DESIGNING A SHAPE SHIFTING OBJECT

Master thesis Tijmen Veldhoen
September 2019

ThermoTILT

Graduation report by Tijmen Veldhoen
September 2019 | Faculty of Industrial Design Engineering at Delft University of Technology

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Designing a Shape Shifting Object

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In front of you is the graduation assignment: Designing a Shape Shifting Object, by Tijmen Veldhoen. This booklet will take you on a journey into the world of shape memory alloys, by showing the explorative route I have taken. Although the road was not yet paved and sometimes very bumpy, I managed to reach my final goal. I am proud to present ThermoTilt, a responsive insulation layer which uses shape memory alloy's unique properties to achieve its shape shifting abilities.

I wish you a pleasant and inspiring read.

EXECUTIVE SUMMARY

The assignment description given by Professor Kaspar Jansen and assistant professor Sepideh Ghodrat of the TU Delft, consisted of two parts: designing a hinge like structure using Shape Memory Alloys (SMA) and incorporating this SMA powered structure in a larger shape shifting object. After establishing that the material served as the starting point for this design process, it was decided that this project would be dedicated to the development of a prototype which showcased the SMAs and its unique shape retaining characteristics in a meaningful and inspiring way. The foundations of this project were formulated in the subsequent Analysis phase. Therein, the boundaries within which the concept had to be developed was defined. Through extensive research and experimentation, the limitations of the materials and their technical abilities were established. This led to the more specific design vision of:

‘Integrating shape memory alloys and textiles to create a thermally self-regulating garment that increases in thickness when exposed to cold temperatures and decreases in thickness when exposed to warm temperatures.’

This was further delineated in the Conceptualization phase, by specifying the intended target group, namely hikers. Subsequently, the conditions and environment in which the product needs to be able to operate and the user requirements it has to satisfy were defined. Continued experimentation and tinkering with the different materials and bonding methods, led to a better understanding of the material and the possibilities it offered. This knowledge of the material resulted in the development of various mechanisms which are eventually incorporated in viable sub-solutions. By combining the different sub-solutions, two viable concepts arose.

After comparing the two concepts, the high neck-loop concept was determined to be most suited to the predefined design vision and was further developed in the Embodiment phase. During the prototyping of this concept, many issues were discovered. This led to a design iteration of the chosen concept, which solved these critical points and culminated in a redesign. With this redesign two user tests were conducted, in order to gain a better insight from the user’s perspective and determine possible shortcomings of the products. These flaws in the prototype were either implemented in the design or incorporated in the recommendations. This project led to a working prototype of the final design, which successfully incorporated SMAs to facilitate a shape shifting garment.

ASSIGNMENT DESCRIPTION

A personal interpretation

Designing a Shape Shifting Object is a graduation assignment formulated by Professor Kaspar Jansen and assistant-professor Sepideh Ghodrat of the Emerging Materials Group of the Industrial Design Engineering faculty, TU Delft. The project will be about designing an object that can change its shape by the use of shape memory alloys (SMAs). Shape memory alloys have the ability to return to their set-shape when exposed to external stimuli, such as an increase in temperature. The main goal of the project is to design a product that changes shape using smart memory alloys in a Meaningful and Inspiring way.

In the first stage of this project I will design a hinge-like structure that is able to bend, using just the force generated by shape memory alloys. Later on, I will design a product that makes use of the designed hinges enabling it to change its shape in a controlled manner, keeping in mind the main objective of translating the material into a product in a meaningful and inspiring way.

Shape memory alloys were discovered a long time ago (1932), however they are not as well-known and accepted among designers, due to a lack of knowledge and tangible examples. Some engineers, on the other hand, know about their existence, but they look at the world with a different mindset and have in my opinion never explored their full potential.

Therefore, the opportunity arises to take a fresh new look into the world of shape memory alloys by creating a product that demonstrates its possibilities from a designer's perspective. For instance, shape memory alloys equally have the potential to provide a meaningful contribution to products where qualities such as lightness, flexibility and simplicity behind the mechanism add a unique value that other materials might be lacking.

However, these qualities have only been applied in very specific fields of design, such as the medical and aerospace industry. Additionally, the general application of SMAs is limited since little is known among designers on the benefits of applying shape memory alloys to create dynamic products. One of the most commonly known examples of its use are stents, which are inserted in the human body when contracted and later expand because of body temperature, to keep a vain open.

I will explore the advantages and disadvantages of using shape memory alloys when designing products in other unexplored fields such as: Seamlessly fitting wearables, Fire safety isolation, Space saving foldouts, Soft (rescue) robotics or Drone accessories.

By doing an extensive research on the material itself and by understanding in what environment it can work smoothly, it will become clearer which of its attributes can benefit a future product. To pinpoint the most appropriate field of application, not only the functionalities of the material

Meaningful

1 Shape memory alloys will be applied in a product in which all the material qualities (for example: low weight, super elastic) will benefit the product in a positive way.

2 Design around the material limitations, such as: low actuation frequency, low controllability, low accuracy and low energy efficiency.

3 The product needs to be designed for a context in which all these advantages have a positive effect on the use of the product. Think of a product you travel with that needs to be light and reactive.

4 The material will not only be analysed for what it is, but also for what it does, what it expresses to us, what it elicits from us and what it makes us do (Material Driven Design)

Inspiring

5 The product needs to provoke a sense of wonder and amazement, so that in the future the material will become more commonly known and used among designers.

need to be researched, but also the true value of what the material elicits in people. This part is often overlooked in the design process when the material is used as a starting point for a design.

The MDD (Material Driven Design) Method will be used during this process. Material driven design is a method which helps designers develop concept ideas when a certain material is the starting point of a design process, facilitating designing for new material experiences. When a new material is discovered it is often only characterized by its functionality, answering the question; ‘what is it?’. However, for designers the more important question that needs to be answered is; ‘what does it do?’. The answer to this question provides a deeper understanding of a material’s properties, potential applications and performance and how these can affect future users and give rise to unique user experiences.

DESIGN METHODS
Approach

This project has a very 'open' beginning the only two given criteria that need to be part of the design are that shape memory alloys need to be incorporated (1) to create an object that can change its shape (2). On one hand this is very exciting because it offers loads of design freedom, but at the same time it is exactly what makes the assignment a bit scary. With only 20 weeks to come up with a design that both meaningful and inspiring, without a very clear starting point will be a big challenge. The potential risk is that the eventual application of the SMAs in a product might be cliché or feel like a gimmick.

To tackle this graduation project three different models are used:

CPS
Creative Problem Solving helps unleashing creativity by freeing the mind of limitations. Leading to innovative and out-of-the-box ideas.

MDD
Material Driven Design is a method that focuses on completely understanding a material, not only on the functional level but also on a material experience level. This method is perfect for a project which has a specific material as a starting point of the design

Basic design cycle (BDC)
The purpose of the basic design cycle is that it describes the natural stages a designer goes through while solving a problem. This cycle constantly repeats itself when trying out new things and to discover or eliminate certain factors.

Analysis CPS MDD BDC

Conceptualization CPS BDC

Embodiment BDC

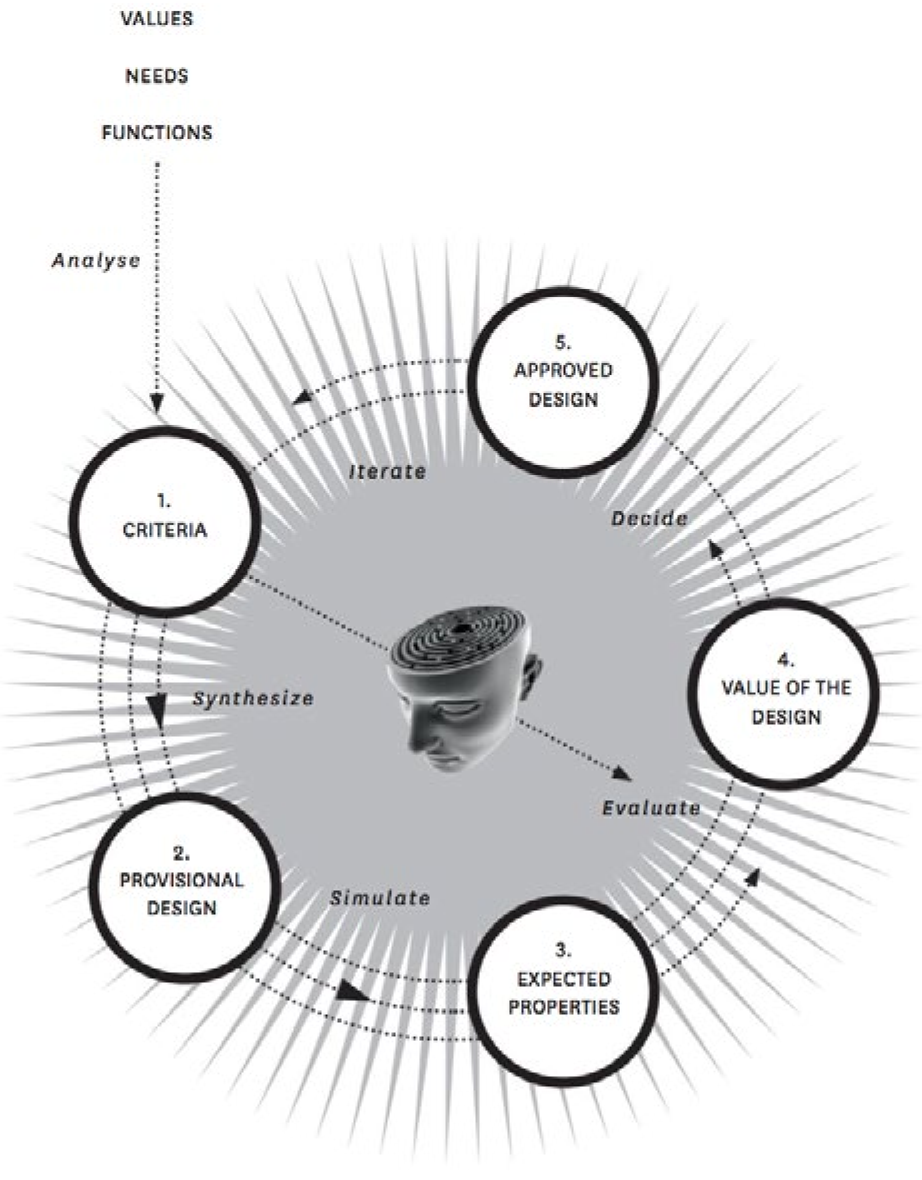


Figure 1 Basic design cycle (van Boeijen, Daalhuizen, Zijlstra, & van der Schoor, 2013)

PROCESS ROADMAP

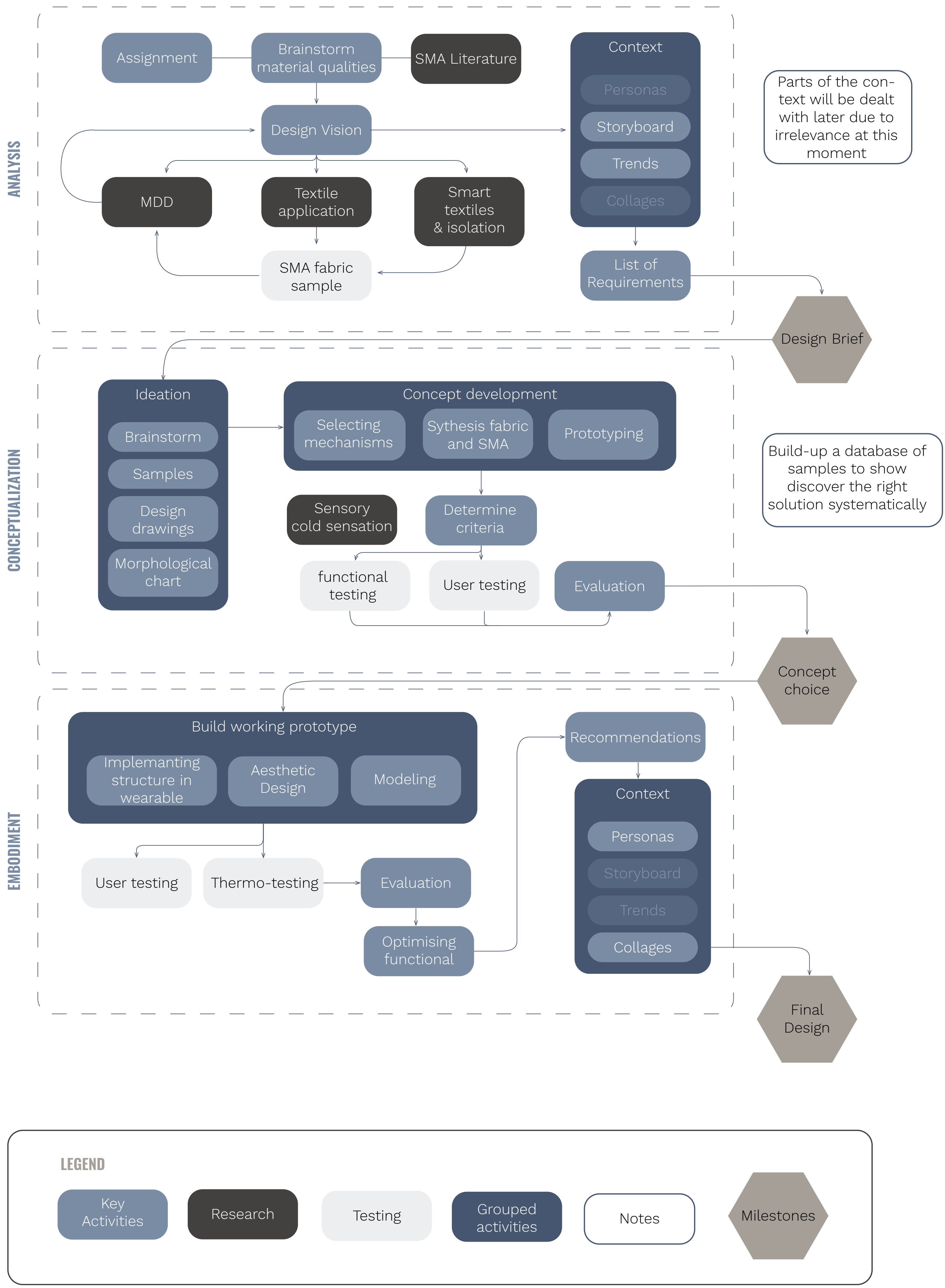
The road to graduation

This graduation project will be divided in three main phases: analysis, conceptualization and embodiment.

During the analysis phase the material will be explored to formulate a design vision. Exploring the material will include a lot of experimentation to get to know the ins and outs of shape memory alloys. The milestone or final result of this phase will be a design brief that contains a clear idea of the design direction.

The conceptualization phase will involve a lot of creative thinking and problem solving that will culminate in a systematic approach, to prevent details from being overlooked. This phase will lead to a concept choice that will be exploited for further development during the embodiment phase.

The final goal of the project, which will be presented in the embodiment phase, is to build a working prototype that can demonstrate the product's functionalities and can be utilized for user- and thermal- tests. Additionally, the prototype should inspire and amaze other designers about the undiscovered potential of shape memory alloys.


ANALYSIS
Assignment
Brainstorm material qualities
SMA Literature
Context
Personas
Storyboard
Trends
Collages
Design Vision
MDD
Textile application
Smart textiles & isolation
SMA fabric sample
List of Requirements
Parts of the con- text will be dealt with later due to irrelevance at this moment
Design Brief
CONCEPTUALIZATION
Ideation
Brainstorm
Samples
Design drawings
Morphological chart
Concept development
Selecting mechanisms
Sythesis fabric and SMA
Prototyping
Build-up a database of samples to show discover the right solution systematically
Sensory cold sensation
Determine criteria
functional testing
User testing
Evaluation
Concept choice
EMBODIMENT
Build working prototype
Implemanting structure in wearable
Aesthetic Design
Modeling
Recommendations
Context
Personas
Storyboard
Trends
Collages
User testing
Thermo-testing
Evaluation
Optimising functional
Final Design
LEGEND
Key Activities
Research
Testing
Grouped activities
Notes
Milestones

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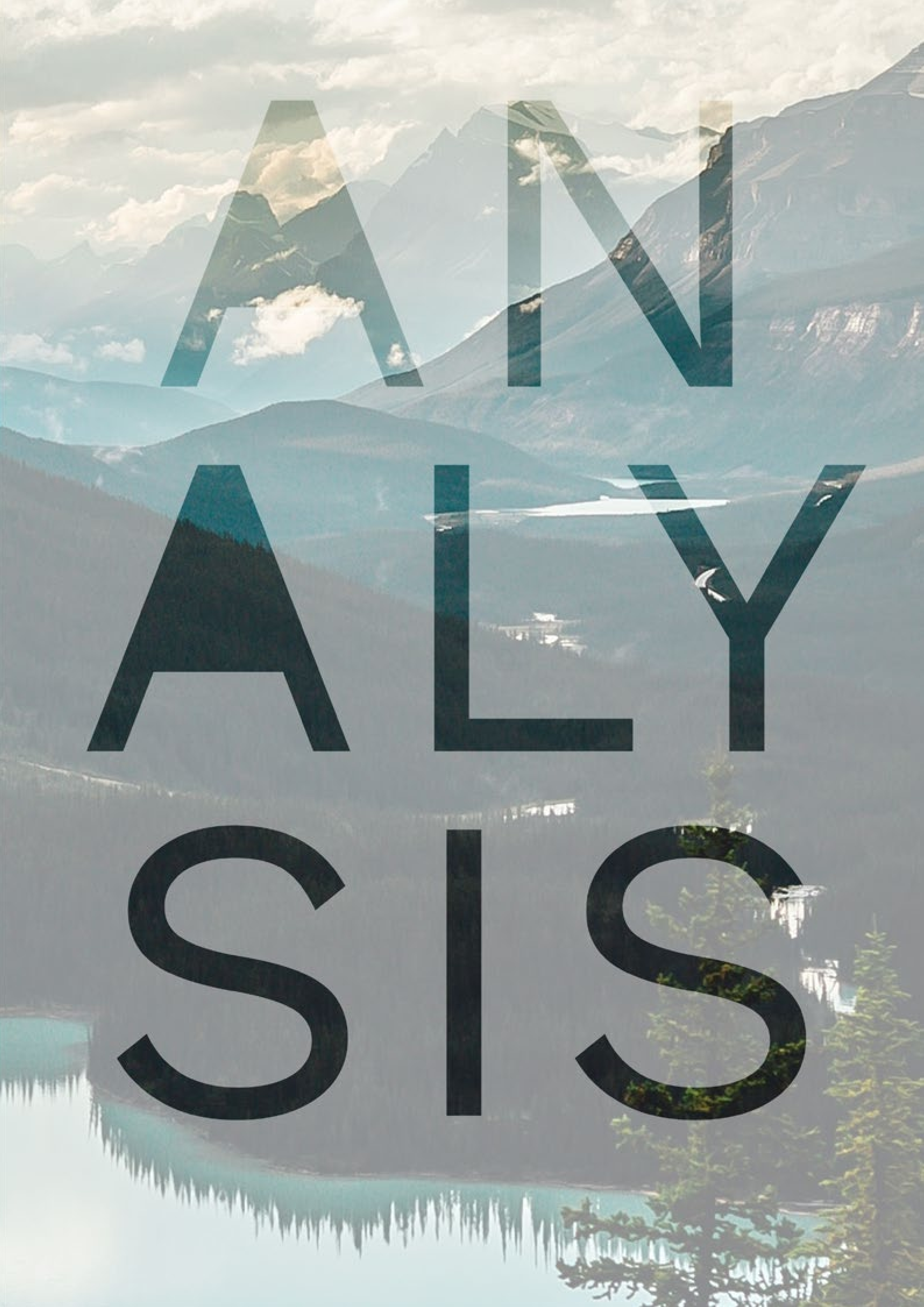
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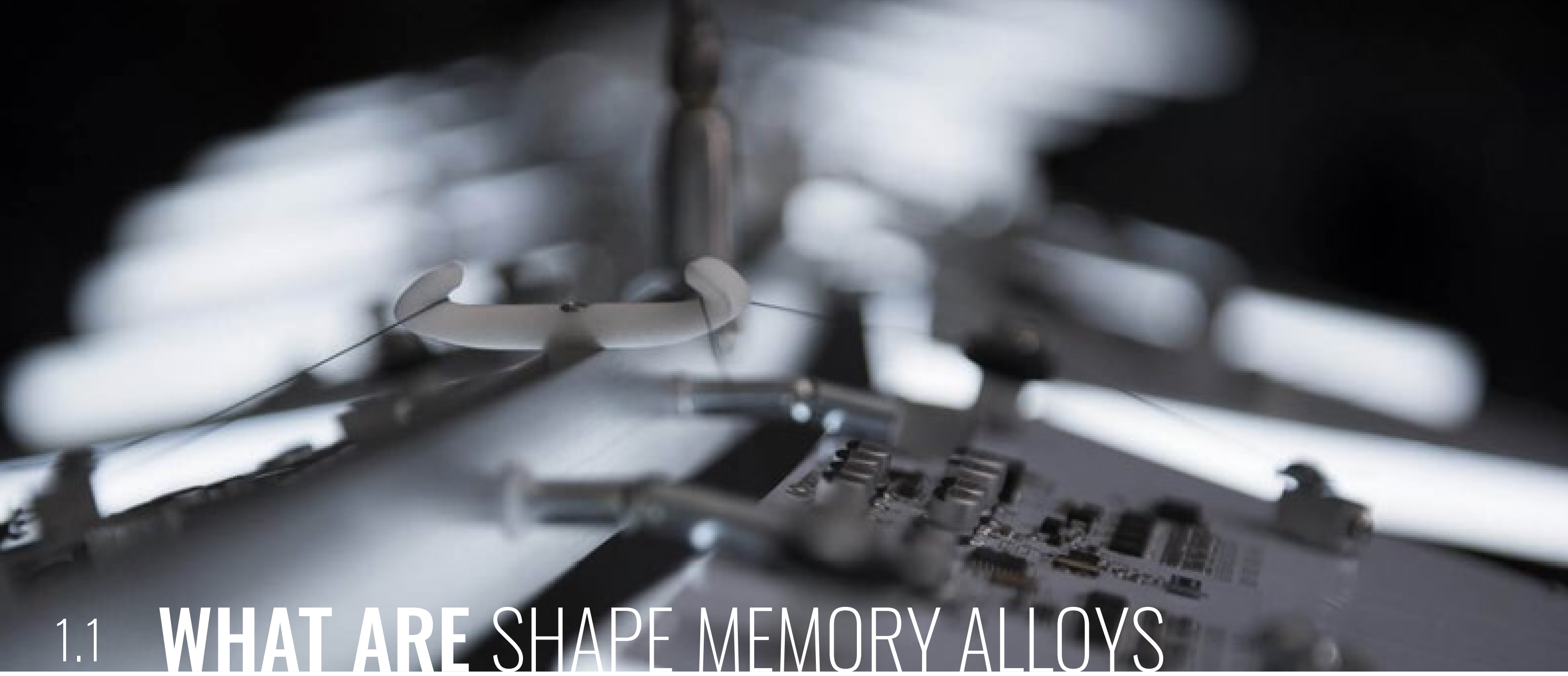


1.1 WHAT ARE SHAPE MEMORY ALLOYS

And what can they do?

Introduction

Shape memory alloys (SMAs) are smart materials made of combined metals that possess the ability of shape memory. This means that they can return to their original, 'set' shape when exposed to external stimuli, such as thermomechanical or magnetic activation.

How does it work

Shape memory alloys have three defined temperature phases: martensite, austenite and annealing. The original shape of an alloy can be 'programmed' by heating it to about 550 c in the desired shape, which is called the annealing phase. The memorization process happens during the transition from martensite to austenite phase. When an alloy is deformed in the martensite phase and is heated above its transition temperature the alloy will change back into its original shape (austenite).

Apart from its memorizing effect, shape memory alloys also possess another remarkable feature. During the austenite phase, the material is super elastic (also known as pseudoelasticity), making it highly flexible and almost impossible to break. Instead, when the material is bent during this super elastic state it will bounce right back into its preset shape upon release.

