.1	The subject's 3D scan data is privately stored.	
						2.1.1.2	The subject's 3D scan data is anonymously stored.	
		2.2	Deliver	2.2.1	Collect from supplier	2.2.1.1	The mannequin is fabricated nationally.	
				2.2.2	Deliver to customer	2.2.2.1	The mannequin is delivered by national postal service.	

3	**Use**	3.1	Store	3.1.1	Place in warehouse rack	3.1.1.1	The mannequin is scratch resistant.	
				3.1.2	Store in warehouse rack	3.1.2.1	The mannequin is temperature resistant from -10 °C to 40 °C.	
		3.2	Transport	3.2.1	Carry to car	3.2.1.1	The mannequin is lighter than 16 kg.	Maximum lifted weight for a woman.
						3.2.1.2	The mannequin consists of few separate parts.	
				3.2.2	Transport by car	3.2.2.1	The mannequin disassembles space-efficiently.	
				3.2.3	Carry to wind tunnel	3.2.3.1	The mannequin is light.	
		3.3	Assemble	3.3.1	Assemble in road position	3.3.1.1	The mannequin can be assembled by a single adult.	
				3.3.2	Assemble in time trial position	3.3.2.1	**The mannequin can change torso & arm position.**	Main differences in bicycle position.
				3.3.3	Re-assemble in between tests	3.3.3.1	The mannequin's limbs are quickly (dis)assembled.	
		3.4	Dress	3.4.1	Dress in cycling suit	3.4.1.1	**The mannequin has detachable arms & legs.**	Cycling suits are tight, one-piece.
				3.4.2	Dress in cycling socks	3.4.2.1	The mannequin has bare feet & lower legs.	Cycling socks reach halfway the lower leg.
				3.4.3	Dress in cycling shoes	3.4.3.1	The mannequin has smoothened feet.	Cycling shoes have stiff soles.
				3.4.4	Dress in cycling helmet	3.4.4.1	The mannequin has a bald head.	Cycling aero helmets cover the neck.
				3.4.5	Dress in cycling glasses	3.4.5.1	The mannequin has facial features.	Cycling glasses rest on nose and ears.
				3.4.6	Change outfit in between tests	3.4.6.1	The mannequin has a smooth surface.	To slide clothes over.
		3.5	Mount	3.5.1	Mount to road handlebar	3.5.1.1	The mannequin holds parallel ⌀ 35 mm Road bars with its hands.	Standard ⌀ 31.8 mm plus handlebar tape.
				3.5.2	Mount to time trial handlebar	3.5.2.1	The mannequin holds parallel ⌀ 25 mm TT bars with separate hands.	Standard ⌀ 22.2 mm without tape.
				3.5.3	Mount to bicycle saddle	3.5.3.1	The mannequin has a 165 mm open area between the legs.	Standard saddle width 165 mm maximum.
				3.5.4	Mount to bicycle pedals	3.5.4.1	The mannequin twists its legs.	Cycling shoe cleat-pedal system.
				3.5.5	Re-mount in between tests	3.5.5.1	The mannequin is quickly (un)mounted.	
				3.5.6	Mount to different bicycle geometry	3.5.6.1	**The mannequin has limited joint flexibility.**	
						3.5.6.2	The mannequin's pose is accurately adjustable.	
		3.6	Test	3.6.1	Test in wind tunnel	3.6.1.1	**The mannequin's shape represents its subject.**	
						3.6.1.2	The mannequin's shape is accurately realistic.	
						3.6.1.3	The mannequin's seams are unobtrusive.	
						3.6.1.4	**The mannequin is rigid on the bicycle.**	Common wind testing speed 50 km/h.
						3.6.1.5	The mannequin is rigid on the bicycle while wobbling sideways.	Caused by wind speeds.
						3.6.1.6	The mannequin's pose is accurately repeatable.	
				3.6.2	Test with Particle Image Velocimetry	3.6.2.1	The mannequin has a matte, black colour finish.	Absorbs laser light rays.
						3.6.2.2	The mannequin is water resistant up to IPX4.	Resistant to water splashes.
		3.7	Use unintended	3.7.1	Drop on the floor	3.7.1.1	The mannequin is impact resistant up to 1.5 m.	Height on bike & when carrying.
		3.8	Repair	3.8.1	Replace limbs	3.8.1.1	The mannequin's custom components are individually manufactured.	
				3.8.2	Replace stock components	3.8.2.1	The mannequin's stock components are individually sourced.	
4	**Discard**	4.1	Disassemble	4.1.1	...	4.1.1.1	The mannequin's stock and custom components are separatable.	
		4.2	Reuse intact parts		...	4.2.1.1	The mannequin is durable.	
		4.3	Recycle materials		...	4.3.1.1	The mannequin's custom components are recyclable.	
		4.4	Discard broken parts		...	4.4.1.1	The mannequin has low environmental impact.	

Figure 7.28: Complete Product Life Cycle and List of Requirements.