Summarizing, there are three different shape change effects that can be reached using shape memory alloys (Figure 2)

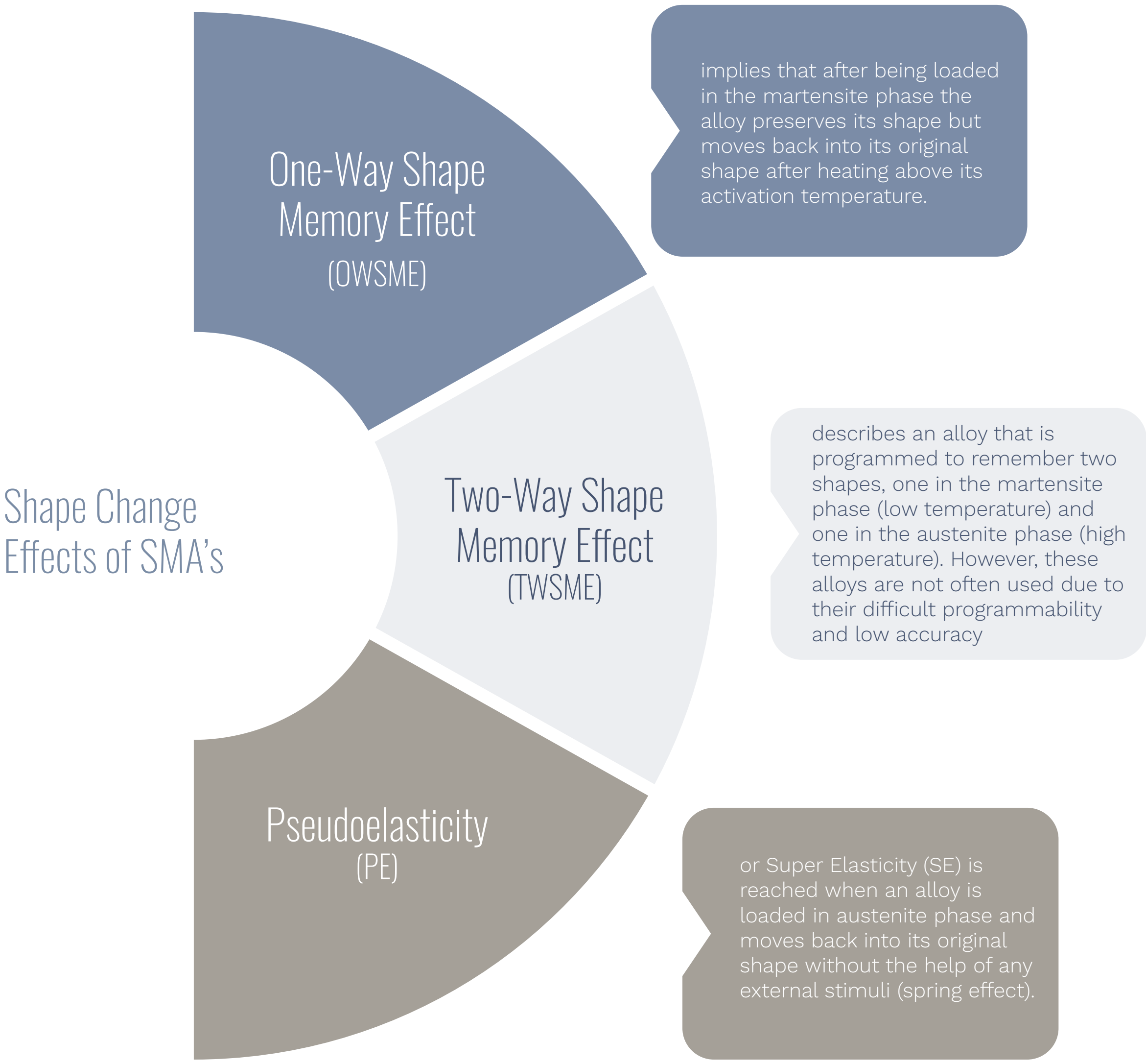


Figure 2 Shape Change effect

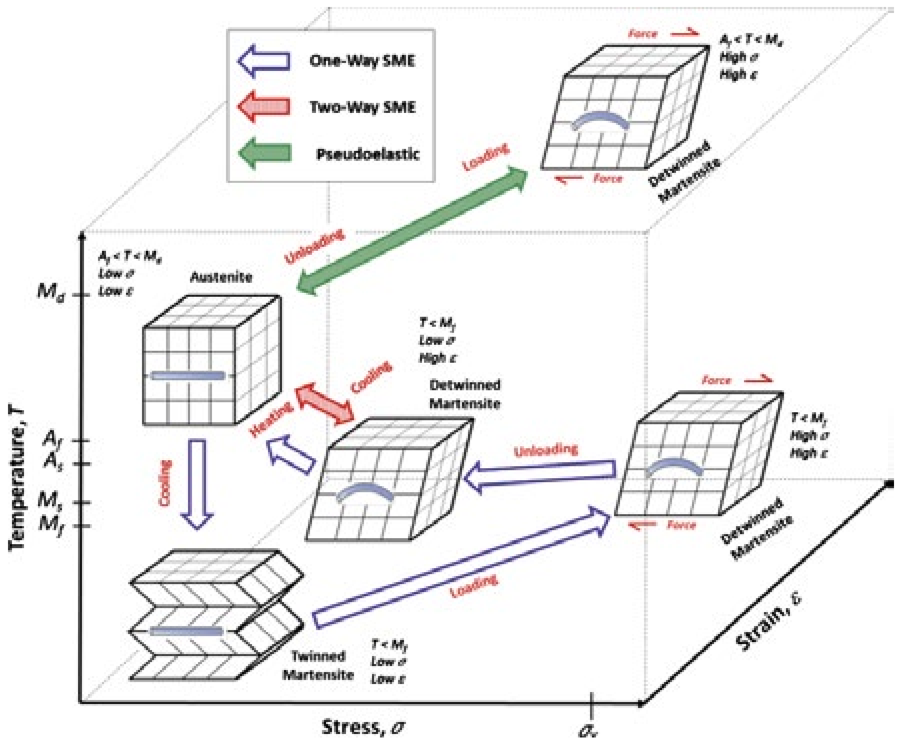


Figure 3 Shape Memory Alloy phase changes (Jani, Leary, Subic & Gibson, 2014)

History

Shape memory alloys were discovered 87 years ago when Arne Ölander first observed the pseudoelastic behavior of an Au-Cd alloy in 1932. Six years later the first OWSME was discovered of a Cu-Zn alloy by Geninger and Mooradian (1938) when they detected the alloy changing its shape upon heating and cooling.

The most commonly known and widely used alloy, nickel-titanium (NiTi), was developed by the United States Ordnence Laboratory in 1962, naming it Nitinol. The abilities of the freshly developed alloy were discovered unintentionally when one of the associate-directors decided to hold his pipe lighter under one of the samples to see how the material would react. Since the sample was subjected to heat, it moved back into its original shape to everyone's astonishment. Luckily, smoking was still allowed inside laboratories back then, otherwise the discovery might never have been made!

Manufacturing process

The manufacturing of shape memory alloys includes many different working processes and each step is crucial for the properties of the final product. The first step in the production process of NiTi is melting the nickel and titanium in the desired ratio. The industry uses vacuum induction melting (VIM), which ensures good homogeneity due to the electromagnetic stirring of the atoms. Even a slight deviation of only 0,1% in the chemical composition of NiTi can drastically influence the transition temperature. Afterwards the material receives multiple vacuum arc remelting (VAR) cycles alternated with water-cooling treatments to ensure an even distribution of atoms, making the final alloy perfectly homogenous.

After melting and homogenization, the alloy ingots are ready for size reduction. This is either done by hot forging or hot extrusion to create wires. Due to the extreme fluctuations in temperature, the alloy products show strong oxidation symptoms. Therefore, the oxide layers are cleaned using electropolishing.

When the semi-finished alloy products are free from oxide they are put into shape. This is done by cold working or by annealing in case of extruded wires. After this, it is possible to apply an aging thermal treatment to enhance the lifetime of the material as well as surface treatments to optimize the finish.

The most prevailing forms in which shape memory alloys are available are wires, springs and sheets.

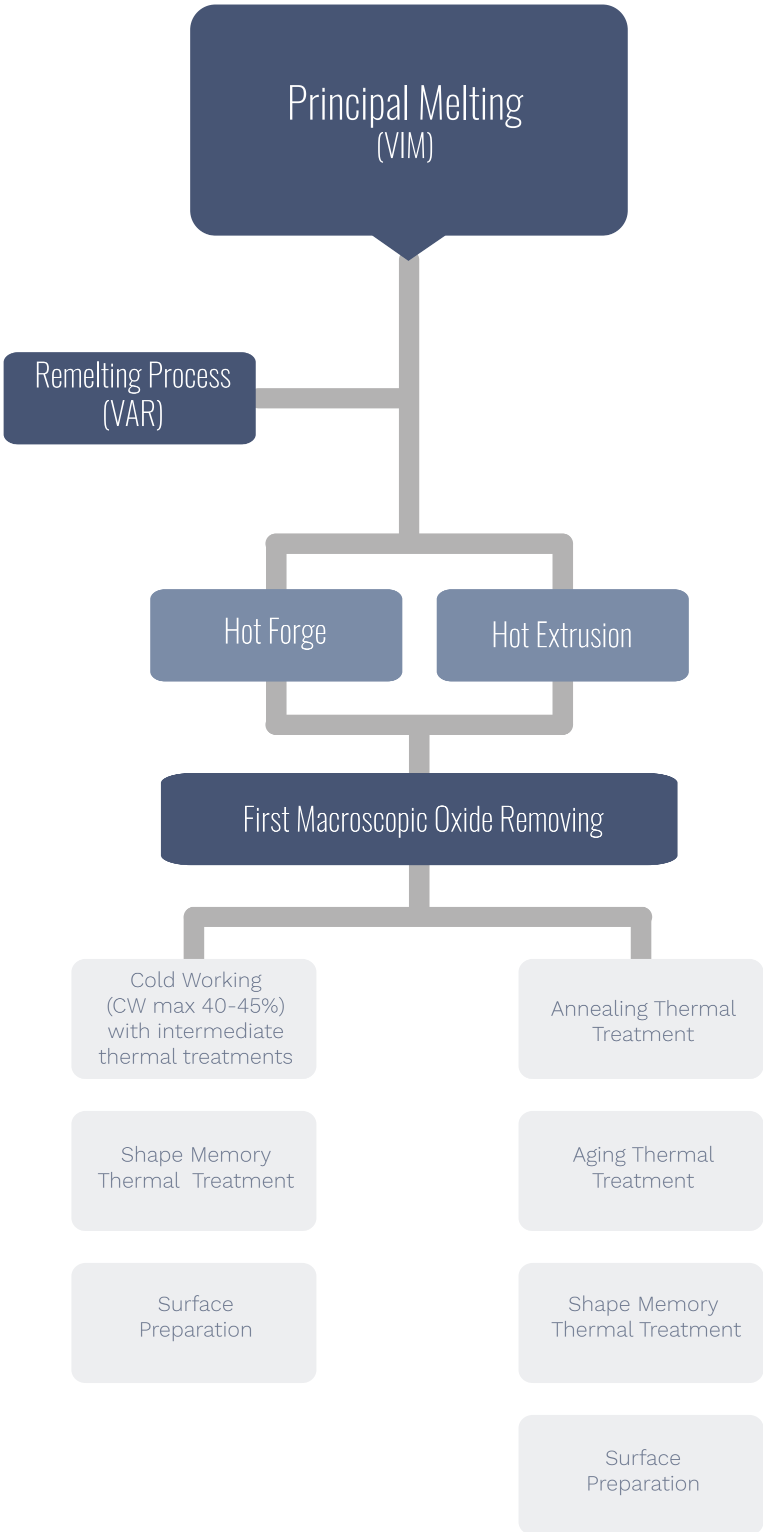


Figure 4 Rough Guide Diagram of Manufacturing Process of NiTi Product

1.2 **MATERIAL** PROPERTIES

What are the numbers

Temperature

Shape memory alloys have the ability to generate enormous amounts of thermal movement (expansion and contraction), up to 100 times greater than other metals. This occurs when an alloy is heated above its transition temperature. The most commonly used alloys which are available in great quantities are those who have an activation temperature of either: 20°C, 35°C, 45°C, 70°C and 90°C. The greater the transition temperature, the faster the alloy can make the cycle, since a larger difference with the environmental temperature will cause the alloy to cool down faster.

Forces

Wires made out of Nitinol are often referred to as muscle wires due to their surprising strength, with the capacity of exerting up to 600 million newtons per square meter. The strength of a wire is determined by its diameter and chemical composition. The direction in which force is applied by the shape memory alloy has a large effect on its efficiency. For instance, an SMA wire is a 100 times stronger when exerting tension force than when it is used to counter bending force. (Jani et al., 2014). (Figure 5)

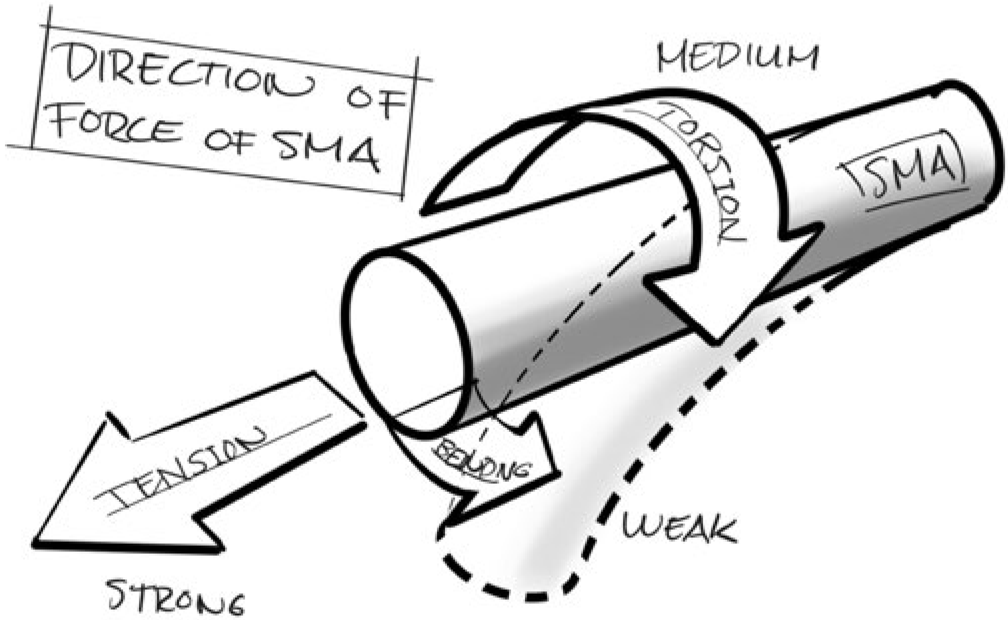


Figure 5 SMA Force direction

Lifetime

The lifetime or fatigue performance of an SMA depends on the applied loading and heat. Increasing both stress and strain on an SMA will have a negative impact on the number of effective cycles it can make. Additionally, overheating plays a key role in the fatigue performance and the material degradation of SMAs. Therefore, it is essential to select appropriate working conditions to obtain high fatigue resistance.

Generally, to guarantee a safe design that can perform over a large number of cycles (106), overheating as well as overstressing and overstraining should be prevented as much as possible. For example, if the maximum load that an SMA can take is 350MPa, the safe design choice would be to load it around 100MPa (less than one third), with a strain of 3-4%. (Jani et al., 2014)

Types

The two most prevalent shape memory alloys are nickel-titanium (NiTi) and copper-aluminum-nickel (Cu-Al-Ni), but they can also consist of alloys comprised of zinc, copper, gold and iron. Although iron-and copper-based alloys are cheaper and more commercially available, NiTi is often the preferred choice given its stability and superior thermomechanical performance. Given that NiTi is more stable than the rest of the alloys, it is often used in research which in turn provides a lot of useful data and knowledge for this project.

Joining

Unlike electrical wires, Shape memory alloys are not suitable for soldering. Nonetheless, soldering is made possible when an aggressive flux is applied to remove the oxide layer. More suitable and conventional ways of joining SMAs are laser- or TIG-welding. However, welding SMAs to materials like steel does not work appropriately, since it creates a brittle inner metallic interface that cannot be stress relieved, causing it to break easily.

Other possibilities include bonding with high-grade epoxy or adhesives and applying mechanical techniques like crimping, sewing and weaving.

Common applications

Shape memory alloys have been used and experimented with in many specialized industries over the years, mostly in the form of actuators. However, it has not yet proven itself viable for the use in everyday consumer products. Some applications are known from the industrial field of air-, spacecraft- or automotive-industry, such as vibration dampers for commercial jet engines or micro-actuators that control the contours of a car seat.

Furthermore, a lot of experimentation is also being done in the field of robotics. The advantage of using SMA wires instead of electric actuators is that they are much lighter and smaller, which in turn opens up many doors to design more lightweight and smaller robotic components. A good example of a SMA robotics is the bio-engineered robotic hand presented in the 2015 International Conference on Robotics and Biomimetics (ROBIO). However, the downsides of using this technology include slow response times and low energy efficiency.

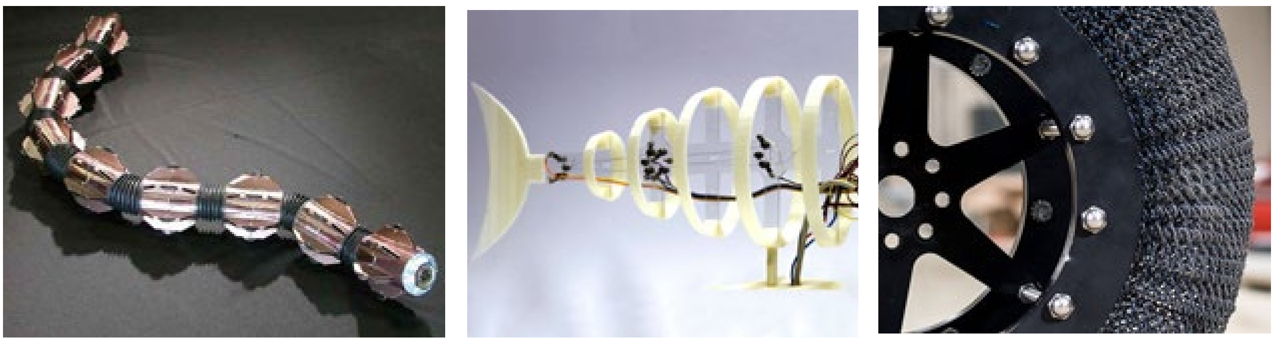


Figure 6 SMA Robotics

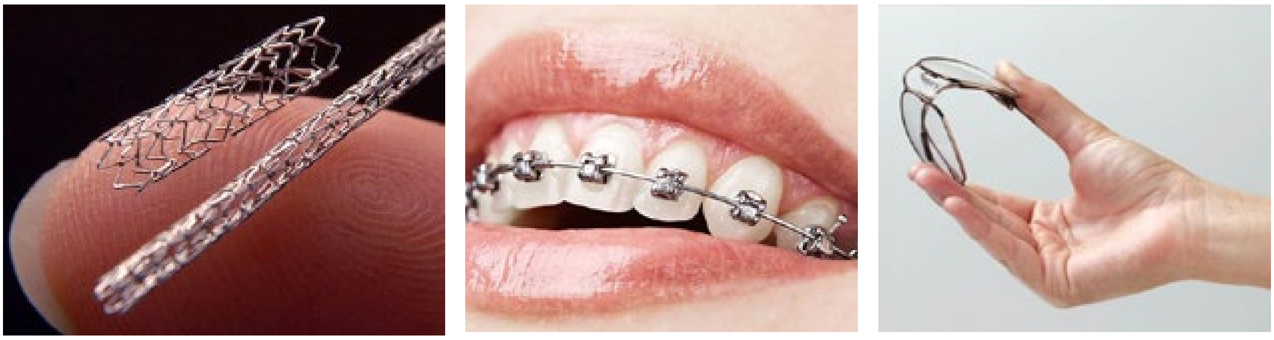


Figure 7 SMA Medical Applications

Figure 8 SMA Artistic Applications

Besides the industrial field, the medical field has also found many opportunities for the application of smart memory alloys. The most well-known application is ‘the stent’, which is a tunnel-like structure used to secure the blood flow inside a vain. The beauty of this application is that it only makes use of body temperature to activate the shape change which enables the structure to expand inside the vain. Other medical applications for shape memory alloys, include: dental braces, eyeglass frames or bone clamping devices.
However, application of Shape memory alloys isn’t confined to the industrial and medical sector, but their unique qualities have also been discovered and experimented with by artist, designers, architects and fashion designers, creating fascinating lifelike structures. The beauty is in the lightness and the simplicity of the mechanism, which almost seems impossible to operate. For example, ‘Hylozic ground’, by Canadian architect and sculptor Phillip Beesley, which was an architectural installation at La Biennale di Venezia in 2010, displays this moving and light surrealism.

Shape memory alloys are a very extraordinary type of metal alloy that possesses the ability to remember a pre-set shape and transform back to this shape when heated above the activation temperature. Because of its unique properties SMAs offer endless possibilities at first sight. However, SMAs are primarily used in very specific and specialized industrial fields, like: automotive, aviation, aerospace and medical.

Except for a few creative and artistic projects, SMAs do not seem to find their way into more conventional everyday product design. The exact reason for this is never clearly mentioned in any research. Nevertheless, by learning more about the material and using common sense, possible reasons can be found.

Although Shape memory alloys have been around for a long time, there is still little known about the exact technical data. For example, the lifetime of a shape memory alloy is very dependent on the distribution of the crystal structure inside of the material, as well as the applied forces and temperatures to which the alloy is exposed. The larger the number of variables, the more difficult it becomes to apply the material with complete certainty of a failsafe system. Consequently, to achieve the perfect SMA application more research and testing is needed.

Additionally, the material costs of SMAs are very high compared to ordinary steel in combination with electric sensors and motors, which in essence can fulfil similar purposes. Although the simplicity, size and weight of this alternative can never match that of shape memory alloys.

To summarise, the use of shape memory alloys is largely limited due to the high costs and risks involved, which stems from a lack of knowledge and unwillingness to learn from sectors falling outside the aforementioned industrial fields that are generally backed by large multinationals.

1.3 MATERIAL QUALITIES BRAINSTORM

Discovering search fields

To give the project more direction and make the intended goal clearer, an open brainstorm was done with five different people to generate possible search fields for innovative ways of applying shape memory alloys. Beforehand, a list was made of the material qualities of SMAs. Then to stimulate the creative process, groups of contradicting aspects of the material were made. This led to many ideas from which six potential search fields were derived.

List of qualities

What defines a smart material is that it can be a sensor, an actuator or both at the same time, making the system they are part of controllable. From the literature research a list was composed describing both the positive and the negative qualities of shape memory alloys.

Shape memory alloy’s are:

Able to change shape when exposed to heat	Silent when moving
Lightweight	Spark free
Very flexible (hard to break)	Smooth, organic in motion
Lightweight	Slow (activation frequency)
Simplifying mechanisms	Not very precise (low controllability)
Thermal to mechanical energy convertors	Not energy efficient (when using electrical power)
Frictionless (no dust)	High power / weight ratio
Both actuator and sensor	Susceptible to degradation and fatigue

Table 1 Material Qualities

Combinations of two aspects of the material were proposed during each brainstorm session. This approach led to a very broad and independent way of generating ideas, enabling the discovery of original connections. The proposed couples were the following:

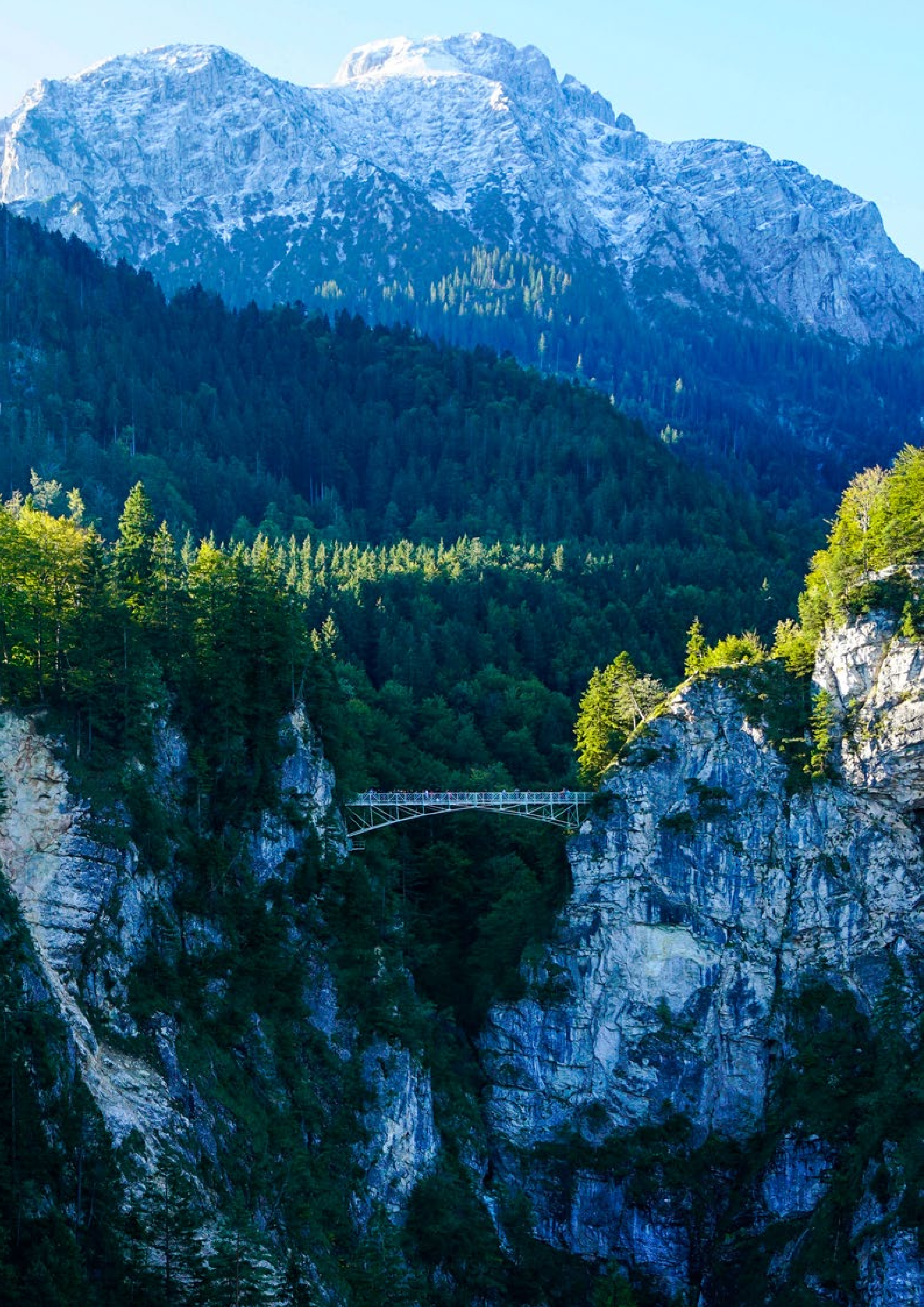
	Quality 1		Quality 2
1	Super flexible	⟷	Shape change
2	Slow	⟷	Low accuracy
3	Hot	⟷	Cold
4	Big	⟷	Small
5	Lightweight	⟷	Strong
6	Heat	⟷	Movement

Table 2 Quality Couples

From the brainstorm sessions, the third couple (hot vs. cold) seemed to be the most fruitful when trying to generate ideas. These ideas ranged from situations, locations to phenomena.

After clustering ideas, six potential search fields commenced:			
1	Wearables (cocooning, thermoregulation)	4	Foldable space-saving solutions (traveling, life jackets)
2	Fire safety (fail-safe system, protection)	5	Drone accessories (gripper, camera jig)
3	Revalidation (staying in motion, braces)	6	Soft robotics (rescue-bots, medical)

Table 3 Potential search fields



The six identified search fields all show potential ways of applying shape memory alloys. However, it is still hard to make a grounded decision in which direction this project should go. The goal, as mentioned in the assignment description, is to design a shape changing product that integrates shape memory alloys in a meaningful and inspiring way.

To do so, the future search field must allow the SMA's material qualities to play a central role in the product, by supporting the positive qualities and avoid the negative ones. To get a clearer idea on which search field best fits the material, a feeling for the material needs to be developed by testing and playing around with shape memory alloys.

1.4 MATERIAL TINKERING

With shape memory alloy's

An important step of the material driven design process is to get acquainted with the material and fully understand it. This can be achieved by tinkering with the material.

First encounter

My first encounter with shape memory alloys was during a meeting with my chair, Kaspar Jansen. He introduced the material with a couple of examples from former projects. For instance, he showed me a spring that had an activation temperature of about 30°C, which had the ability to change back into its 'set' shape through the simple change in temperature caused by exhaling air onto it. I remember being mystified and surprised when seeing the material's reaction to temperature change for the first time. Amazed by his 'magic trick', my curiosity drove me to start some experiments of my own to see what the material could do.

Tensile testing

To see how strong the material is in practice, tensile tests were done on the Zwick drawbench. It was difficult to properly fix the wires between the two brackets given their small diameters (1mm or less). Eventually a way was found to fix the wire, by winding the wire around a steel bolt, make a knot and lock the bolt in on both ends of the clamps. The wire's shape memory strain was found to be between 3-5% in the martensite phase.

Lifting

In theory, when a shape memory alloy is loaded under a constant vertical force, using a weight, it is stretched out. This elongation can be countered by heating the alloy above its activation temperature, which makes the wire lift the weight. In order to observe this process in practice, a simple setup was made using a 60 cm NiTi wire with a diameter of 250 mm and a weight of 200 g. The wire was vertically suspended, and the weight was secured on the bottom end (Figure 9). The wire was heated with a DC power supply connected to the top and bottom end of the SMA wire. The voltages that were used varied between 8V and 12V. The higher the voltage the faster the weight was lifted to an approximate height of 3 cm, about 5% of its total length. Additionally, the literature suggests that the ideal strain to prevent degradation in SMA wires is between 1-8%, meaning that this test was executed within the proper range. After repeating this process several times and gradually increasing the voltage, the shape memory alloy suddenly stopped working. What I learned from this is that when the alloy is heated extensively, it will reach the annealing temperature, causing it to reprogram the wire's memory. memory.

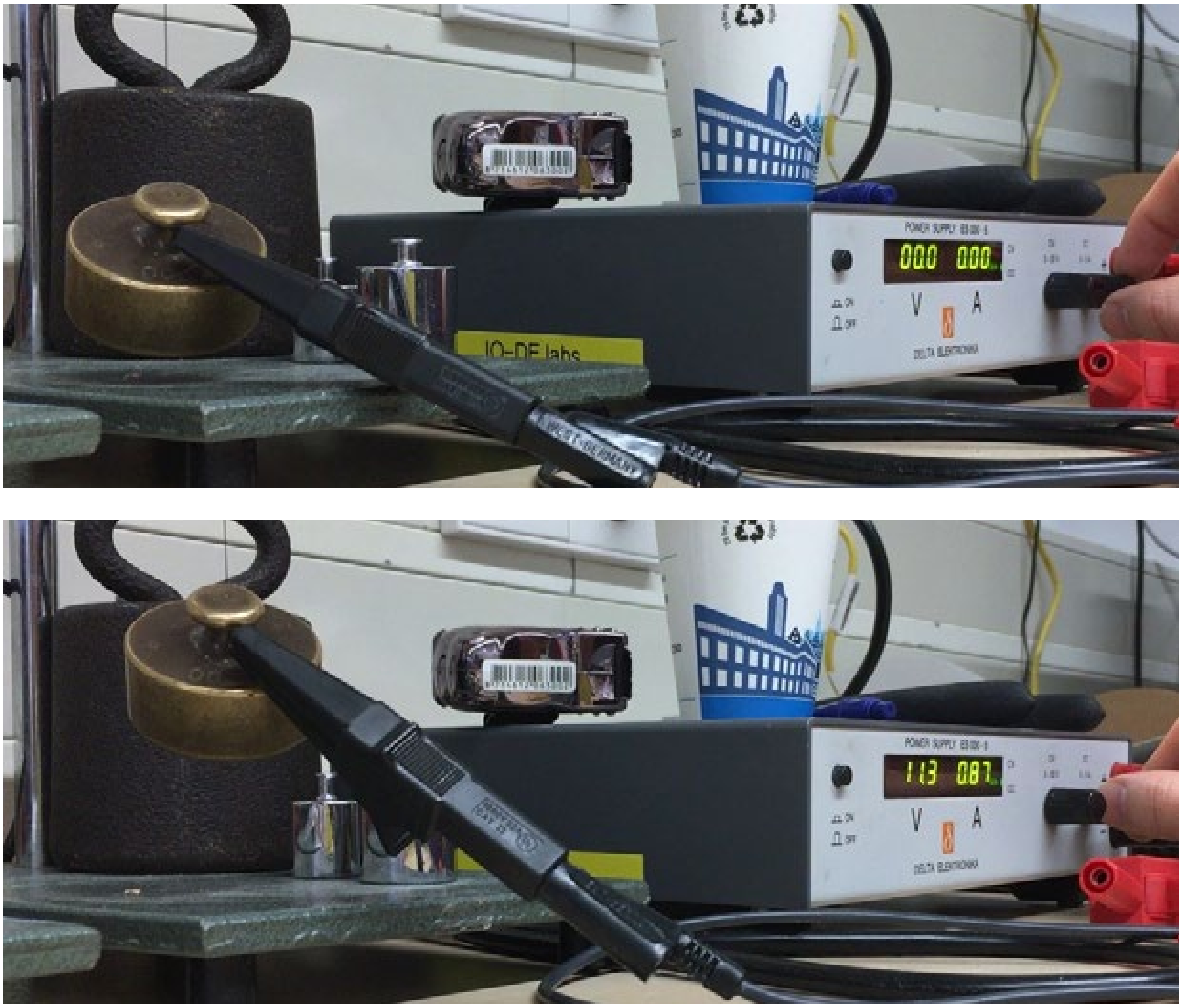


Figure 9 Lifting weight using SMA wire

Training 2D

Training shape memory alloys, also called annealing, is done by heating the wire to temperatures around 500-550 degrees Celsius. During this experiment a ceramic oven was used in combination with a perforated aluminum plate on which the wires were set into shape through the use of bolts. For the first test a simple T-shape was created.

After annealing the wire for thirty minutes, it was quenched in cold water to accelerate the cooling process and to remove most of the oxidation layers. After heating the wire above its transition-temperature, the wire indeed converted back into the programmed T-shape, which was pretty amazing to see for the first time.

Figure 10 Colleague 2D Programing SMA wires

The following 2D programming experiments that were conducted, made use of zig-zag patterns and X-shapes, utilizing NiTi wires with varying diameters and transition temperatures. An important observation that was made during this process was that the transition temperatures mentioned on the packaging of the shape memory alloys are not very accurate. This problem is mainly due to manufacturers often overlook the austenite phase, which has an austenite start (As) and austenite finish (Af) temperature. Consequently, what is described as the transition temperature by manufacturers actually corresponds with the austenite finish temperature rather than the austenite start, meaning that alloys will start reacting at a lower temperature than is described on the packaging.

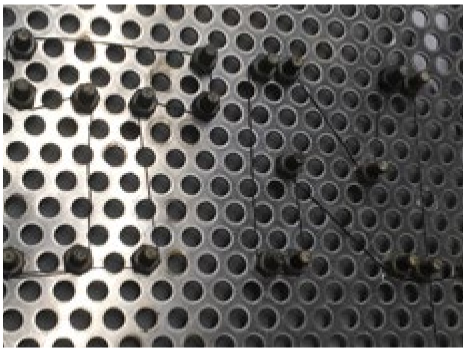


Figure 11 Programmed 2D Shapes

Training 3D

To see how the material would react when trained into a 3D shape, a long 12mm bolt was used to wind up the SMA wires. The spiral grooves of the bolt were used as a path to guide the wires into a spring-like shape. The wires were fixed on both sides using two nuts to remain in shape while they were inside the oven.

After curing, cooling and deforming the different wires, they were subjected to their activation temperatures. As a result, all wires shifted back into their preprogramed shape when heated. However, an interesting observation was made when the wires (especially the smaller diameters 0,2mm and lower) cooled back down to room temperature. Above their activation temperatures the shape exactly resembled to programmed shape, yet when they cooled down the spiral shape relaxed a bit increasing the inner diameter and the free length of the spring.

On hindsight, this might have been caused by the unintended tension that was created while winding up the wire on the bolt.

Figure 12 3D SMA Training

Transition temperature

The purpose of this experiment was to clarify the observed deviations in transition temperature as stated by the manufacturers and measured in reality. Additionally, as stated on manufacturers' websites, the transition temperature could change after annealing. Therefore, this test involved the exact same NiTi wire before and after training to verify whether this would also occur in reality.
A special thermoregulated bath was used to apply a constant, regulated temperature to the smart memory alloy wire. Furthermore, the wire that was used had a diameter of 0,5 mm with an activation temperature of 70 degrees Celsius. Before annealing the transition temperature was measured at:

	50°C	60°C	70°C
Time (s)	5	2	1
Recovery (%)	60	80	100

Measured   Estimation

Table 4 Results before programming

Table 4 shows that the range in which shape memory alloys become active is quite broad and that the transition temperature which is stated by the manufacturer corresponds with the austenite finish temperature of the alloy.

Consequently, the exact same wire was subjected to an annealing cycle of 20 minutes at 550°C, after which the same measurements were executed.

	50°C	60°C	70°C	80°C
Time (s)	-	6	3	2
Recovery (%)	0	30	50	80

Measured   Estimation

Table 5 Results after programming

This experiment confirmed that the transition temperature of a shape memory alloy increases after training. Although measurements were rough and the percentage of recovery was estimated, the difference at 50 degrees was easily noticeable. In this experiment the transition temperature increased somewhere between 10-20°C.

Cooling test

Cooling shape memory alloys after annealing can either be done by cold water quenching or air cooling. To see if these methods caused any changes in the properties of a trained alloy, two samples of the same wire were subjected to both techniques. However, both samples behaved exactly the same after training. The only noticeable difference was that the quenched sample showed a nicer surface finish, due to the removal of oxide layers in the cold-water bath.

The first-hand experience with the material through experimentation and tests, has proven to be very helpful in the process of deciding which direction this project should take moving forward. It is amazing to see how thin the wires can be, while still being able to exert a decent amount of force. Additionally, I discovered that the very thin wire shares many similarities with thread and has a silk-like feel to it, encouraging me to focus this project on finding an application of shape memory alloys in combination with textiles. More specifically, to create a smart textile that can change its shape by activation of the incorporated SMA wires.

This decision also relies on the super-elastic quality of the material, which allows the wires to be forced in all sorts of awkward positions without breaking. Furthermore, integrating the wires in a wearable textile takes away the need of precise movements and fast reaction times, which are two negative qualities of SMAs. Thus, a smart-textile incorporated into a shape changing wearable that reacts on temperature changes, fits all the qualities of the SMAs perfectly. This fruitful combination has the potential to result in a meaningful and inspiring design.

1.5 DESIGN VISION

With shape memory alloys

Integrating shape memory alloys and textiles to create a thermally self-regulating garment that increases in thickness when exposed to cold temperatures and decreases in thickness when exposed to warm temperatures.

In order to have the desired result, the fabric needs to expand when it cools down to create an extra layer of air between the user and the shell of the garment, increasing the level of isolation. Strikingly, expanding when cooling down is contradictory with the conventional functioning of shape memory alloys since they are programmed to react when heated. However, when a foam (or other type of spring) is added to the system, the shape memory alloy can act as a counter force that contracts the system when temperatures exceed the activation temperature (making the fabric less insulating). When the temperature decreases and becomes less than the activation temperature, the SMA will lose its power and will become easily deformable. Consequently, the foam (or other kind of spring) will now deliver just enough force to open the structure to create an extra layer of air isolation.

To make the system self-regulating, multiple layers can be combined in such a way that each layer reacts to a slightly different temperature change. Consequently, the system will become self-regulating and keep the user's body temperature levelled at all times.

The main goal of this project is to create a self-regulating garment that can change its shape from 2D to 3D when exposed to changes in the environmental temperature, allowing users to maintain a constant bodily temperature due to the garment's change in insulating value when exposed to different conditions.

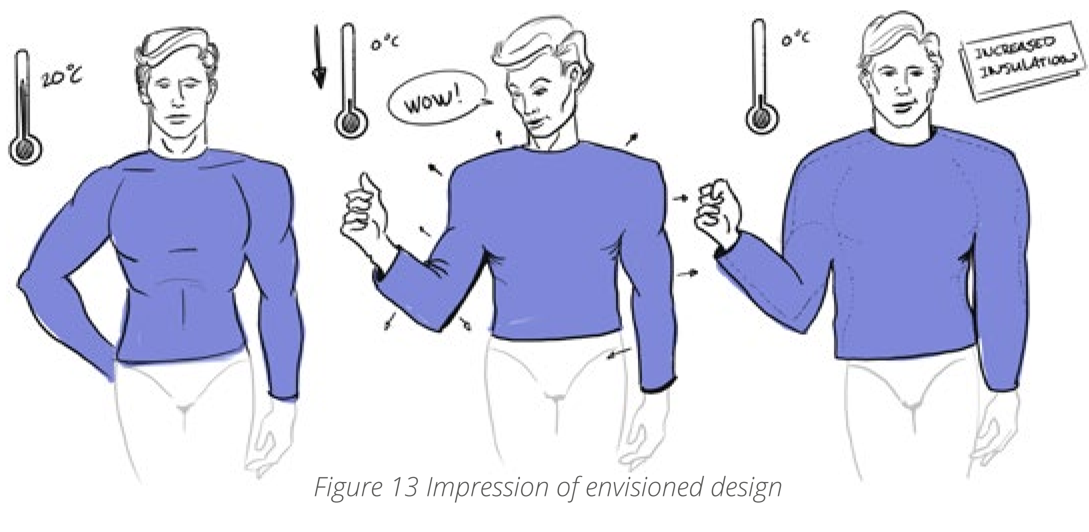


Figure 13 Impression of envisioned design

"Integrating shape memory alloys and textiles to create a thermally self-regulating garment that increases in thickness when exposed to cold temperatures and decreases in thickness when exposed to warm temperatures."

1.6 LITERATURE REVIEW

Benchmarking shape changing textiles

A literature review was done to discover to which extent shape memory materials have been applied in textiles so far. There is much to learn from what has been done in the past and this research will also show possible uncovered gaps, which could be of interest for further development. Therefore, a broad research was done on smart textiles involving only projects that incorporate a form of shape change or movement (adjustability), using shape memory technology. In Table 6 former projects are displayed which are relevant to the topic at hand.

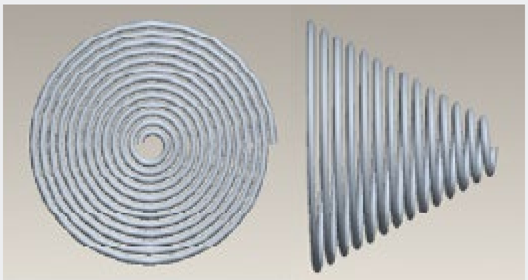
Materials

Description

Actuation

Topic

Thermo-insulation
(cold protection)



(Yoo, Yeo, Hwang, Kim, Hur & Kim, 2006)

TWSMA coil springs + fabric layers

Coils springs expand when low temperature is registe-red, to keep user warm

Body and environmental temperature

Topic

Thermo-insulation
(protective clothing)

(Kim, 2014)

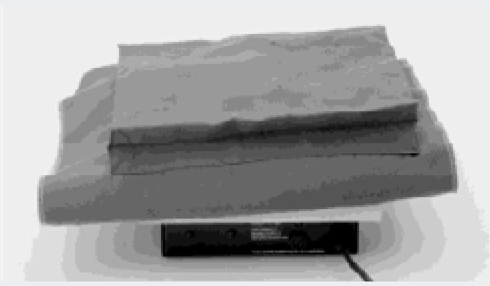
NiTi springs between fabric layers

Preventing heat and cold stresses in protective clothing

Body and environmental temperature

Topic

Thermo-insulation
(heat protection)



(Congaltion, 1999)

NiTi coil springs + pleated fabric for expansion

Coil springs expand at high temperature to protect from flames

Environmental

Table 6 Shape Changeing Textile Papers

Topic

Comfort fitting to all and standardisation

(Wang, Chen & Huang, 2017)

Shape memory polymers

One size fit all after heating and wearing

External device (oven & heatgun)

Topic

Shape memory textiles designed for inhouse aesthetics

(Stylios & Wan, 2007)

SMA & SMP used to create yarns and woven fabrics

SMA & SMP woven into fabrics to create adjustable partitions in room

Not specified or tested

Topic

Shape changing clothing

(Pelton, 2004)

SMA and Fabric yarns

Automatic rolling-up mecha-nism in sleeves

Environmental

Topic

Bio-Smart Sportswear

(MIT Media Lab and Tangible Media Group, 2015)

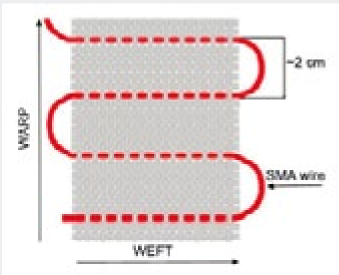
Bacteria

Ventilating sportswear, regulated through athlete's body temperature

Humidity (Sweat)

Topic

Self-ironing clothing (hybrid woven fabrics)



(Vasile, Grabowska, Ciesielska-Wrobel & Ghitaiga, 2010)

SMA and textile yarns woven together

The super-elastic feature keeps the textile wrinkle-free

External device (oven & heatgun)

Topic

Shape changing clothing

(Howard, 2013)

SMA embedded in fabric

Expanding garment as a means to define personal space

Body and environmental temperature

The first three projects presented in Table 6 correspond closely which the intended design goal of this project. They all integrate shape memory alloys and textiles to create a self-regulating thermo-insulating system, either for cold protection, or to prevent heat stress.

The one thing that these projects have in common is that SMA springs were used in between two textile layers to create an adjustable air gap between the user and the outer shell, subsequently increasing the insulating value of the garment. This solution is tested to be effective by the authors and result in a better insulating and more comfortable whole. However, suggestions for further development of this concept, mentioned in the conclusions of these papers, are mainly about the way of integrating the SMA wires with the textile. The two-way shape memory springs, or spring coils, are one way of establishing an increase in thickness of the air gap, but there might be other more efficient mechanisms that could achieve the same result, which would be interesting to explore.
Other applications found during this research involved: comfort fitting, aesthetic shape changing fabrics, shape changing garments and hybrid woven fabrics for wrinkle prevention. All these projects show interesting ways of applying shape change technology into textiles to give more meaning and functionalities to ordinary textiles. For example, MIT created a suit for ballet dancers that automatically opens its venting structure upon contact with moisture (sweat) to make the dancers cool down when needed, by the use of special hydrophobic bacteria.

To conclude, the takeaways from this research are that an insulating fabric using of SMA springs has been done before, but the way these mechanisms are integrated still leaves room for improvement. Additionally, research proves that activation through body- and environmental-temperature is feasible if the right alloy is selected. Furthermore, the application of weaving SMA wires together with fabric yarns has been proven effective, which also opens up new doors for further concept development. While developing a new and better version of an SMA integrated garment, an optimal scenario would involve a minimization of the use of shape memory alloy wire to save costs and a convenient way of integrating the wire with the textile to simplify production. Keeping in mind that the textile needs to be light weight and have sufficient compression resilience.