7. Appendix

6. Personal Reflection

At the end of this project, I look back at the original learning goals from the Project Brief. The leaning goals are:

- Experience the cycling industry.
- Learn about Digital Human Modelling & Advanced Manufacturing.
- Manage a design process.

The learning goals are reflected upon with the Kolb Learning Cycle. The method divides the learning cycle into four stages: Concrete Experience, Reflective Observation, Abstract Conceptualization & Active Experimentation (McLeod, 2013). All four stages are discussed for each learning goal.

Experience the cycling industry.

Concrete Experience

At multiple moments in this project I felt challenged by the competitive nature of the cycling industry. My case owners had a great attention to detail and challenged me in the same way. I tried to bring this project to a higher level by involving third parties in the development of the mannequin. However, budget was a limitation in instances and often limited the possibilities. As a result, the full-scale mannequin is completely manufactured by myself and that affected the quality of the prototype and advancement of the research.

Reflective Observation

I experienced the cycling industry as competitive, result-focussed but limited by a budget. Science plays an important role in professional cycling as differences are marginal. There is great attention to detail and a strive to perfection. However, I felt the financial means often did not align with the ambitious goals. In these scenarios I sometimes attempted to find an impossible solution, but in the end the case owners make the decision by granting the budget or not.

Abstract Conceptualization

Professional sports generate revenue by sponsorships and competition prizes. The result is all expenses must be substantiated and they are generally kept to a minimum. In this scenario it would be better to study if expectations at the start of the project are realistic or not. In my project, this became apparent about halfway the project and it proved challenging for me to act accordingly and manage expectations with my case owners correctly.

Active Experimentation

In future projects, I aim to gain an understanding of expectations early in the project and to reflect if those are realistic. I personally must realize if the goals are realistic and I must communicate those thoughts with all relevant stakeholders. If the expectations are not realistic, I must act on time instead of postponing the moment until late in the project.

Learn about Digital Human Modelling (DHM) & Advanced Manufacturing (AM).

Concrete Experience

I experienced DHM and AM as interesting, exciting and challenging. At the start of the project I was unfamiliar with these fields. Nonetheless, they sparked my interest and the countless opportunities made it lots of fun to work in these fields. I received lots of help from my supervisors and others in the faculty. However, near the end of the project my inexperience became apparent as the full-scale mannequin proved challenging to manufacture and had flaws that could have been avoided.

Reflective Observation

Looking back, I learned a great deal about DHM and AM. I had never used a handheld 3D scanner before and this project instantly involved challenging 3D scan subjects. The project also introduced me to possibly ten types of software I had never used before. The same went for all digital fabrication involved. That makes it explainable why I made errors during the project and I believe they are a rightful part of my learning process.

Abstract Conceptualization

Although I believe my learning process regarding DHM and AM has its rightful place in this project, they did not have to influence my full-scale prototype as much. A lot of activities involves in that process were new to me, but I could have used the opportunity to perform some of them earlier on in the project. That would be a lesson I take into future projects, as they will always involve new challenges and lessons for me.

Active Experimentation

In the future, I hope to keep learning about new fields in design to me, such as DHM and AM in this project. It is exciting to set such challenges and to learn as much However, I aim to experiment more with individual aspects of such fields throughout the project. Errors and lessons are always involved, but by facing those earlier in a process, I can apply those lessons to improve my end result.

Manage a design process.

Concrete Experience

Managing such a large design project individually was an exciting challenge to me. I like to concern about structure and planning, but I am eager to learn about how to apply it effectively. I used a flip-chart day-to-day planning with post-its holding points of action, meetings and milestones. I took a moment at the start of each day to prepare my activities. I took a moment at the end of each day to reflect on my activities and to adjust my planning accordingly. It worked effectively to give me a feeling of control and to motivate me in my activities.

Reflective Observation

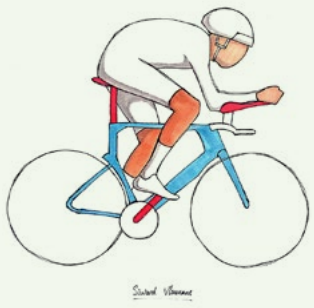
Looking back, I am impressed I managed my structure all the way though to the end, not only in my planning but in my structure overall. I received many compliments throughout my project and it is something I am proud of. It gave structure to hold onto when feeling lost, but in some way it may have limited me when it would have been better to adjust the structure or planning. It sometimes felt as a given, but in reality it can be adjusted at any moment.

Abstract Conceptualization

In the future I wish to use my project management skills more and to develop them further. I hope to challenge myself by conceiving set structures more as fluent, able to change when a project needs it. I aim to use physical methods such as flip-charts and post-its more, because it is a distractions from screens and an effective communication method.

Active Experimentation

In future projects, I aim to develop my project management not only in individual projects, but in the context of a group too. During my thesis, I could make all decisions myself and mostly had to communicate them with my stakeholders. In group projects, all decisions are made together and that involves new challenges. I hope to learn about those experiences and see if my methods lend itself to become a project lead someday.



"It never gets easier,
you just go faster"

Greg LeMond

TUDelft KEEP CHALLENGING FIELDLAB UPPS