1.7 TEXTILE REVIEW

Types & production techniques

The need to protect ourselves from the cold through the use of clothing, is a principle that originates from prehistoric times. Back then, animal skins might have been the main life saver of many people, however, much has changed since then. This is primarily due to the industrialization period and the rise of modern manufacturing techniques. However, there are still many similarities between the basic principles of both main modern textiles and ancient production method.

Textiles are flexible materials comprised of a network of fibers (yarn or thread). The terms 'fabric' and 'cloth' are synonyms of the word 'textile' and are often used to describe the same materials. Yarn is the basic wire-like component of every textile, which is created by spinning raw fibers, like wool or cotton, into long strands. Henceforth, there are multiple ways to form textiles like: weaving, knitting, crocheting, knotting, felting or braiding.

Types

There are four different base material-sources of which textiles can be produced. Three of these sources are natural, namely: animals (wool, silk), plants (cotton, flax, jute, bamboo) and minerals (asbestos, glass fibre). The latter The fourth material-source is synthetic, often referred to as artificial fibres which is made from petroleum (nylon, polyester, acrylic, rayon).

Synthetic materials are primarily used in the modern clothing production. Polyester is one of the most commonly used materials, either alone or spun together with natural fibres to create a material with blended properties. Another famous synthetic material is spandex (Lycra), which is well known for its exceptional elastic properties. It can easily stretch up to five times its own length without breaking. Therefore, it is often used in skin-tight garments and activewear, such as swimwear and bodysuits.

Uses

Textiles know a great variety of uses and play a dominant role in our daily lives. Think of the clothing we wear every day, or the bags we carry to school or work. Besides clothing there are other applications to be found around us:

House

Carpeting, upholstered furniture, towels, window shades, cleaning rags, coverings for beds and tables and art.

Active

Kites, sails, balloons, parachutes

Other

Tents, nets, backpacks, flags

Industrial uses of textiles, commonly referred to as technical textiles, are to be found in many applications. Think of structures for automotive parts, medical textiles (implants), geotextiles (dikes), agrotextiles (farming) and protective clothing (heat, radiation, bulletproof). Not to forget is that textiles can also be used as reinforcement of composite materials, like fibreglass or carbon fibres.

Figure 14 Textiles in daily life

Production methods

Weaving

The most commonly used textile production method is weaving. This method interlaces a set of long threads (wrap), with a set of crossing threads (weft). This technique can be done by hand, using a frame or a loom, but it is mostly executed by mechanized looms.

Knitting & Crocheting

These techniques are grounded on interlacing of loops of yarn and produce very similar end products. Knitting needles, or crochet hooks are used to form the loops. The difference between knitting and crocheting is that a knitting needle is able to hold multiple loops at one time, while a crochet hook can only handle one active loop. Therefore, knitting can be done mechanically.

Braiding

This method involves twisting three or more textile yarns together to form a complex structure or pattern, comparable to braiding of hair.

Felting

Felting is the tangling of fibres by pressing them together while lubricated.

Bonding (non-woven)

The bonding of non-woven materials shows many similarities with felting (felt is a non-woven. However, bonding can either be accomplished chemically, mechanically, thermally or by solvent treatments (Muller & Saathoff 2015).

Sewing (joining)

Sewing is used to combine different pieces of textile together using stitches made with a needle and thread, or a sewing machine.

1.8 CLOTHING INSULATION

How does it work?

Theory

Clothing insulation can be seen as thermal insulation provided by clothing. In thermodynamics there are three kind of heat transfer: conduction, convection and radiation. All materials have a thermal conductivity known as k, which is measured in watts-per-meter per kelvin (W·m−1·K−1 or W/m/K). The advantages of air are that it has a low thermal conductivity, meaning a low rate of heat transfer, making it a good insulator. Additionally, air is everywhere around us and is therefore extremely mobile. The value of insulation of a garment is dependent on two basic principles:

1. Creating a layer of insulation (air) between the user and the outer shell, trapping body heat inside, using fibres.
2. Making sure this heat is not lost, by preventing wind from penetrating the warm layer and replacing it with cold air.

It is equally important to keep in mind that humidity also plays an important role in this principle. Water is a better conductor than air, this means that when a garment is wet, due to sweat or rain, a part of the air insulation is replaced with water which results in a less insulating whole.

Heat transfer (P) is approached as power (heat loss) and is dependent on four different factors: thermal conductivity (k), surface area of thermal contact (A), difference in temperature (△T) and the thickness of the material (d).

This results in the formula $P=(kA \triangle T)/d$

What can be derived from this formula is that a well-insulated piece of garment has a lower P-value, compared to a less insulated variant. Decreasing the P value can be reached in three ways: choose an insulator with a low thermal conductivity, decrease the surface area and increase the thickness of the material. However, decreasing the surface area is an unrealistic option in this case, considering that the garment is constrained to the measurements of the human body.

Clo-units

There are special units in which clothing insulation may be expressed which are named clo units. There are numerous ways to determine the level of clothing insulation, but according to ASHRAE (American Society of Heating, Refrigerating and Air-conditioning Engineers) the most accurate way is to perform measurements on heated mannequins in regulated conditions. When a clo value equals 1, the subject maintains a perfect thermal equilibrium in rest, at a room temperature of 21°C. The ASHRAE gave out a handbook in 2017 in which they show tables of typical insulation values for clothing ensembles (ASHRAE 2017). For example:

CLOTHING COMPOSITION	CLO-VALUE
Walking shorts, long-sleeved shirt	0.36
Trousers, long-sleeved shirt	0.61
Trousers, long-sleeved shirt, long-sleeved sweater, t-shirt	1,01

Table 7 CLO-unit example

In the handbook there is a second table that shows the clo values per garment item and they claim that the numbers addable. This means that if you add up all the values given per item you will get the clo value of a specific outfit, as an outcome of the equation.

Jacket build-up

A warm winter jacket should give the user warmth without adding a lot of weight to the garment. It also needs to be waterproof windproof and comfortable. These jackets are usually build-up of three different layers that are sewed together, an insulation jacket on the inside and a windbreaker on the outside, with a membrane layer in between. The inner insulation jacket begins with a nylon lining after which the inner components will be layered on top. Secondly, a film of fleece line is placed to stabilise and protect the insulation. Then, the insulating material is placed on top and sewed together, creating pockets that are able to trap air inside. When the fabrics are composed all the pieces are sewed together creating the insulating jacket.
Next step is the windbreaker which is often made from a heavy nylon together with a perforated membrane layer with holes small enough to keep rain droplets out, but big enough to let moisture escape from the inside. This layer makes the jacket both waterproof and windproof. An example of a band producing this special layer is Gore-tex. The material used to produce the wind- and waterproof layer is polytetrafluorethylene (PTFE) more commonly known as Teflon.

High-tech outdoor materials

There are a lot of high-tech outdoor materials available these days and due to expired patents, every top of the line garment manufacturer likes to create their own adapted formula of each alternative and make up their own name for it. In Table 8 the breakthrough fabrics are listed with their original names and a short description of their properties.

	Description
Gore-tex	Breathable waterproof membrane that lets transpiration escape.
PrimaLoft	Synthetic polyester-based microfibre used for insulation.
Polartec	Synthetic polyester-based fleece mimics wool, but is lightweight
FutureLight	Breathable waterproof fabric made from recycled materials, the environmentally friendly version of Gore-tex.
Cordura	Nylon blend fabric known for its high level of durability.
Aerogel	Thinnest, lightest and warmest insulating material, the material basically a gel in solid state.
Thinsulate	Relatively thin synthetic water-resistant fibres, used as a replacement of down.
eVent	Breathable waterproof fabric, specially designed to keep the user dry by letting moisture escape immediately by venting.
DownTek	Special coated down feathers with enhanced moisture resistance, to maintain their loft.
Dyneema	Strongest fibre in the world, that is lightweight, thin and completely waterproof.
Spectra	Lightweight, tough and durable, used in tactical gear.

Table 8 High-tech Outdoor Textiles (Becker 2019)

What do the experts say?

With all the knowledge about fabrics and garment construction gained so far, it is now time to take a look at what the outdoor experts have to say about the matter. How do hiking, climbing and skiing enthusiasts stay warm in cold conditions?

Figure 15 Basic outdoor layering system

By searching and reading many blogs and websites for outdoor lovers a couple of basic principals were derived that generally apply to all.

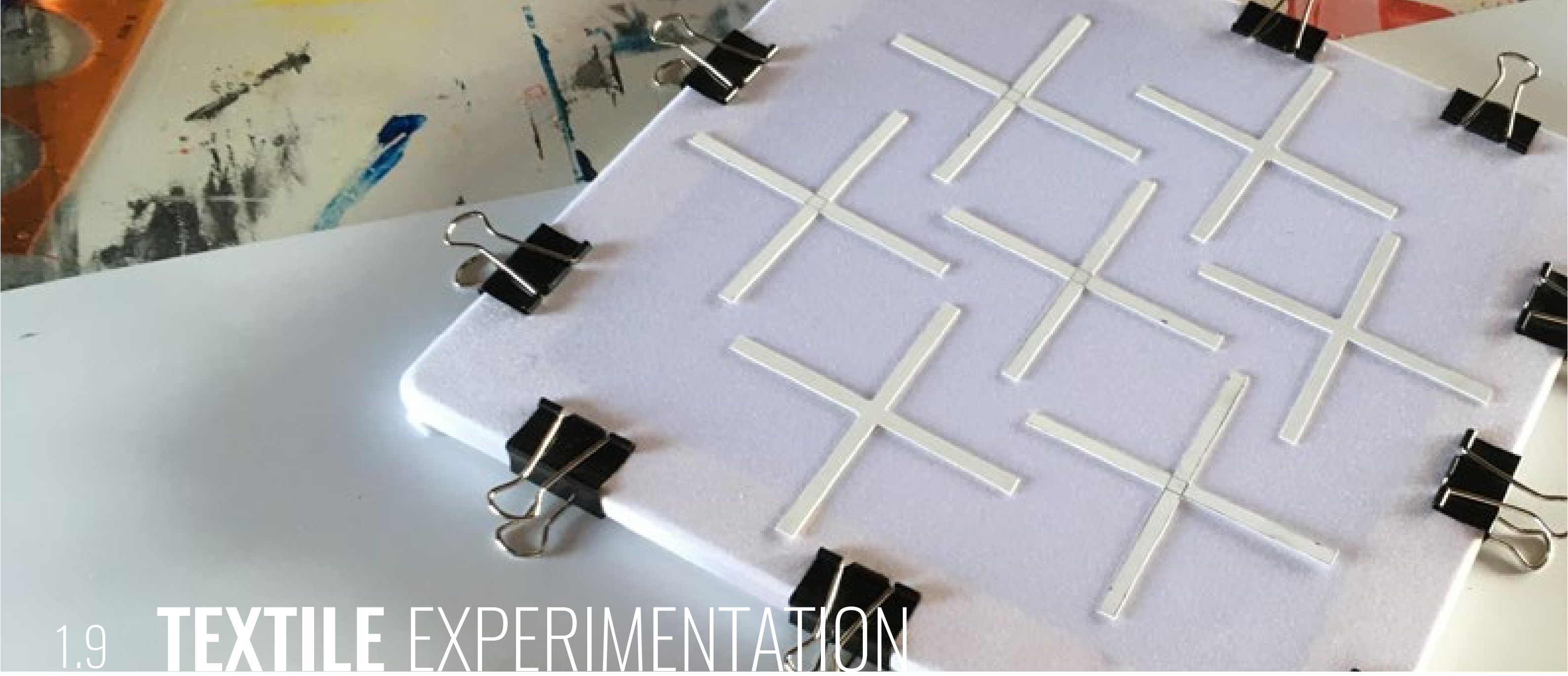
They all say that layering is key to dress properly for cold weather conditions. Layering means, wearing a base layer, a middle layer and an outer layer. The base layer is meant to keep your body as dry as possible, so it has to absorb perspiration and dry quickly. The most effective base layers are made of either merino wool, or polyester and need to be worn close to the skin (tight). The middle layer needs to insulate, maintaining the warm air created by the body. This layer can either be an insulated jacket or a fleece. The outer layer needs to be breathable and protect from rain and wind to maintain the inner climate. This layer can either be a hard shell or a soft shell, the first is fully waterproof and works best in rainy conditions, the latter offers more comfort in dryer conditions due to its flexibility. These are the basics to dress accordingly for cold weather conditions.
Outdoor enthusiasts are very active people, which means that choosing the right gear is often a big challenge. While hiking, climbing or skiing the body generates a lot of heat. On the other hand, the body cools down really quickly while resting in cold conditions. It is recommended to put on a fat, synthetic insulation jacket immediately while taking a break, to prevent the body from rapidly cooling off. Then, take it off again right before you start moving again. Effectively, you always have to be carrying an extra jacket around while being active in the cold outdoors. Wouldn't it be nice to make an insulating layer that can adjust itself to maintain a thermal equilibrium over a larger range in temperature?

Thermometer test clothing

To get more clarity on the levels of temperature maintained inside a jacket while outside, I took my thermometer out for a stroll in the park. The outside temperature that day was 8°C and I was wearing my warmest jacket, a Patagonia parka. The thermometer was placed inside the inner pocket close to the heart, which is placed in-between the insulation layer and the shell. I walked for about thirty minutes and I felt comfortable all through; not too hot, not too cold. Afterwards the maximum and minimum temperatures were verified. During my walk the temperature varied between 16,5°C and 19,2°C. Clearly the conditions were not very extreme, but what can be conducted from this experiment is that the comfortable temperature inside the insulation layer of a jacket corresponds closely with the settings of the home thermostat.

Although this may be true the physical effort exerted during walking not is not comparable to the more extreme sports like climbing or skiing. Imagine doing jumping-jacks in the living room with a room temperature of 21°C, Therefore, the assumption is made that the comfortable thermal values during more extreme activities will be lower. Further research has to be conducted to prove this assumption and determine the right temperature value boundaries at extreme physical effort levels.

Air is one of the best insulating "materials" due to its low thermal conductivity and its superb mobility. Therefore, it would be a shame not to use it to my advantage in the future concept design. By analysing the expert's ideas on how to dress properly for rough outdoor conditions the layering system was derived. In this layering system the mid-layer, or insulation layer is the one keeping the user warm, by trapping air which is then heated by the body. Consequently, this layer shows potential opportunities to apply my design vision on.



1.9 **TEXTILE** EXPERIMENTATION

Tinkering with textiles

The goal of this project is to create a thermally self-regulating fabric that can vary in thickness, using shape memory alloys. But since the austenite temperature and the martensite temperature are regularly quite far apart from each other, another force is needed to counter the shape memory alloy to make the structure fold open and increase in thickness and close again.

To figure out how this works in reality, prototyping and making samples is the way to go. The goal of this explorative process is to find a material, or a combination of materials that can change from 2D to 3D (increase thickness) and can be implemented in garments.

Paper prototypes

This basic first experiment focussed primarily on folding a shape that could transform from flat to three-dimensional. The book Folding techniques for Designers, by Paul Jackson gave me a lot of inspiration. Making paper prototypes that could move from a 2D sheet to a 3D made me see that a lot is possible. It is very hard to imagine this without getting your hands dirty.

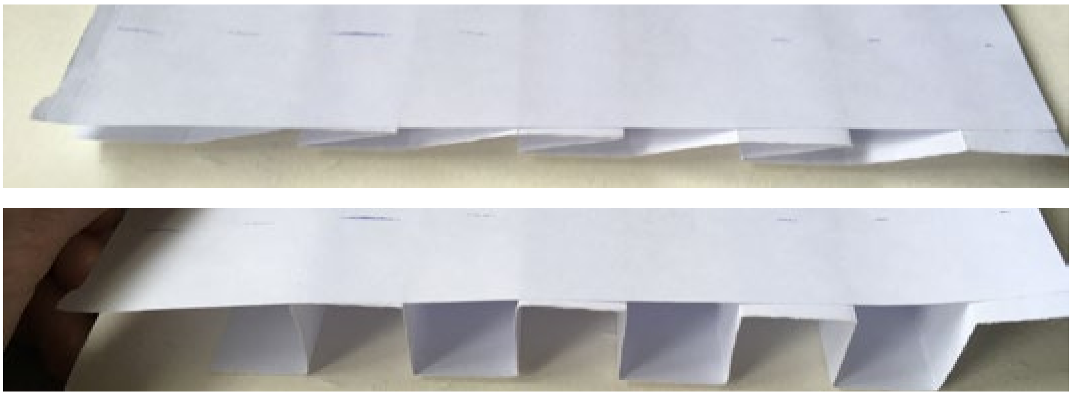


Figure 16 Paper prototypes

Shape exploration on Lycra

After studying the basic principles of transforming a 2D surface into a 3D structure, the step was made to textiles. My inspiration for this exploration came from seeing a video from Tessa Petrusa, about het 4D printed responsive tactility skins . She uses a flexible fabric, which is put under tension while a shape is being 3D printed on it. After releasing this tension, the shapes start to bend creating very beautiful organic curves.

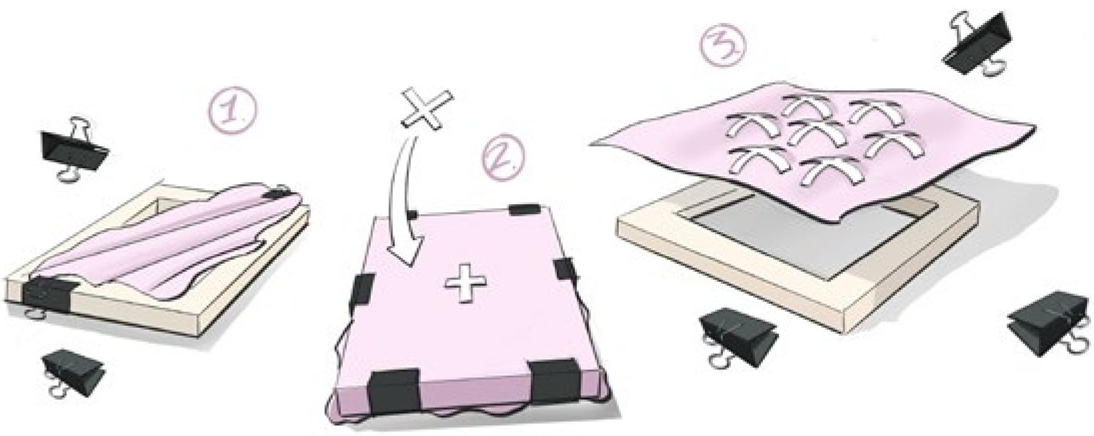


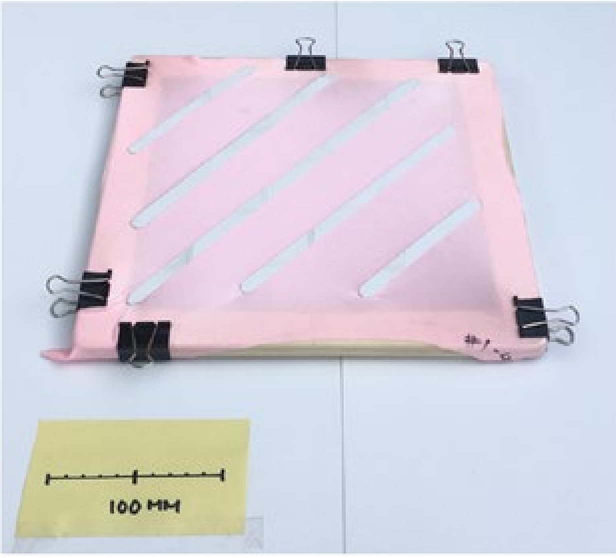
Figure 17 Process shape exploration on Lycra

HOW THE PROCESS WORKS

1. The stretchy fabric (Lycra) is tensioned on a framework using clamps.
2. The shapes are attached while the fabric is under tension, either by gluing, stitching or ironing.
3. The fabric is release from its tension, while the tension under the shapes is maintained making the structure expand in the vertical direction.

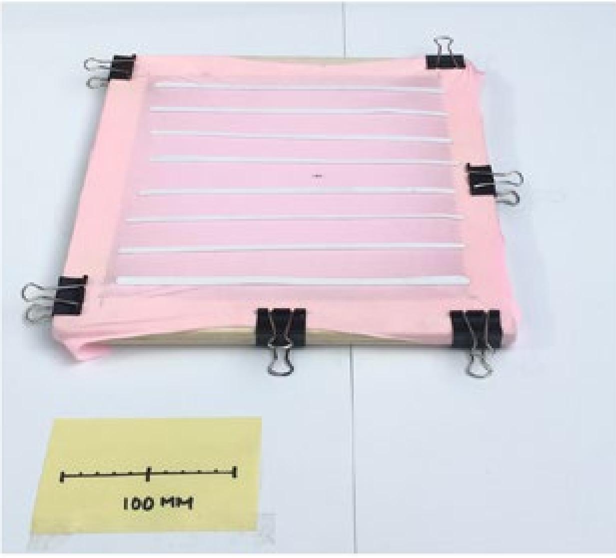
A form study was done to explore the most effective shapes to create an increase in thickness of the textile, while maintaining the original size and shape of the textile as stable as possible. Various shapes were cut out of poly-sheet and glued onto Lycia which was put under tension beforehand.

Test 1.1 Shape: Strips	Materials: Lycra + PVC 1mm Bonding method: Textile glue



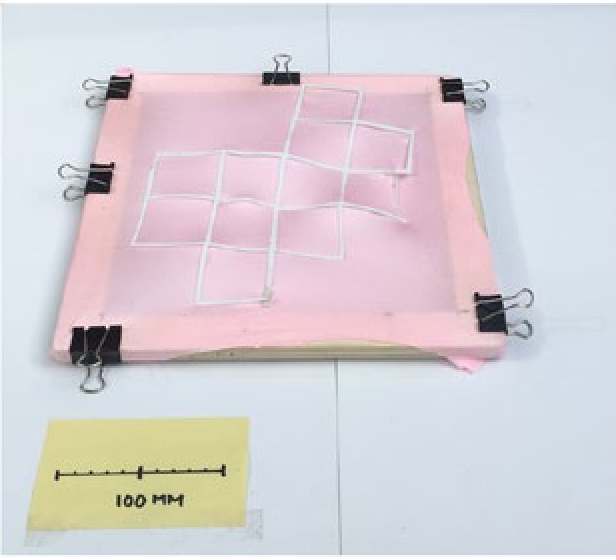
Five long strips of 10mm wide are glued onto the Lycra under tension. In the unloosened situation the longest strip generates the largest expansion. The piece of fabric remains close to its original shape because the strips are applied at a 45-degree angle on the 4-way directional tension.

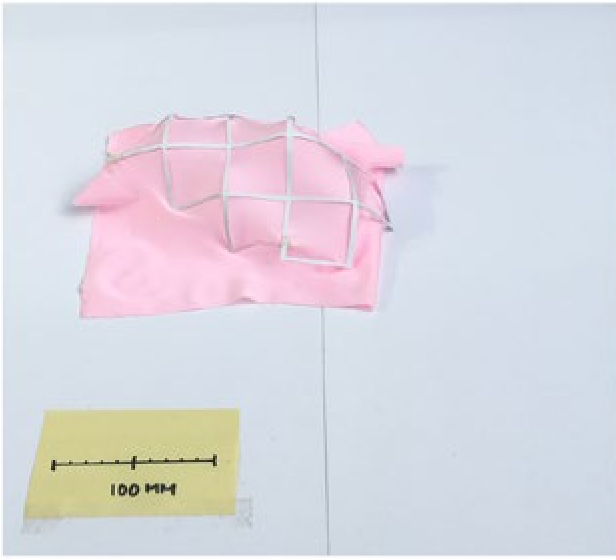
Test 1.2 Shape: Strips	Materials: Lycra + PVC 1mm Bonding method: Textile glue



Eight less wide strips of 3-4mm are applied parallel to the horizontal tension, to see if the strips would generate a larger curvature. In this sample it is clearly visible original size of the fabric shrinks a lot in the vertical direction. This is because only the width of the strip is maintaining the applied tension under the shapes. Another interesting observation is that the curvature of the two most outer strips is larger than the others. This is because the fabric was mounted on the frame from corner to corner, making the tension closer to the edges of the fabric larger. Additionally, the majority of the vertical tension is caught by the outer strips.

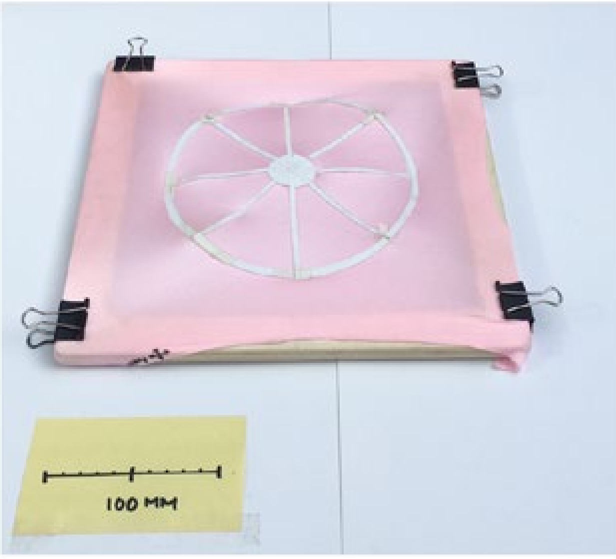
Test 1.3 Shape: Cubical structure	Materials: Lycra + PVC 1mm Bonding method: Textile glue





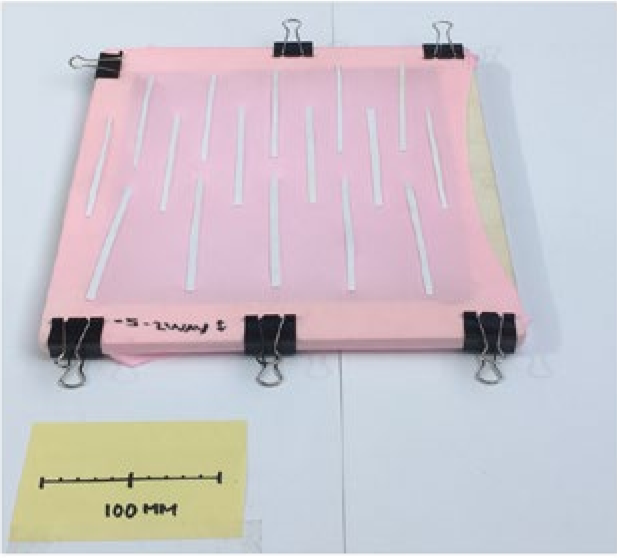
The reason for test 1.3 to was see which effect a larger interconnected shape would have on the textile. The result is a giant dome-like structure that is very unstable and uncontrollable. The tension remains the same under the entire shape after removing the frame, making it behave as a unit. The instability of the shape was mainly caused by its asymmetrically distributed pattern. Besides, the squared pattern has very sharp corners which will cause discomfort for the future user.

Test 1.4 Shape: Wheel-like	Materials: Lycra + PVC 1mm Bonding method: Textile glue



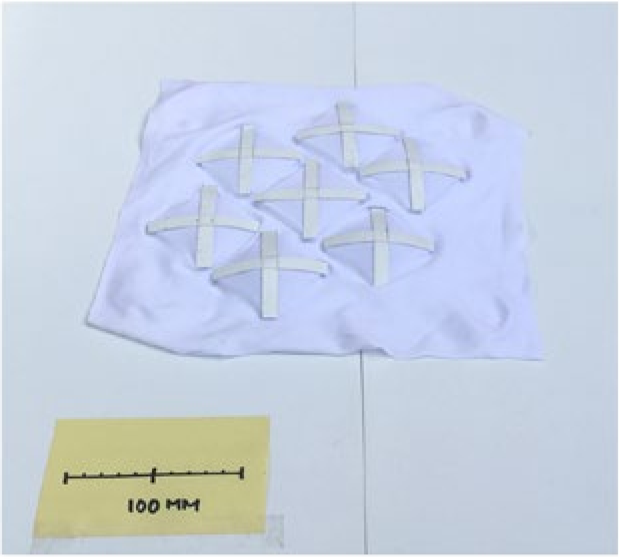
To see if asymmetry is a problem and to get rid of sharp corners a wheel-like shape was designed and tested. While the shape was being cut out some interconnections of the shape where cut by accident, and later fixed with tape. This made the shape more unstable, which created the hard folds in the plastic, visible in the frame-less situation. However, this sample shows some special behaviour. By accident a plop-in, plop-out effect was created that is interesting for further development.

Test 1.5 Shape: Strip structure	Materials: Lycra + PVC 1mm Bonding method: Textile glue



The interconnected structures did not result in an efficient solution for a controlled way of expanding the textile, therefore a new structure was designed consisting out of individually bending elements. Short strips of 4X80mm were applied in an alternating stacked composition in the vertical direction. The result is a very continuous in its curvature and astatically pleasing. However, the tension in the horizontal direction still causes the fabric to shrink a lot in the horizontal direction. This resulted in the realisation that the individual shapes needed to be able to catch the tension in all four directions, instead of only two directions.

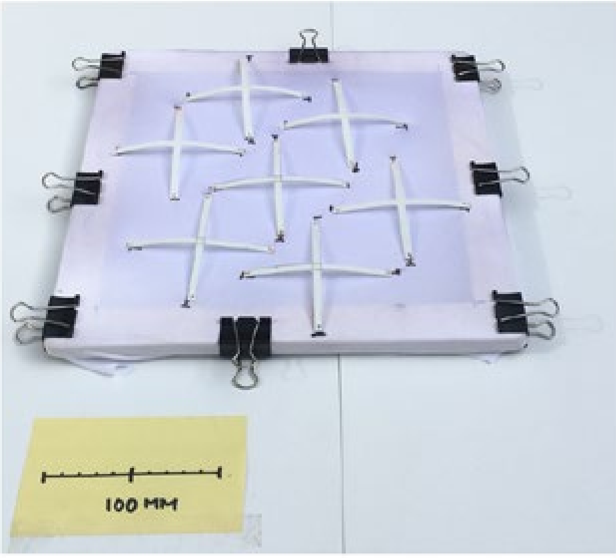
Test 1.6 Shape: Cross	Materials: Lycra + PVC 1mm Bonding method: Textile glue

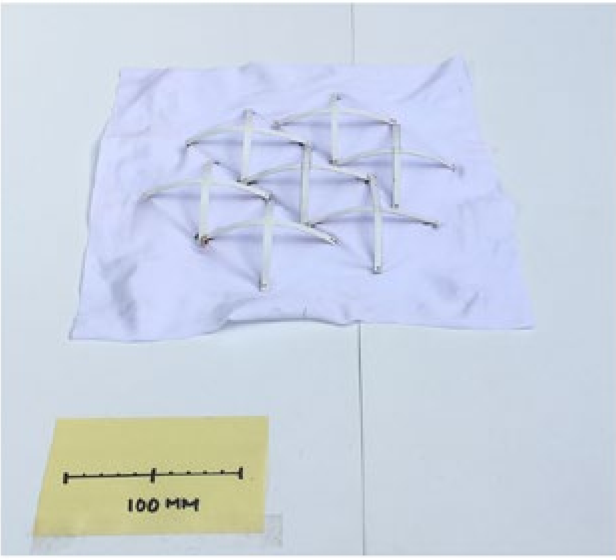


The individual cross shapes catch the applied tension in all four directions, which makes the fabric maintain its original shape while creating an increase in volume under the shapes. This sample shows a very neat and controllable distribution of the desired effect, creating individual air pockets, or cells within the textile itself. However, the crosses are a bit over-dimensioned causing the shape to be too rigid to properly allow the structure to bent properly. This sample is the first of many to come, because this shape is a potentially good solution to make a textile move from 2D to 3D.

Test 1.7
Shape: Cross

Materials: Lycra + PVC 1mm
Bonding method: Stitches by hand





The width and length of the legs of the crosses were adjusted in this test to increase the expansion value. Also, the bonding method was changed to examine the effect this would have on the fabric. The four ends of each cross were attached to the fabric using needle and thread. The effect this gave was that the intended increase in thickness of the fabric by creating air pockets was now taking place between the shape and the textile, instead of underneath it. As in the former cross sample the textile perfectly maintained its original shape and size. However, this method proved itself to be very labour intensive, and hard to optimize for production.

Generally speaking the cross-shaped plastic parts give the best results, because they are able to catch the tension from all four directions creating nice individual compartments. This reaction can be tweaked and finetuned by either playing around with the dimensions, material thickness, material type, bonding method, or by varying the initial tension in the fabric.

Tule tests 3D print

To increase the precision of the application of the plastic and play with the dimensions, another experiment was done that involved 3D printing on tulle and Lycia tulle. Tulle is a synthetic textile with a lot of small holes in it. This is perfect for 3D printing because it lets the plastic flow through the small holes, making it possible to connect and melt shapes together on both sides of the textile. During these tests the printer was paused at a certain layer height, then the tulle was fixed on the printing bed, thereafter the print was continued. This made the plastic shapes grab into the textile in a solid and neat manner.

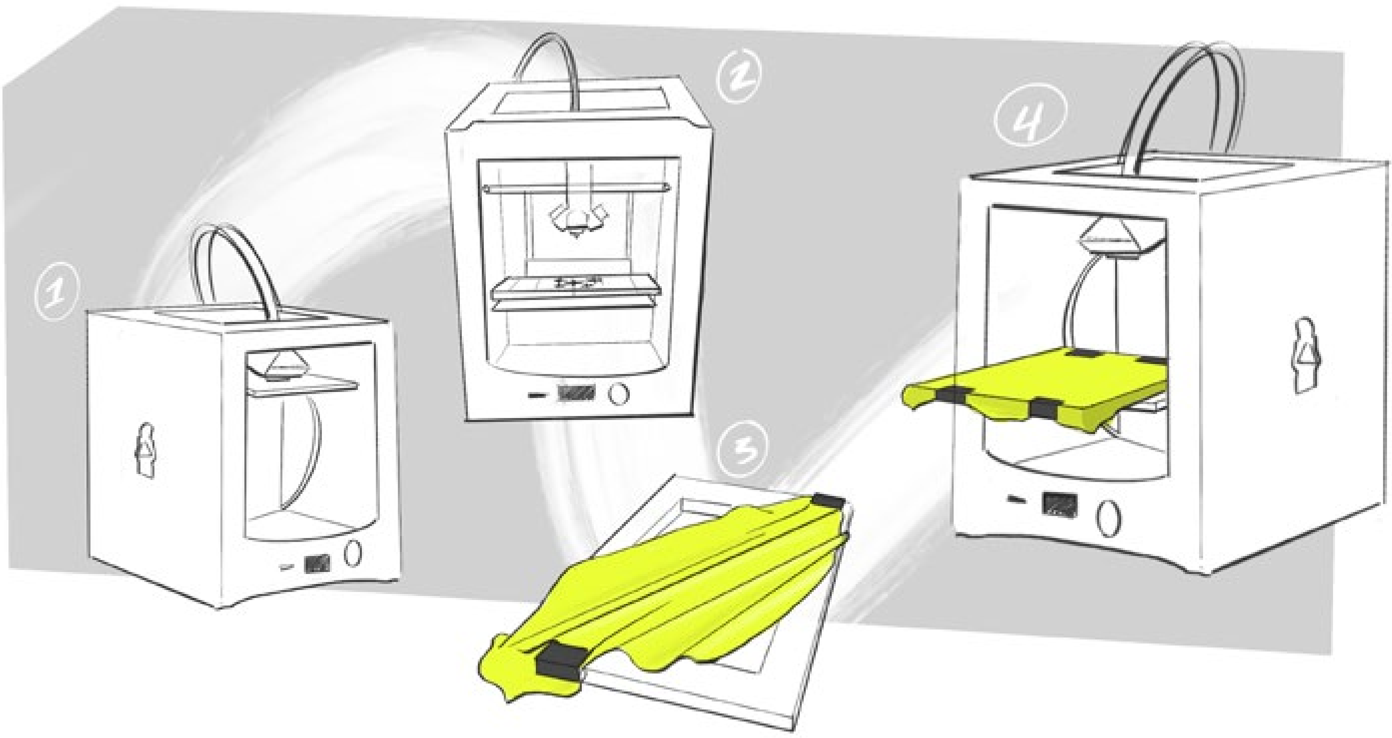


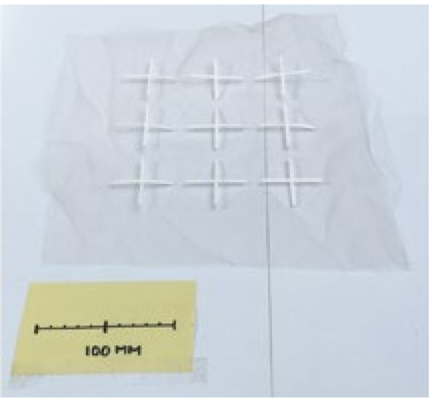
Figure 18 3D print test on Lycra tule

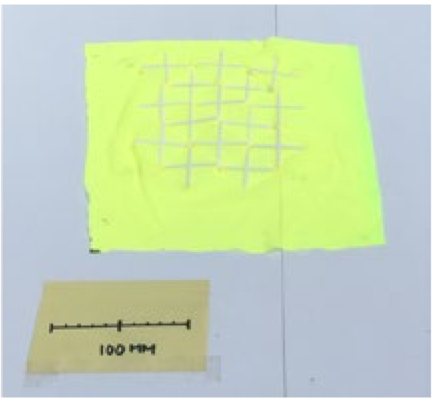
HOW THE PROCESS WORKS

1. Start the print
2. Pause print at desired layer height and make sure that the parts that need to bond the plastic to the fabric are not completed yet
3. Tension the Lycra tulle on a frame that fits over the print bed
4. Resume the print and wait for it to finish

Test 1.8, 1.9 & 1.10
Shape: Cross

Materials: (Lycra) Tulle + PLA 0,8mm
Bonding method: Additive manufacturing



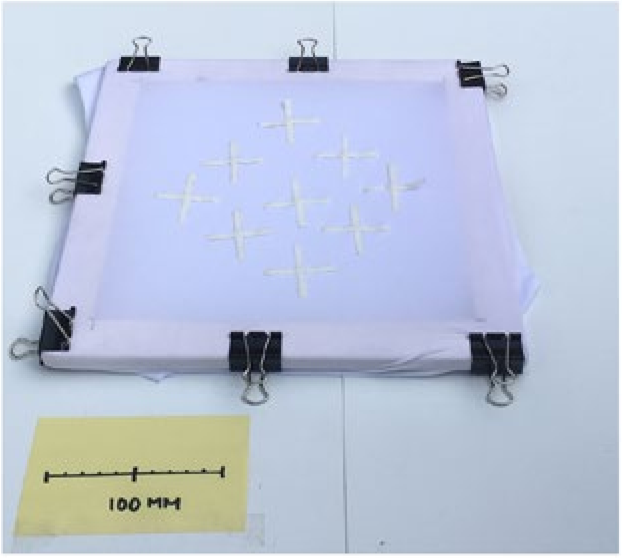


It was really difficult to get the textile nicely tensioned inside the 3D printer, which led to little deformation in the plastic parts. On top of that the discovery was made that the PLA did not have the right sensory quality to be worn as a garment and could break, or plastically deform to easily. Therefore, the search began for a more flexible and forgiving material to replace the poly-sheet and the 3D printed PLA, used so far.

Material exploration

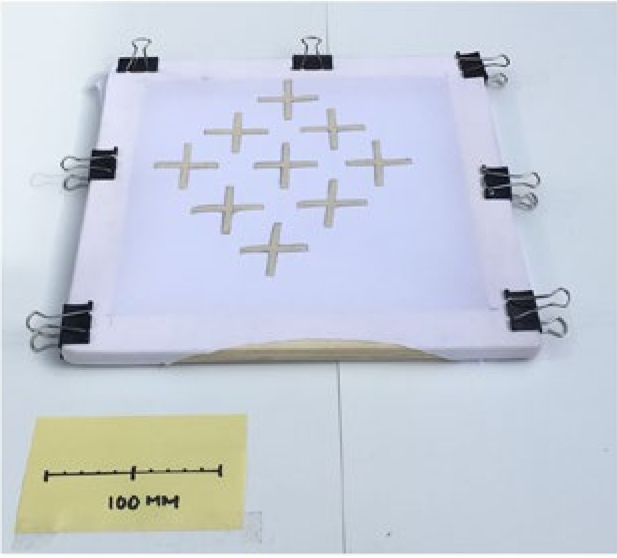
With the cross shape established as the best way of expanding the stretchy fabric, another study was done to see which material combination works best for this concept. The plastic shapes cause three problems, the first being the sensory quality. It is too hard and sharp to be implemented in a garment. Secondly the plastic is sensitive to irreversible deformations or even break that can occur when the textile is folded. Lastly, the production of a textile will become drastically more complicated, due to difficult bonding and alignment issues. Unrevealing the best material combination is important for comfortability, lifetime and producibility.

Test 1.11 Shape: Cross	Materials: Lycra + Fleece line (thin) Bonding method: Ironing



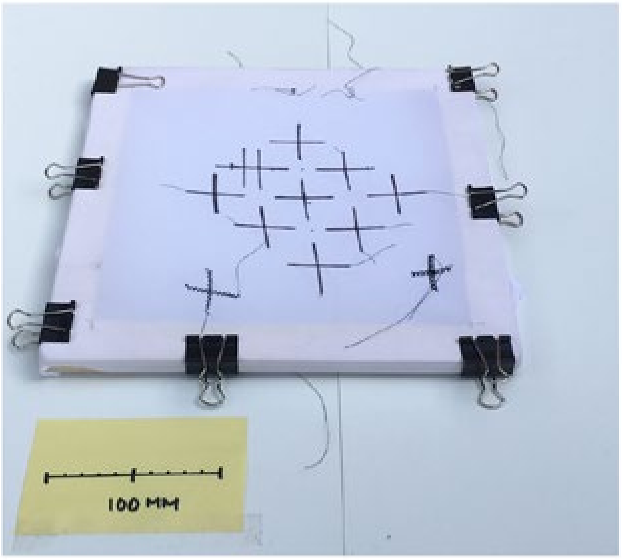
This sample shows that the rigidity of the shape is not important to create an expansion of the fabric. Additionally, this combination's sensory quality drastically improved compared to former tests where plastics were used. Fleece line is a material that is often used in garments to create more support in sensitive areas of a garment, like pockets or collars. Therefore, the material is optimised to blend well with any textile in terms of flexibility and softness. The fleece line used in this sample even had a special layer of glue incorporated to simplify application through ironing it on. The curvature of the crosses in this sample are too large, making the outer ends of the legs bend inwards. This means that when the rigidity of the shape is less, also the initial tension on the Lycra needs to be decreased.

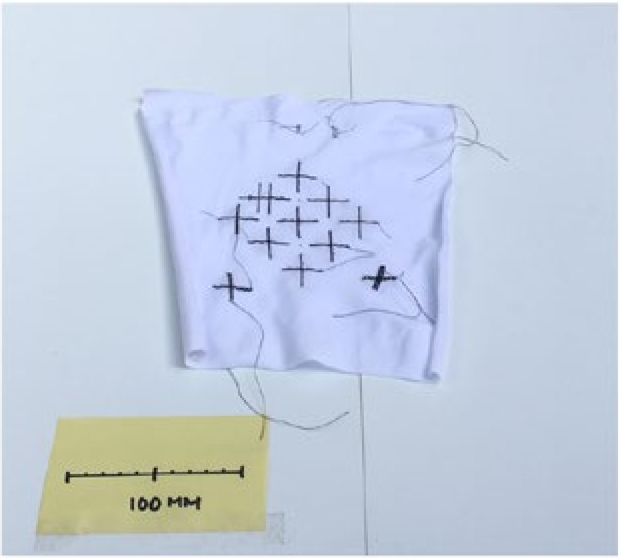
Test 1.12 Shape: Cross	Materials: Lycra + Fleece line (thick) Bonding method: Ironing



Sample 1.12 and 1.11 are much alike, only the thickness of the fleece line is changed. This sample felt a less flexible and soft than sample 1.11. However, the small individual compartments created by the small crosses make the fabric curve nicely around the body. A downside of the thicker fleece line is that it is more shape-retaining when folded. This could cause deformation over time and cause life-time issues.

Test 1.13 Shape: Cross	Materials: Lycra + Thread Bonding method: Machine sewing

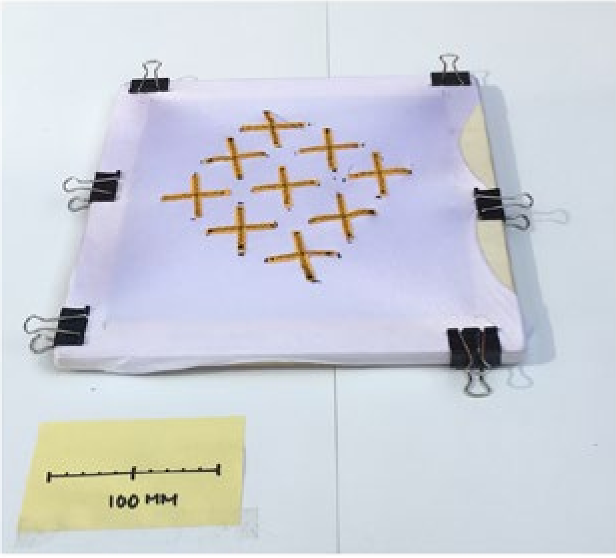




While I was discovering all the features of the sewing machine, this sample was made trying to use special stiches to maintain the tension under the shapes. Sadly, there was no stitch that could do this, which proves the fact that an extra martial is needed to create the intended 3D effect.

Test 1.14
Shape: Cross

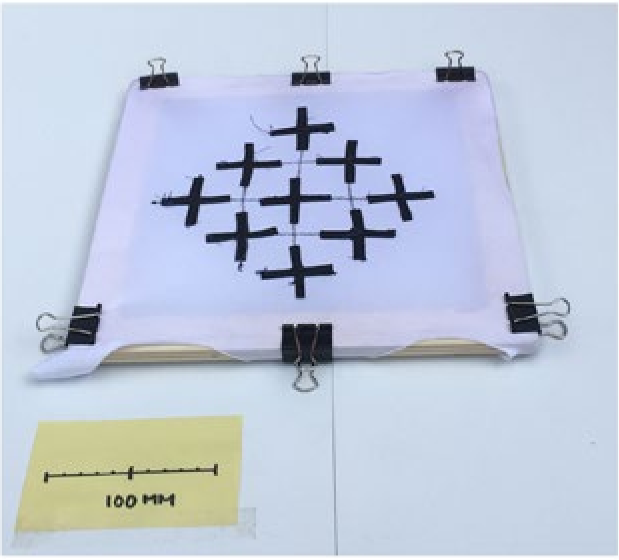
Materials: Lycra + PVC coated nylon
Bonding method: Machine sewing



Each cross in sample 1.14 was individually sewed with the sewing machine using a zig-zag stitch. This stich almost covers the entire width of the crosses ensuring an optimal bonding to the fabric. The PVC coated fabric behaved nicely and gave the intended effect. The finishing feels a bit rougher than the fleece line, but the material is way less susceptible for nod.

Test 1.15
Shape: Cross

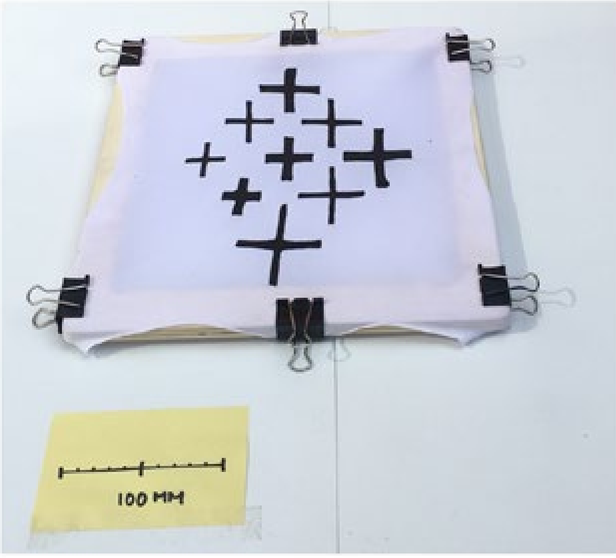
Materials: Lycra + Nitrile rubber 1mm
Bonding method: Machine sewing

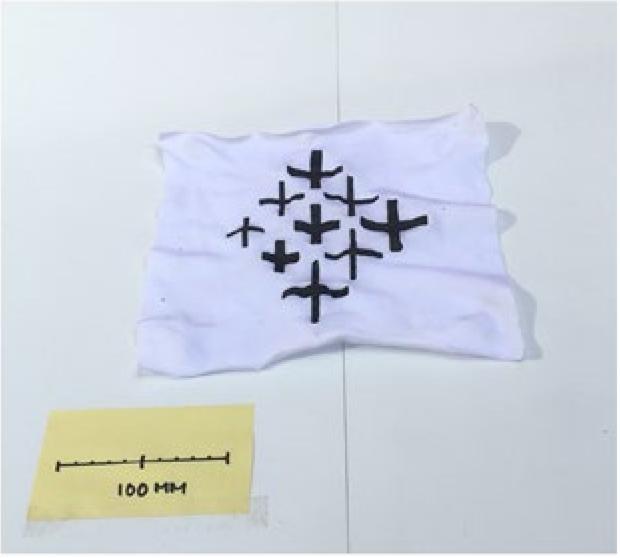


The rubber gives the best sensory quality so far and behaves nicely. However, a material thickness of 1mm might be too much, because it makes the sample much heavier. In this sample continues stitching was applied to see if this would influence the behaviour of the fabric. Since only sewing did not lead to any 3D effect (sample 1.13) my expectations were that this should not lead to any implications, and it didn't. This is a huge advantage for production, because it saves a lot of time due to the continuous thread.

Test 1.16
Shape: Cross

Materials: Lycra + liquid rubber (thin)
Bonding method: casting onto fabric

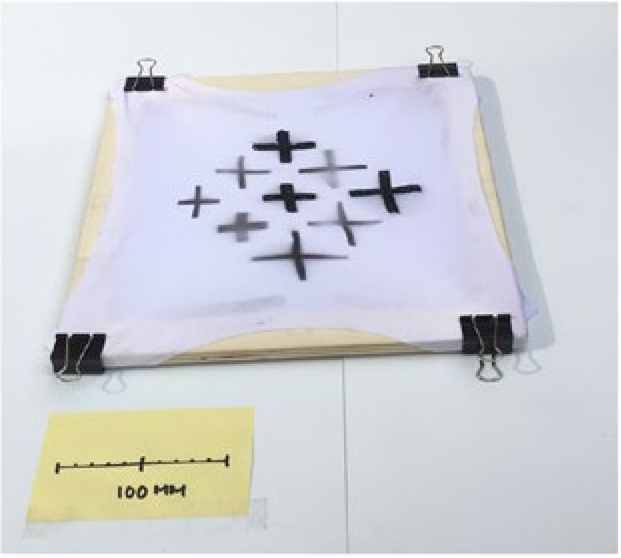


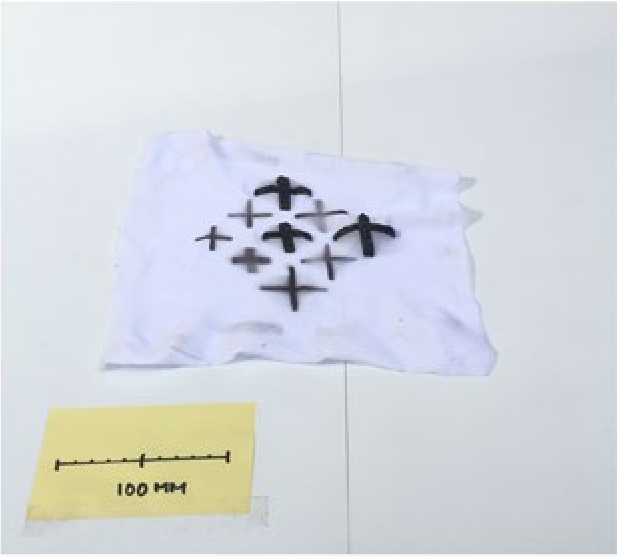


Since rubbery material seems like the way to go for this concept, a different form of liquid rubber was tried that is normally used to make roofing watertight. The idea behind this experiment was to optimise the production process. The process is very similar to silk-screening, a technique often used on garments to create prints and visuals. Beforehand, a stencil mould was made of the pattern, which was later used to paint over using a paint roller. However, this sample did not work out. The reason behind this is that the rubber was applied way to thin, which made it shrink together with the textile, not creating an arc.

Test 1.17
Shape: Cross

Materials: Lycra + liquid rubber (thick)
Bonding method: casting onto fabric

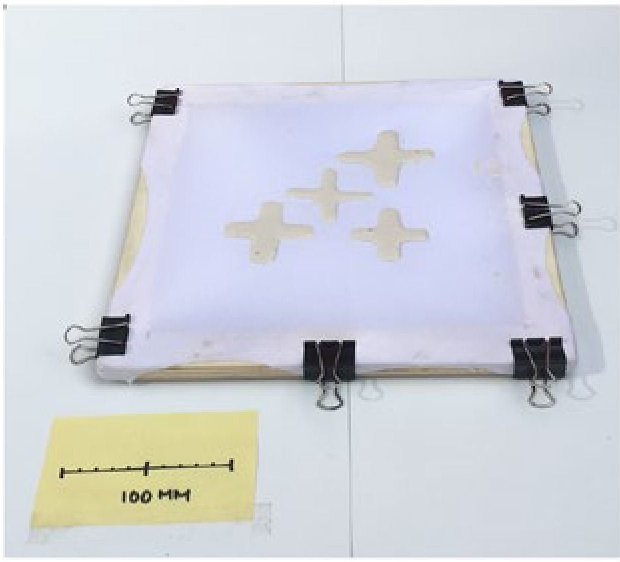




In this sample the same liquid rubber was used but this time applied with a larger thickness. Due to the stickiness of the rubber it is very hard to get it evenly distributed. This causes the shape to be less stable and bend at thinner points. Even after drying the rubber remained very sticky, which is not acceptable. Therefore, the liquid rubber was considered as inappropriate for this concept.

Test 1.18
Shape: Cross

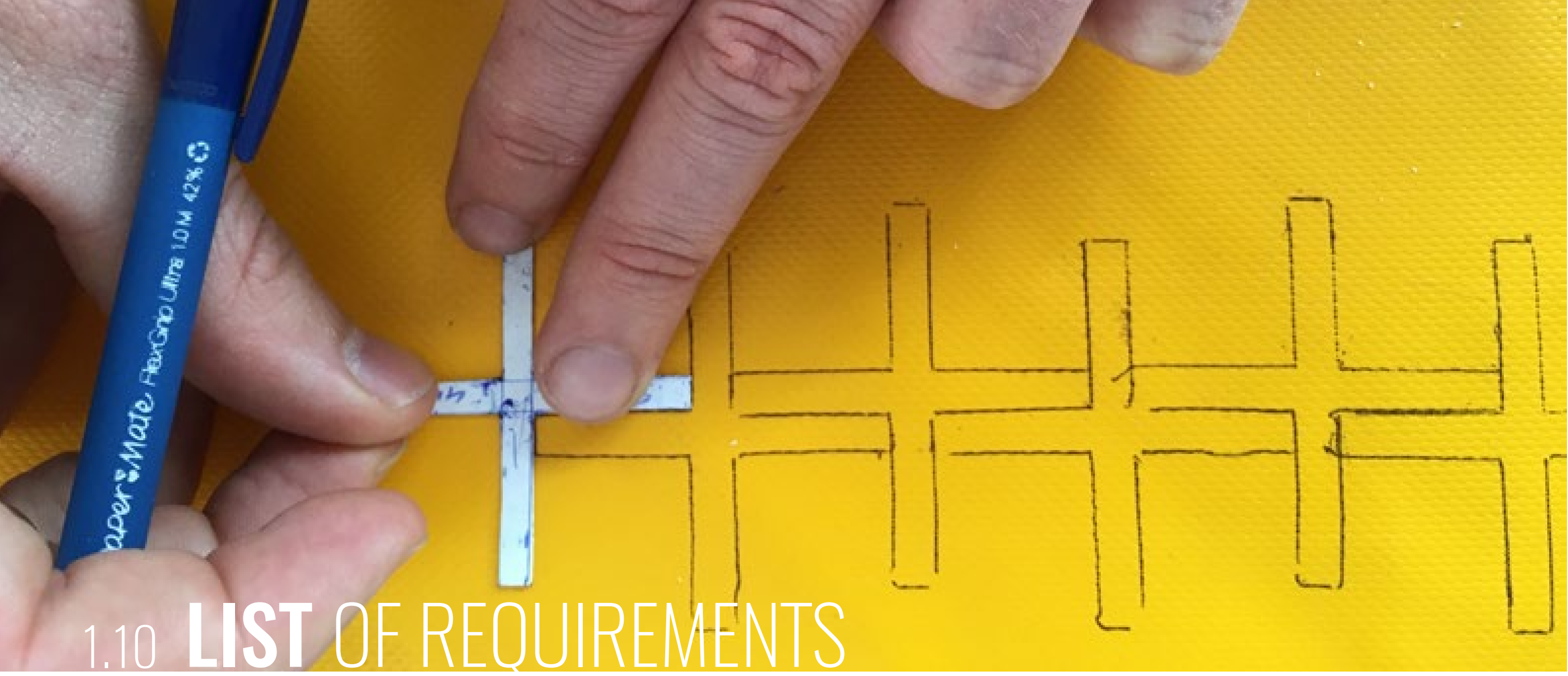
Materials: Lycra + Silicone rubber
Bonding method: casting onto fabric



Sample 1.18 was made with silicone rubber and a cardboard mould. The mould was quickly removed after applying the silicone to ensure a proper release, which made the shapes expand a little bit, because the silicone was not yet hard enough to maintain its shape. The 3D effect works as intended, and the sensory quality of this sample is very nice and soft. The shapes are bonded to the Lycra really well because the silicone is applied in fluid form, which makes it creep through the fibbers a little bit before hardening. Additionally, the roundness of the hardened silicone rubber makes the shapes more durable, compared to former samples, because it gets rid of sharp corners which are very stress sensitive. However, the sales man warned me about the fact that washing silicone might be a problem, this still needs to be tested.

To conclude, the ideal material for the shapes of this concept is rubber-like. The flexibility, toughness, softness and its shape-retaining ability are perfect for processing it in a piece of clothing. Also, the shapes need to be rounded-off more to increase wearing comfort and decrease stress sensitive points. However, in the next phase of this project a step back will be done to look at other ways of creating a shape change from 2D to 3D in textiles. The development of this concept made me engage into the world of fabrics and gave me much insight on how to construct and combine different mediums.


#5.2WAY



1.10 LIST OF REQUIREMENTS

The product needs to meet

The list of requirements defines the boundaries a product needs to live up to. If one of the requirements is not met by a concept the concept is not valid. The wishes are a bit more forgiving, they illustrate the less explicit goals that designers strive for during product development. The wishes can also help designers a lot while choosing a concept, the one that lines us best with the wishes often is the best choice.

As this project is about the creation of a new application for SMA's from the ground up, the list of requirements is still very elemental. The longer the product development track takes the larger and more detailed the list of requirements gets.

List of Requirements

The SMA must:

- Start contracting when colder than 22°C
- Start expanding when warmer than 12°C
- Be loaded in the strain direction
- Have an active area of 3-5% of the total length
- Perform over 10000 cycles
- Be used in smal quantities

The unit must:

- Be compression restoring
- Be washable
- Working components must be reachable to carry out maintenance
- Withstand outdoor temperatures from -40 to 50°C
- Close by force provided by SMA wire
- Open by counterforce
- Be water resistant

The fabric must:

- Dry quickly
- Be synthetic
- Be flexible

Final prototype must:

- Increase air gap 200% in thickness
- Be activated with electrical current
- Show the working element

List of wishes

The concept design must:

- Be as light as possible
- Use as little SMA wire as possible
- Be adjustable in temperature
- Not wrinkle
- Look futuristic
- Not hinder the user while moving
- Inspire designers and show the possibilities of SMA's

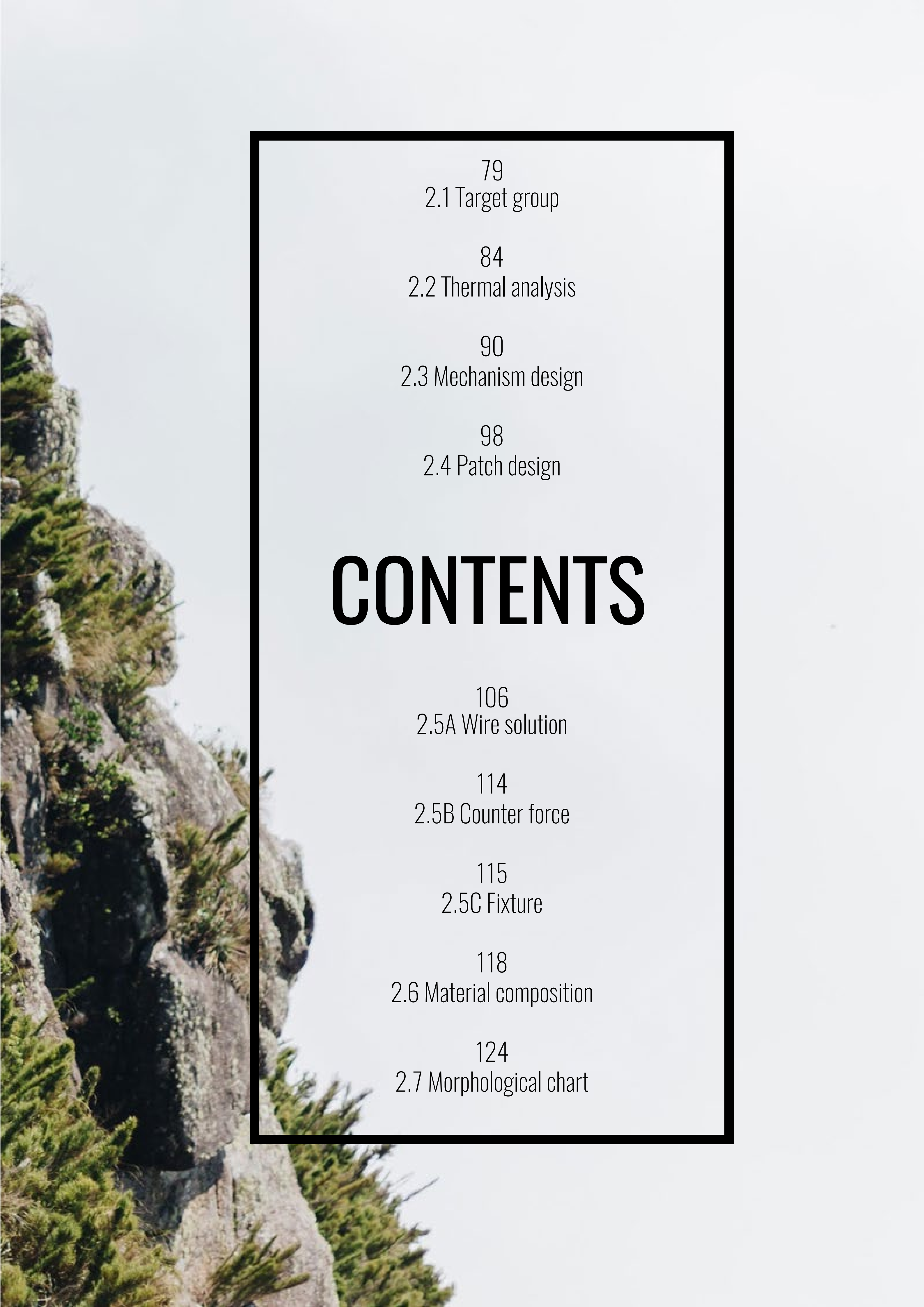
END OF ANALYSIS PHASE

Learning about both shape memory alloys and textiles first hand has been very clarifying for my project. Likewise, it helped in forming a design vision on which the rest of the project will be focused from now on. "Integrating shape memory alloys and textiles to create a thermally self-regulating garment that increases in thickness when exposed to cold temperatures and decreases in thickness when exposed to warm temperatures."

A lot of questions might arise when reading this sentence, like: How to increase thickness? How cold and how warm? How are the two elements integrated? During the conceptualization phase, which will be the next phase of this project, answers will be provided to these questions through either testing or more extensive research.

The process of getting to know the two materials was quite rough because I started this project without any foreknowledge about both of the main materials and processing techniques. Therefore, I tried to create a large database of small physical models that helped me to getting to understand the materials in a structured way, constantly changing only one variable from one model to the next. Besides being a lot of fun this approach has proven to be very effective when exploring unknown territory.

CONCEPTUALIZATION



CONTENTS

INTRODUCTION

Concept phase

This part of the report will go into more depth on the development of the concept design. To do this the right way, firstly potential target groups will be established that could possibly benefit from this concept design. When the suited target group is defined the environmental factors will be analysed that the target group has to deal with. Consequentially, the working temperature range for the concept design can be further defined and the right alloys can be selected.

The concept design for this project will depend on five different factors that need to come together in one design. Sub-solutions need to be designed, determined, or tested for: the mechanism, the patch design, the wire solution, the counterforce and the system fixture. Furthermore, the materials need to be defined as well as the bonding methods for all the different elements. Each of these factors will be individually discussed in the following chapters.

All the sub-solutions will be mapped in a morphological chart to give an overview of all the possible solutions. This chart will help to point out the best possible approach to create comprehensive concept designs.

2.1 TARGET GROUP ANALYSIS

Who can it benefit

To make the concept design desirable, a certain target group needs to be taken into consideration. So far, the intended target group for this concept design has not been determined yet. The reason for this is that this project revolves more around a proof of concept, than a finished product. However, the need for some additional context will help a lot in the design process. The intended target group will add a lot of requirements and details to the design. By pinpointing the target group at this point of the project, avoids overlooking a lot of details that could make or break the concept design which would otherwise be very hard to determine, or even neglected. Even though not all the findings might be integrated in the concept design, they will at least be translated and taken into account when formulating the recommendations later on.

Figure 19 Possible target groups

The possible target groups that arose during the analysis phase, which fit the design vision the most, can be categorised in three groups:

1. Sports (runners)
2. Outdoor enthusiasts (hikers and mountaineers)
3. Professional workers (forklift driver entering and leaving cold room)

Gear Analysis

The people in all three situations get to deal with large temperature differences, which makes it possible for the SMA's to work independent of any additional input apart from the combination of environmental and body temperature.
To discover the importance of clothing for each different target group, the recommended gear for the activity was analysed.

Runner

The most important functions for running gear:

- Stay Cool
- Lightweight
- Quick Dry

A runner goes out for a run for 20-60 minutes on average. Compared to hiking or a working day this is quite short. Running is the most physically demanding activity of the three and therefore the body produces a lot of heat. The heat is released as sweat an absorbed by the clothing, which then needs to dry quickly to keep the garment airy.

Figure 20 Runner clothing composition

Also, the main functionalities of the garment combination were derived by clarifying the role of each clothing item worn by the user. The main reason of this gear analysis is to reveal implementation opportunities for the SMA embedded thermal regulation system. Additionally, it will support the decision in which garment and for which user the system is best suited.

Hiker

The most important functions for outdoor gear:

- Weatherproof
- Quick Dry
- Adjustable Layering System (Insulation)

A hiker usually goes out for a day or longer, which means the weather can change a lot during the activity. Therefore, it is important to wear an outfit that is adjustable to the weather conditions. The backpack is a unique item that stands out compared to the runner's and cold worker's gear but is essential for the hiker to bring supplies or optional clothing items along.

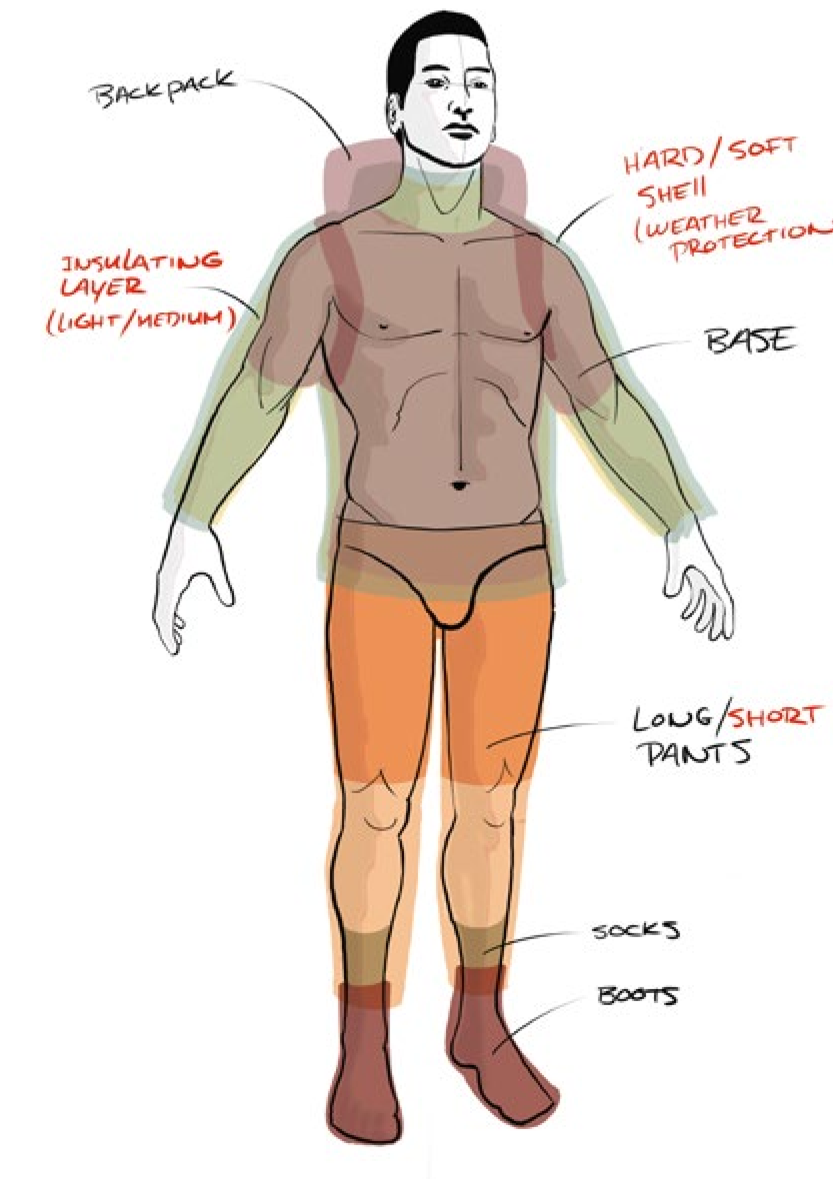


Figure 21 Hiker clothing composition

Cold Worker

The most important functions for cold worker gear:

- Stay Warm
- Enhance Safety (Protectikon Gear)
- Adjustable Layering System (Insulation)

The forklift driver can be seen as a cold worker if he/she is working inside a cold storage. Most of their 8 to 10-hour shifts will be spent in the cold storage. There are three different types of cold storage according to the European Pharmacopoeia: deep-freeze (-15°C), refrigerator (2-8°C) and cool (8-15°C) . The temperature inside the storage is regulated to be as consistent as possible to conserve the stored goods and is constant all the way from the racks to the trucks. This means that the cold worker does not get to deal with large temperature fluctuations during work, just when he takes a break.

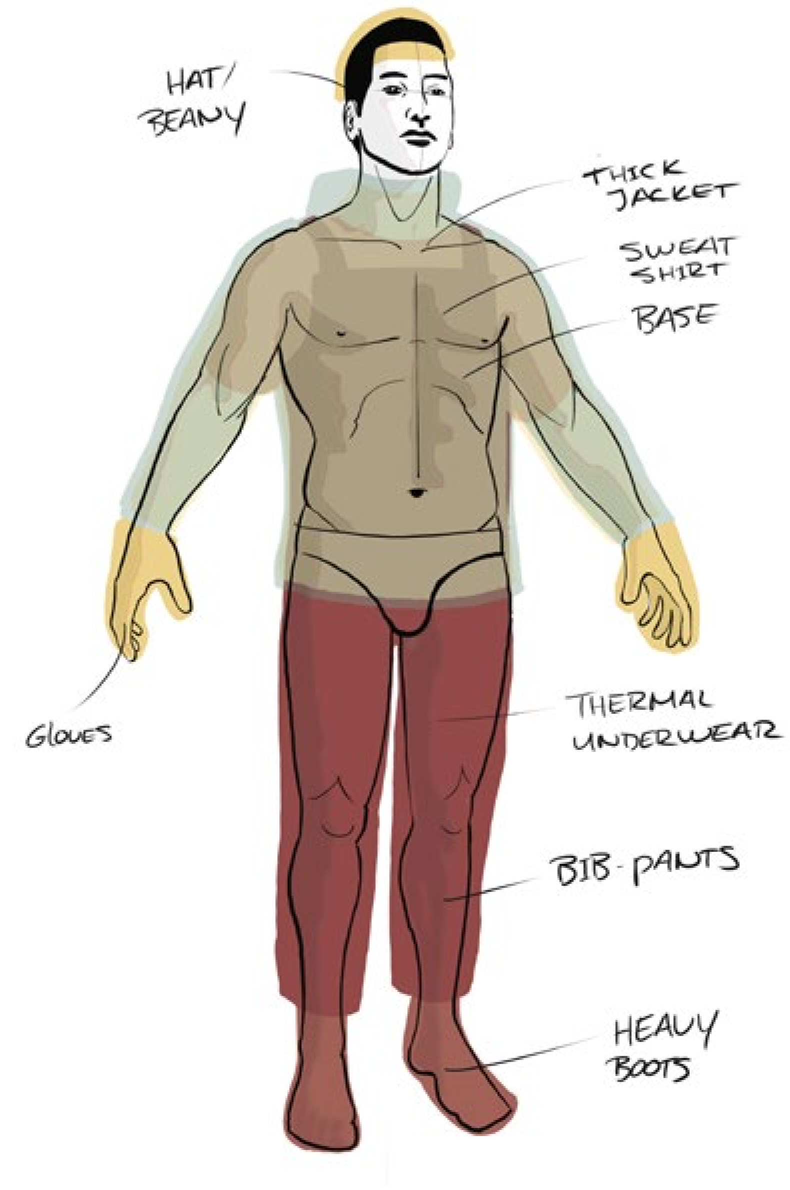


Figure 22 Cold worker clothing composition

Target Group Selection

The concept design revolves around a self-adjusting insulation layer that becomes thicker when cold and thinner when warm. Fluctuations in temperature are key to this concept design as it is meant to keep the user at a comfortable thermal equilibrium over a slightly larger range in temperature. Additionally, the concept design needs to be implemented in a clothing layer that is worn on top, because the mechanism needs to have the space to expand.

The cold worker gets to deal with fluctuations too little to make this concept design meaningful for this target group. That leaves the runner and the hiker. Looking at the gear compositions of these two different target groups there are two opportunities for implementation.

The first is the wind/rain breaker the runner might be wearing in rougher conditions, where implementation of the SMA embedded system might offer some benefits. However, the most important functionalities of the running gear are to stay cool and be lightweight. Extra insulation will not be desired by runners, because the physical activity they are exerting generates enough body heat to stay warm during a run. Also, the system will add some extra weight to the gear which will make running less comfortable.

The second implementation option is the insulation layer the hiker might be wearing when it gets a little chilly. The insulation layer is worn under the shell in very rough conditions, but when the weather is more forgiving the insulation layer of the hiker will be worn as a top layer. If we take a deeper look at the operating level of the hiking gear, we find that picking the right insulation layer (fleece) can be challenging. There is a large variety of fleeces available that range from light-, medium-, to heavyweight. The opportunity here is to create a fleece that works over a larger range in temperature and will eliminate the decision hikers have to make between a light- and medium weight fleece.

Conclusion

The concept design will be targeted to outdoor enthusiasts and will be implemented in the mid-layer of the gear composition that facilitates the insulation. The additional challenges that come with this decision and need to be kept in mind during the design phase are: the backpack (particularly, the chest and shoulder straps), the zipper, the pockets and the styling which should match current outdoor trends.

2.2 THERMAL ANALYSIS

establishing the active temperature range

The SMA wires that will be incorporated into the system will need to contract the insulating layer when the user is warm enough and open the layer when temperatures drop below a comfortable level. Therefore, it is important to analyse the temperature ranges the target group gets to deal with in order to make the right decision on what kind of shape memory alloy wire to incorporate in the design. Shape memory wire (NiTi) is commonly known to cover a range of transition temperatures from -100°C to 100°C.

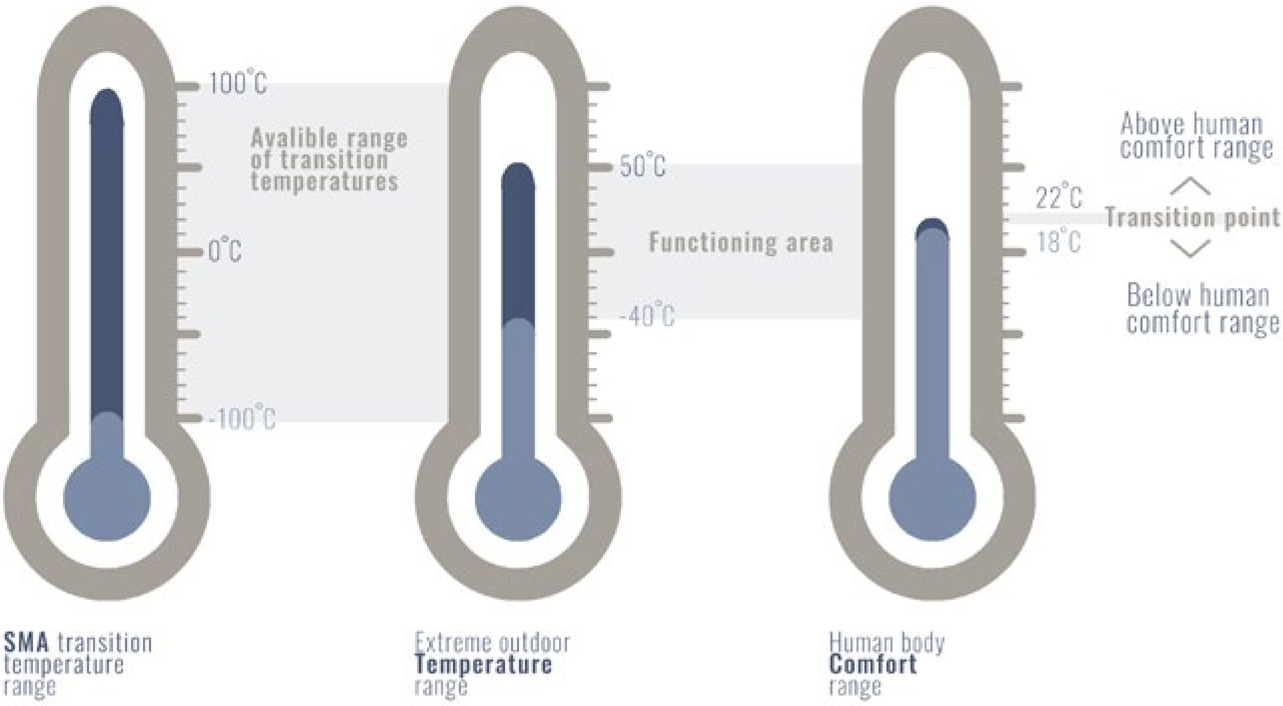


Figure 23 From SMA's to comfort

The functioning area will be the outdoors and extreme temperatures situations which can range from -40°C to 50°C. The comfortable temperature range for people to live in is rather small and can be derived from our home thermostat. Generally, the comfortable range is between 18 to 22°C. In Table 9 this theory is visualised without taking weather conditions, physical activity and clothing ensemble into consideration.

The design is focused on a mid-layer insulation layer that is worn during moderate, to heavy physical activity (hiking). The Clo-unit system discussed in chapter 1.8 (clothing insulation) was used to make an estimation of the hiker gear when the insulation layer is worn as a top layer (Table 9). Hiking gear without the shell scores 0,93 if all the values are added up, assuming the sweater equals 0,36. This means that when in complete rest, the body will almost reach a thermal equilibrium at an ambient temperature of 21°C (the Clo-value would then be equal to 1).

Clothing Item	Clo-Value
Briefs	0.04
T-Shirt	0.08
Socks	0.02
Boots	0.10
Sweater (long sleeve)	0.25 - 0.36
Trousers	0.15
Total:	**0.82 - 0.93**

Table 9 CLO-value calculation

There are two questions that need to be answered to make the right choice on what type of shape memory alloy wire needs to be embedded in the system:

1 Over what temperature range should the user wear the mid-layer when hiking?

2 At what temperature does the insulating value of the mid-layer become too little to maintain the user's neutral to slightly cold temperature sensation?

CBE Comfort Tool

The Center for the Built Environment (CBE) comfort tool was used to analyse this clothing ensemble, to provide an answer on the two questions above. This tool is actually designed to generate data on indoor climate control situations relative to clothing ensembles, but it also generates results that fall outside the designated policy area, namely the outdoors. The results of this test must therefore be seen as an estimation, rather than an exact indication.

The ambient weather conditions that were selected for this test were: air speed of 1,6 m/s (light breeze) and a humidity of 60% (average humidity during summer evenings) and the Clo-value for the outfit varied between 0,93 (outfit with sweatshirt) and 0.57 (outfit without sweatshirt). The metabolic values were set to match the walking speed of 3.2, 4.8 and 6.4 kmh, these values belong to the tool's standard options.

Figure... defines the transition range from slightly cold to cold, depending on the walking speed. The structure should be fully opened at 12.1°C to lower the transition point and prevent a cold sensation for all three situations. This means the wires need a theoretical austenite start value of 12.2°C, because the activated wire closes the structure gradually over the range. Opening the structure gives a better insulating value to the garment, which means that all the turning points will be experienced at lower temperatures by the user. This makes sure that the user will experience a cold sensation at a temperature lower than 3.2-12.1°C, depending on the walking speed.

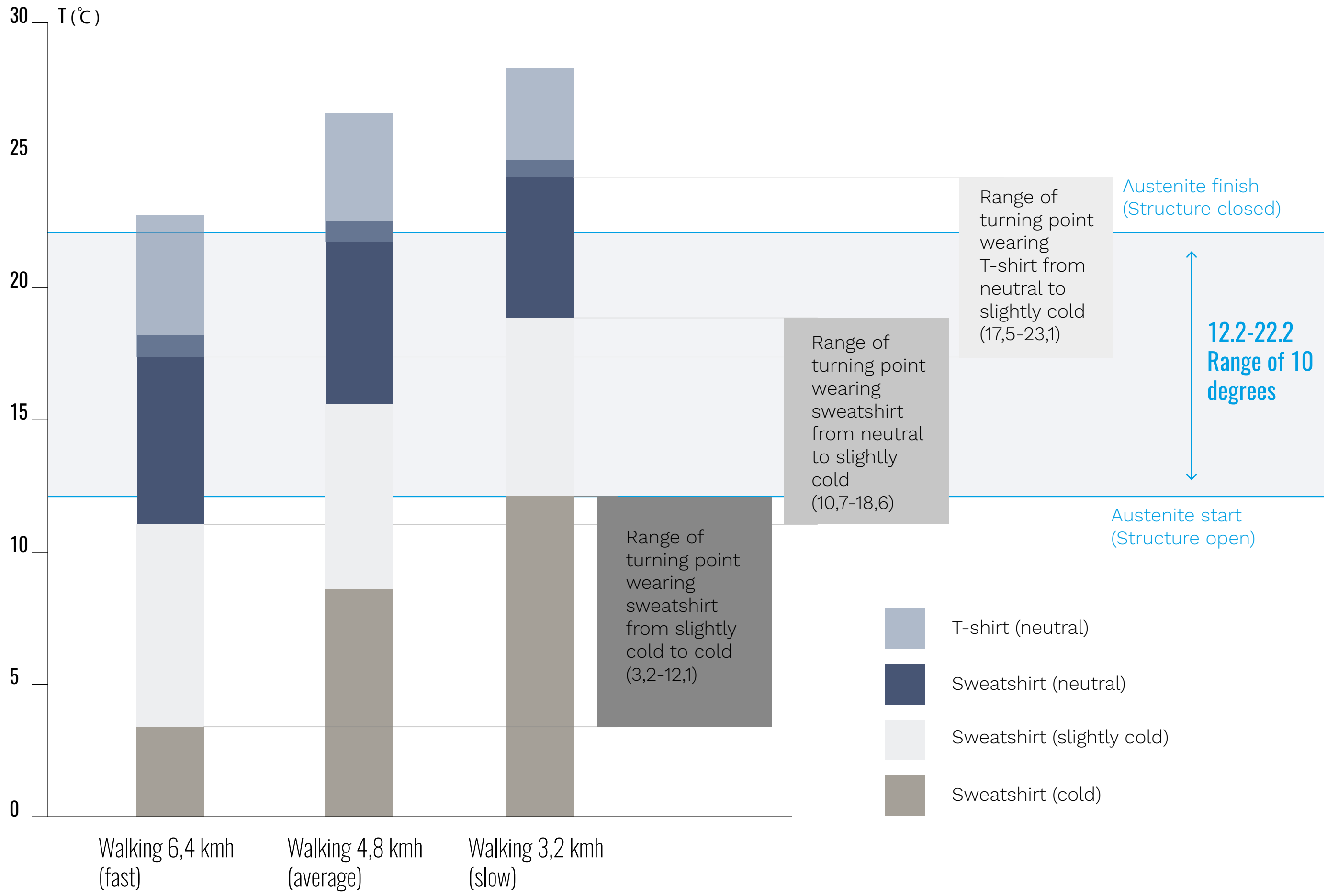


Figure 24 Thermal comfort during hiking

To optimise the system's response the wire should be placed on the outside of the garment, as close to the outdoor conditions as possible. The heat of the body can influence the average temperature in the wire because the garment is worn close to the skin (35°C). When the layer is open the wire moves further away from the skin where it will be less influenced by the body temperature. When the structure is fully opened the wire is below the austenite start temperature. When the outdoor temperatures exceed 12.1°C the wires will become active and start closing the mechanism. However, the closing motion will take place over a range of 10°C (Figure 24), which means the structure will be fully closed at 22.1°C, theoretically .

Thermal	IT Alloy	HT Alloy
Activation Start Temp. (°C)	68	88
Activation Finish Temp. (°C)	78	98

* Based on a Table from Muscle Wires Book, p.

Table 10 Standard Range of activation temperature

When the structure is closed and the wires are closer to the body, they will be influenced by the heat radiation emanating from the body. Therefore, the wires must be placed as exposed as possible to the outdoor conditions and if needed, insulated from the body heat. If the wires are excessively influenced by the user's body heat the opening of the structure will be delayed which will lead to a malfunctioning in the system.

Conclusion

the range in which the SMA's should be active is very specific and therefore unavailable in the standard market. It is possible to produce the right alloy, since the activation range is between -100°C and 100°C. However, ordering it at a specialised company would cost a lot of money and probably demands a very large order quantity. Therefore, the decision is made to use an alloy with a standard activation temperature of 70°C and incorporate electrical wires into the prototype of the concept design. By doing so the functionality of the prototype will be easier to test and demonstrate.

2.3 MECHANISM DESIGN

from 2D to 3D

The mechanism that will be incorporated in the design concept must be able to change from a 2D surface to a 3D structure. In Figure 25 a collage is displayed showing daily things and feelings that helped inspire the process of developing ideas for possible mechanisms. The brainstorm session based on this inspirational collage, led to eight different mechanisms. Four of these show a significant potential for further development and should be prototyped more extensively to establish which one is most suited to be incorporated in the concept design (Figure 26).

Figure 25 Mechanism inspiration

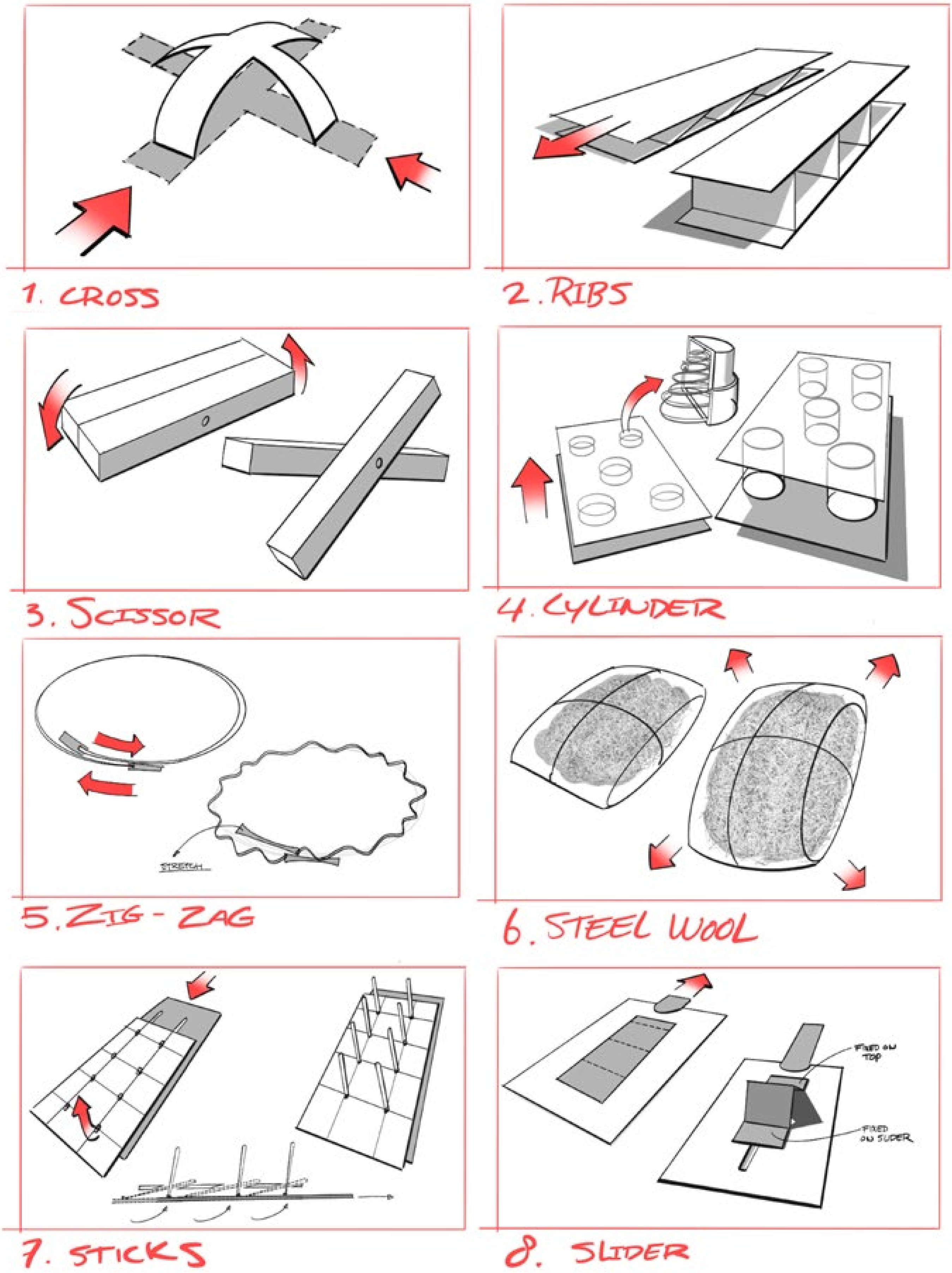


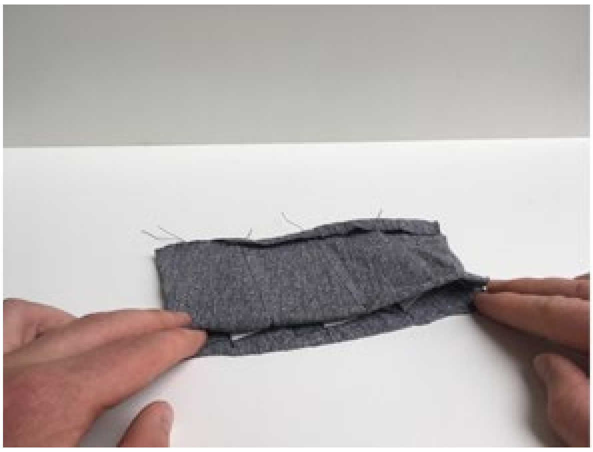
Figure 26 Mechanism concepts

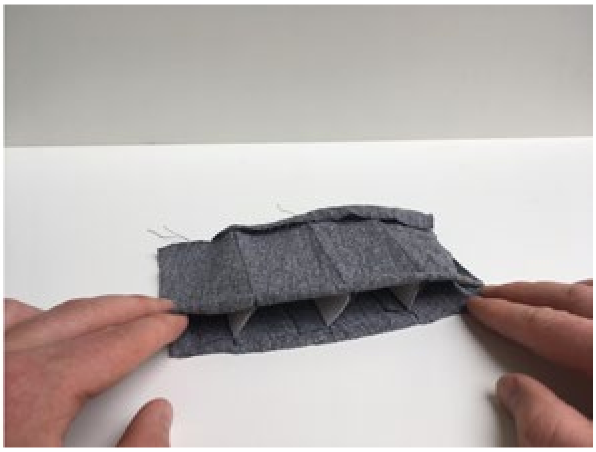
MVP Testing of Textile Mechanisms

To discover which of the textile mechanisms is most appropriate to create a working concept, prototypes were made in textile, of the four most promising mechanisms. A lot of experimentation has already been done on the Cross (See Chapter 1.9, Textile experimentation), so now Ribs, Slider, Zig-Zag and Sticks will be examined.

The samples of these four mechanisms are composed from different textile layers and they all expand in a slightly different way when forces are applied on them. To see which of these mechanisms works best for the concept design all samples were examined on the following criteria: force, thickness, expansion and range of movement. Additionally, an estimation will be made on the following, less measurable criteria: producibility, flexibility, compression resiliency and applicability.

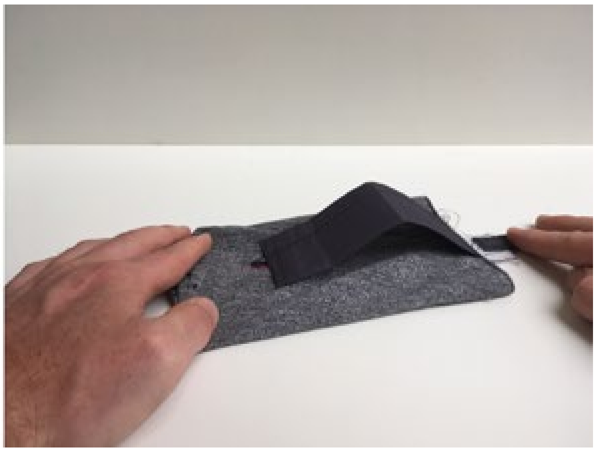
Ribs





The ribs-mechanism shows many similarities with ordinary window blinds. When the top layer is pulled to the left the structure automatically opens due to the rotation of the ribs, which are attached to the top and bottom layer at each different end. The ribs are reinforced using fleece liner which enables them to retain their rigidity.

Slider

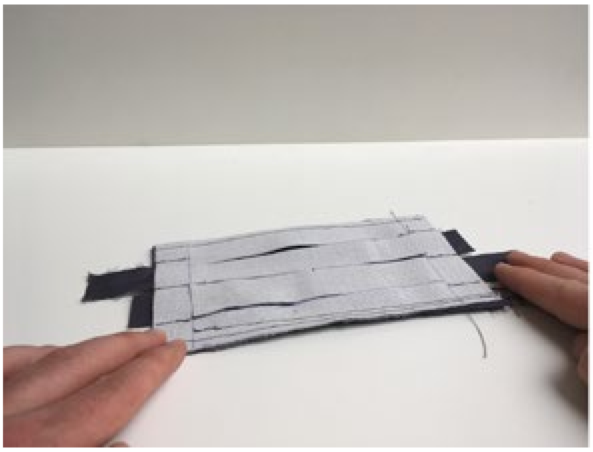


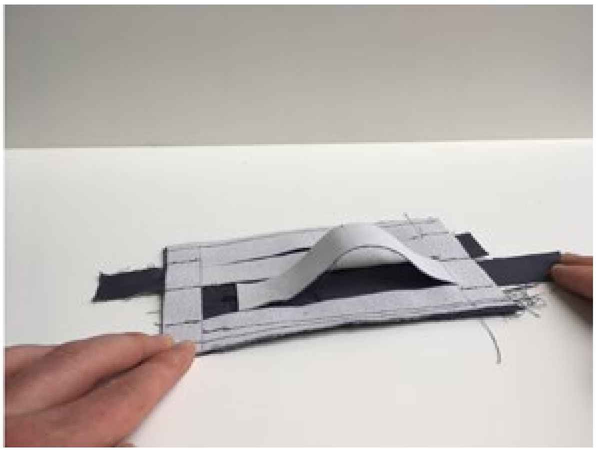
The slider-mechanism is inspired on the mechanism that is often used in pop-up cards. When the slider is pulled to the right, the left side of the upper layer moves to the right due to a connection that was made through a slot in the second layer. Because the upper layer is connected to the second layer on the right side, the upper layer folds upwards in the premade plaits.

Sticks

The sticks mechanism is inspired on the mechanism behind a foldable traveling hairbrush. The mechanism consists of long sliders on which the scales (sticks) are attached. The scales are then guided through a horizontal slot in the layer above the sliders. When the sliders are forced downwards the scales stand up just like the hair on your arm, when it is cold.

Zig-Zag





The zig-zag is very similar to the slider-mechanism, the only difference being that the sliding direction is alternated so that the increase in thickness is more evenly distributed along the surface.

In table ... the values of each test are displayed per mechanism. Force was measured on a horizontal surface using a force meter attached to one side of the sample while the other side of the sample was pulled away, causing the mechanism to increase in thickness. De distances were measured using a digital calliper. The last four criteria are displayed in normal font (not bold) and the corresponding values were estimated on a scale from one to five. The estimations come from own experience in making and handling the samples and general knowledge.

	Ribs	Slider	Sticks	Zig-Zag
Opening Force (N)	0.1	1.2	4.3	0.6
Thickness (mm)	1.7	3.7	1.8	1.6
Expansion (mm)	20.5	31.2	25.8	30.3
Displacement (mm)	2.0	1.8	0.8	2.0
Easy Production (1-5)	4	2	3	2
High flexibility (1-5)	5	3	3	2
Good Compression resilience (1-5)	4	4	3	1
Easy Applicability (1-5)	3	2	3	2

Measured Values — Estimated Values

Table 11 Mechanism test results

Low force as well as low thickness are the most important criteria for this design, since the mechanism will be implemented in a wearable and need to naturally drape around the shape of the body. The expansion is adjustable by the dimensioning of the design of the folding elements, so this factor is less relevant for decision making. Range of movement on the other hand is important, because this value can be used to calculate the initial length of the to be incorporated SMA wire. Pre-annealed NiTi wires are known to show shrinkage in length of about 4-5% of the total wire length, this means that the initial wirelength must be 25 times as large as the range of movement of a mechanism.

By comparing the results from this table, the mechanism Ribs scores the best in almost every category. Also, by feel this mechanism shows the most potential to be worn in a garment. Therefore, the Ribs mechanism will be chosen as the best mechanism for this concept design and will be further developed and explored.

2.4 PATCH DESIGN PROCESS

Shaping & styling

The ideation process for the patch design starts with a rapid prototype incorporating the gained knowledge about the mechanism and the target group. The ribs mechanism is extended to fit the torso and applied on a t-shirt. The shape of the patch was improvised by drawing on the t-shirt while wearing it and looking in the mirror.

While making the prototype the discovery was made that the ribs are very difficult to attach to the t-shirt by sewing. Each rib needs to be sewed individually to the shirt and to do this the whole textile composition needs to be folded very precisely to be able to reach just the edge of the rib and the base with the sewing machine. This makes the alignment of all the ribs very difficult. The prototype of the patch and the ribs was therefore attached using pins.

The idea behind the orange strips on top of the patch is to serve as a housing for the wires. The wire was fed through the orange path which is open on both ends. The intention was to lock the wire at the bottom of the strip, so that it could lift up the entire patch when pulling from the top. However, the low stiffness and the instable base of the patch caused the whole patch to crease. In contrast, pulling the top of the orange strip did cause all the ribs to close, as can be seen in Figure 27 The shape closes surprisingly well and needs very little force. when released the shape opens up again by just by the gravitational force.

Figure 27 Rapid full-scale prototype

The improvised patch design consists out of one piece of fabric and covers a large are of the torso. This causes the ribs to be very long, especially in the chest area. The ribs are made from straight pieces of fleece liner. This causes the patch to look very static and flat and also creates extra resistance when folding open. Therefore, the ribs should be curving along with the shape of the body. A small prototype was made to see if the curved ribs could offer a solution to this problem. The round ribs open and close very smoothly and create a more dynamic look, this means that during the embodiment phase a deeper look needs to be taken into the contour of the part of the body under the shape of the patch.

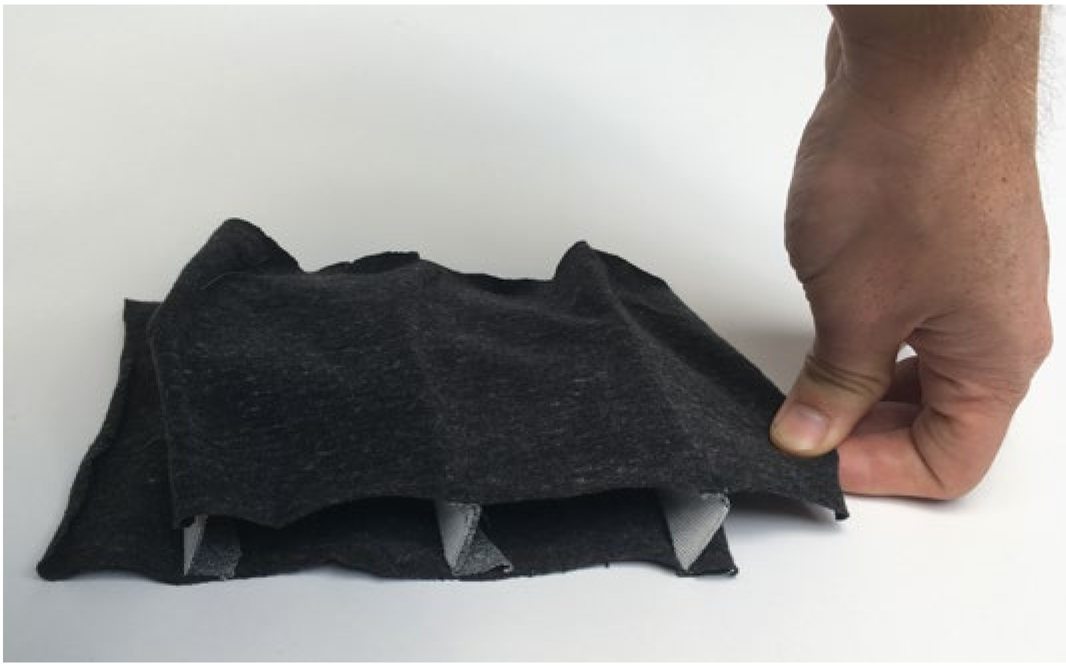


Figure 28 Round ribs test

While making this test sample another bonding method instead of sewing was tried to see if this would simplify the attachment to the garment. Vliesofix was used to attach the ribs to the second layer. Vliesofix is a layer of glue between two paper sheets. If one of the sheets is removed the open side can be ironed onto a surface. When the glue cools off a bit, the top paper sheet can be removed, and the new open side can be ironed onto another textile surface. Beforehand the Vliesofix can be cut into any desired shape, so in this case just the edges of the ribs were fixed. This method allows the entire shape to be put down flat on the garment and by adding heat and pressure, the whole shape will be attached to the garment. This makes sure that all the ribs are perfectly aligned. However, Vliesofix bonding is resistant to washing and is usually finished with stitching. For the prototype this will do the job.

Design implications

The patch design is all about the shape and location of the mechanism. The design of the patches is depending on a couple of factors that need to be taken into account. First of all, the hiker will always be wearing a backpack which causes implications for the design. The insulating patches can only be placed on the frontside of the garment, because at the back of the garment the mechanism will not have room to move freely which prevents expanding. The usual hiking backpack incorporates two straps over the front of the torso to keep the backpack stable during walking. The top one is called the sternum strap and the lower one is called the hip belt. Both these straps should be fastened during hiking to more evenly distribute the carrying load of the backpack and take some weight off the user's shoulders. When the straps are fastened the frontal area in which the patches should be able to fit decreases. In Figure 29 this area is visualised and referred to as the design space.

Figure 29 Design space illustrated

Secondly the design needs to fit in the current market for outdoor gear and needs to match a certain style to express the extra features. The current available outdoor gear was analysed to discover trends and styles. A clear division was found by comparing items from different outdoor stores. There are two distinctives styles in outdoor gear that can be found on the current market.

Figure 30 Hiking gear style analysis

The first is a rough lumberjack style that uses green and brown colours and lays extra focus on a more pronounced material expression, like the coarse structure of the fleeces.

The second style that visually distinguishes itself in the outdoor gear branch is the smooth technical style. Part of this style are the use of bright colours, two-tone divisions and mainly smooth and seamlessly finished fabrics.
The latter style is most suited for the concept design, because it is a highly technical garment. The two-tone differences and the use of bright colour can be used to emphasise the shape and the function of the patches.

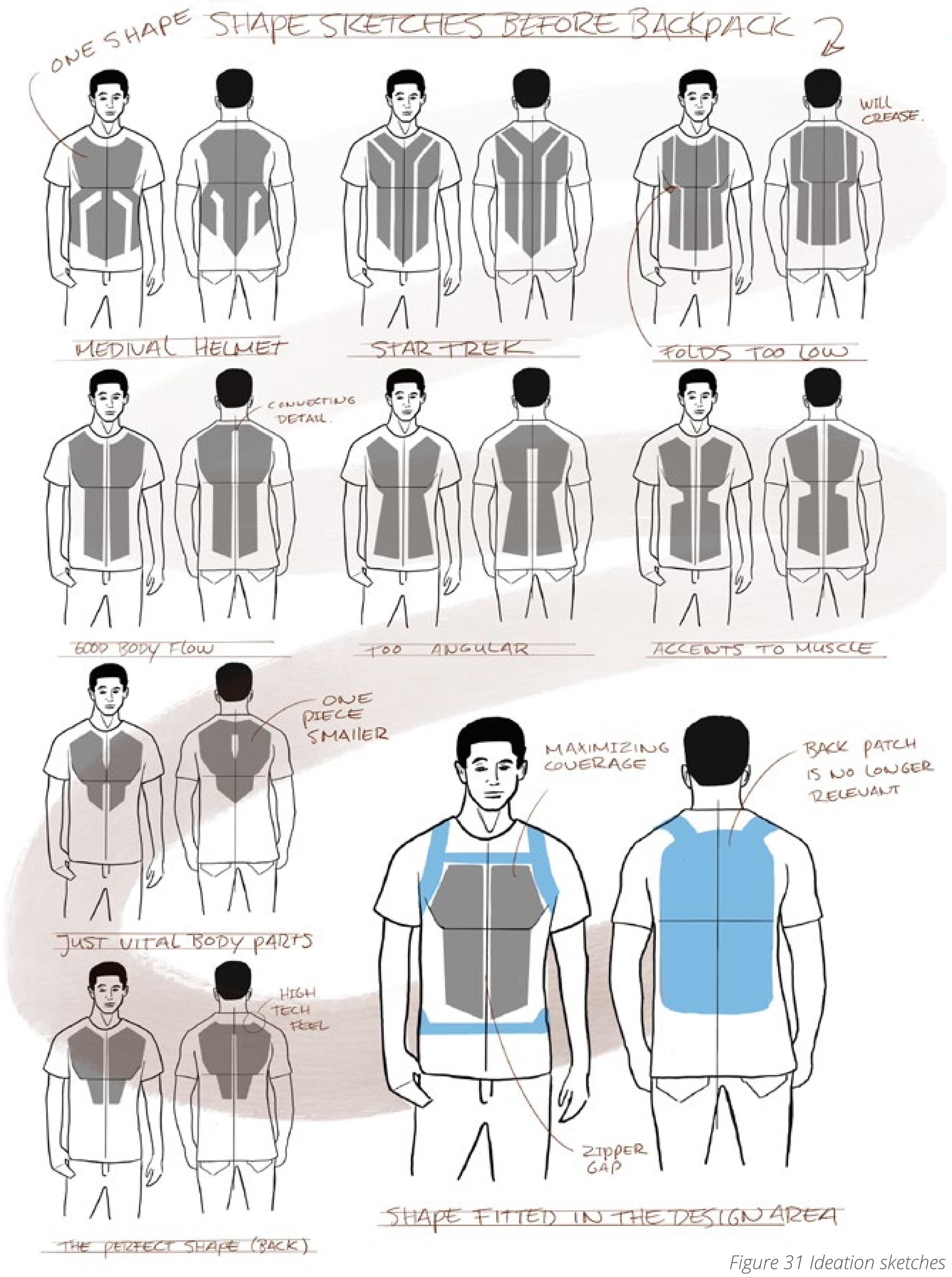


Figure 31 Ideation sketches

The ideation sketching process begins with a very open shape exploration, to discover what effect the shape has on the look and feel of the garment. The shape needs to accentuate the natural lines of the body and have a high-tech feel. The sharp corners help to make the overall picture look a bit robotic, which fits with the futuristic and high-tech feel. The shape tapers just under the chest muscles to give a masculine look that nuances the body. The lower part of the shape follows the line of the abdomen to and meets in the middle at belly button height. In the last, larger sketch the shape is readjusted to fit inside the earlier determined design space.

To study the result a render was made that is translates the design to the real-world (Figure 32). The smooth technical style was used in this render to see if the style and the shape would match. The result is very pleasing, but the colour scheme can be exploited more to convert the functionality of the product clearer. This could be done by creating a more distinct difference between the colour and finish of the patch, edge finish and the base of the garment.

Figure 32 Artistic Impression

2.5A **FORCE SYSTEM** WIRE SOLUTION

SMA orientation & Passage

This chapter will discuss three concepts of SMA wire applications. These concepts are tested to see if the wires could generate enough displacement in more organic orientations than a simple vertical suspension, to get the system to work.

The wire solution is dependent on 4 factors: (even) displacement, number of fixtures, wire orientation and SMA passage. The SMA passage is the path the SMA is guided through over the face of the garment.

The theory on shrinkage of pre-annealed NiTi wires says that normally the wire shortens about 3-5% of the total length when heated above its transition temperature . For this concept design a displacement of 20mm is required over the entire length of the ribs to close the structure. This means that the shape memory wire needs to be 500mm (4% of 500mm = 20mm). When the wire shrinks the most outer ends of the wire show the largest displacement respectively. Therefore, this amount of displacement needs to be distributed evenly over the entire length of the ribs. This can either be done by connecting the end of the wire to a non-stretch strip of fabric which guides the systems movement.

Another option is to encapsulate the wire in a microtube which is connected to the end of the wire but allows the rest of the wire to move freely inside the tube, just like a brake cable. Both these options were explored and tested during the test.

4% of 500mm = 20mm

Wire concept 1: Low neck-loop

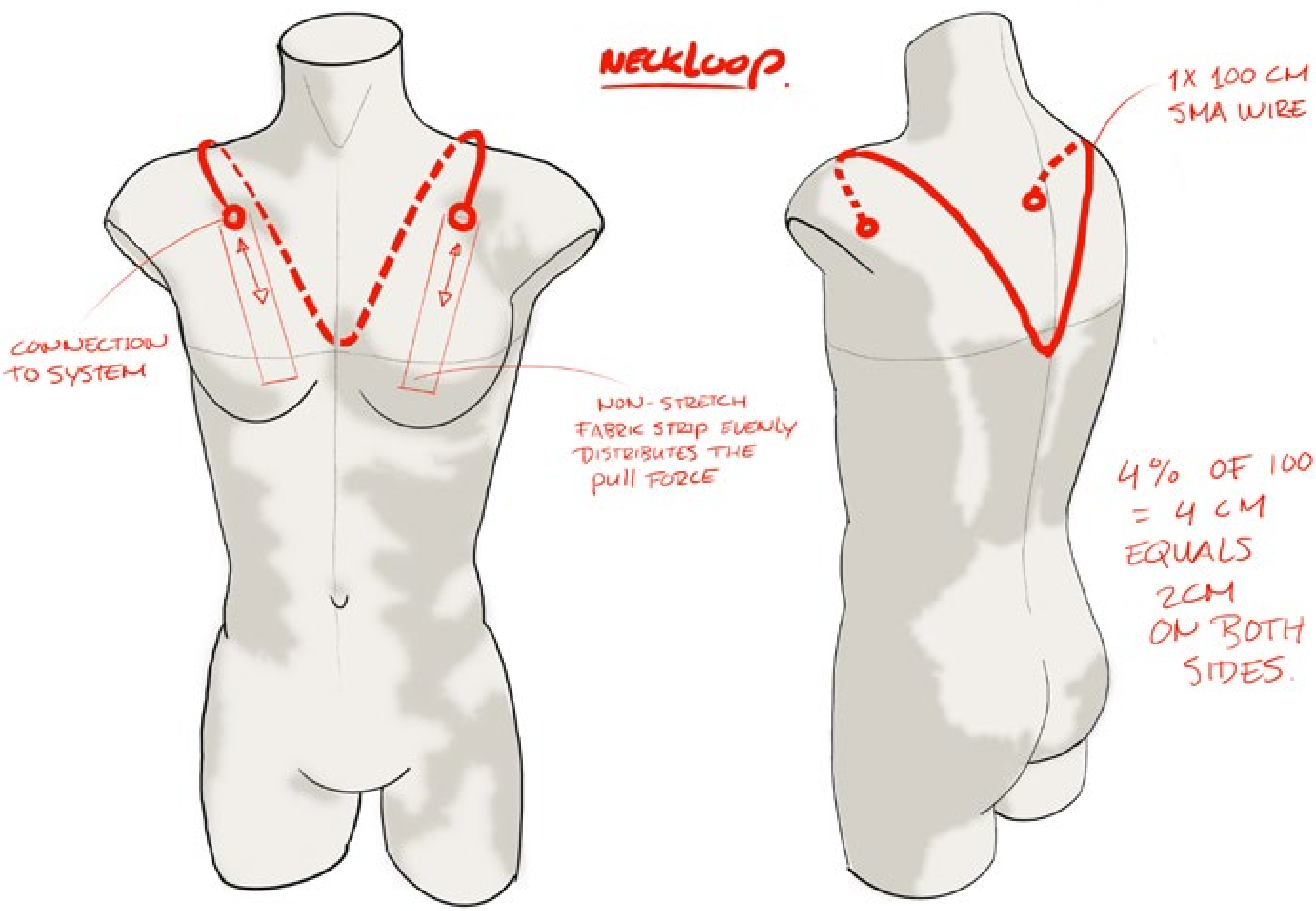


Figure 33 Wire concept 1

This concept incorporates one long SMA wire of 1m that is guided over the shoulders and curves around the back to create sufficient wire length. The wire is 1m instead of 50cm because in this concept the one wire lifts both system patches, so it needs 4cm of shrinkage.

Wire concept 2: Brake wire

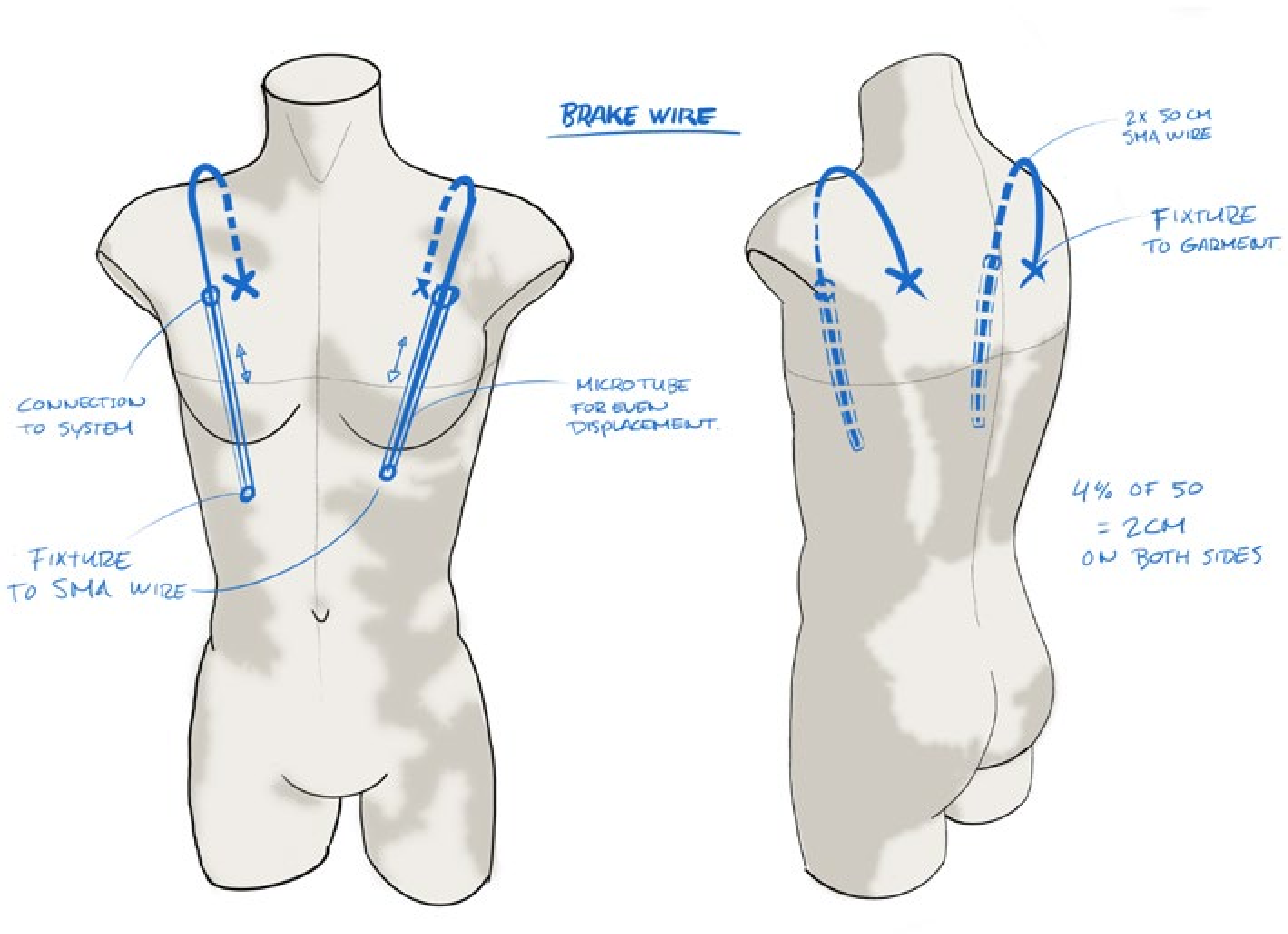


Figure 34 Wire concept 2

This concept makes use of two, 50cm long, SMA wires. Both are guided over the shoulder and fixed at the back of the garment. The wires continue further down on the chest side of the torso, all the way to the lowest point of the mechanism. Here, the wire is inserted in a silicone microtube which is fixed to the end of the wire. This means that when the wire shrinks, the displacement will be translated over the entire system patch and it won't crease due to the force.

Wire concept 3: Shoulder cross

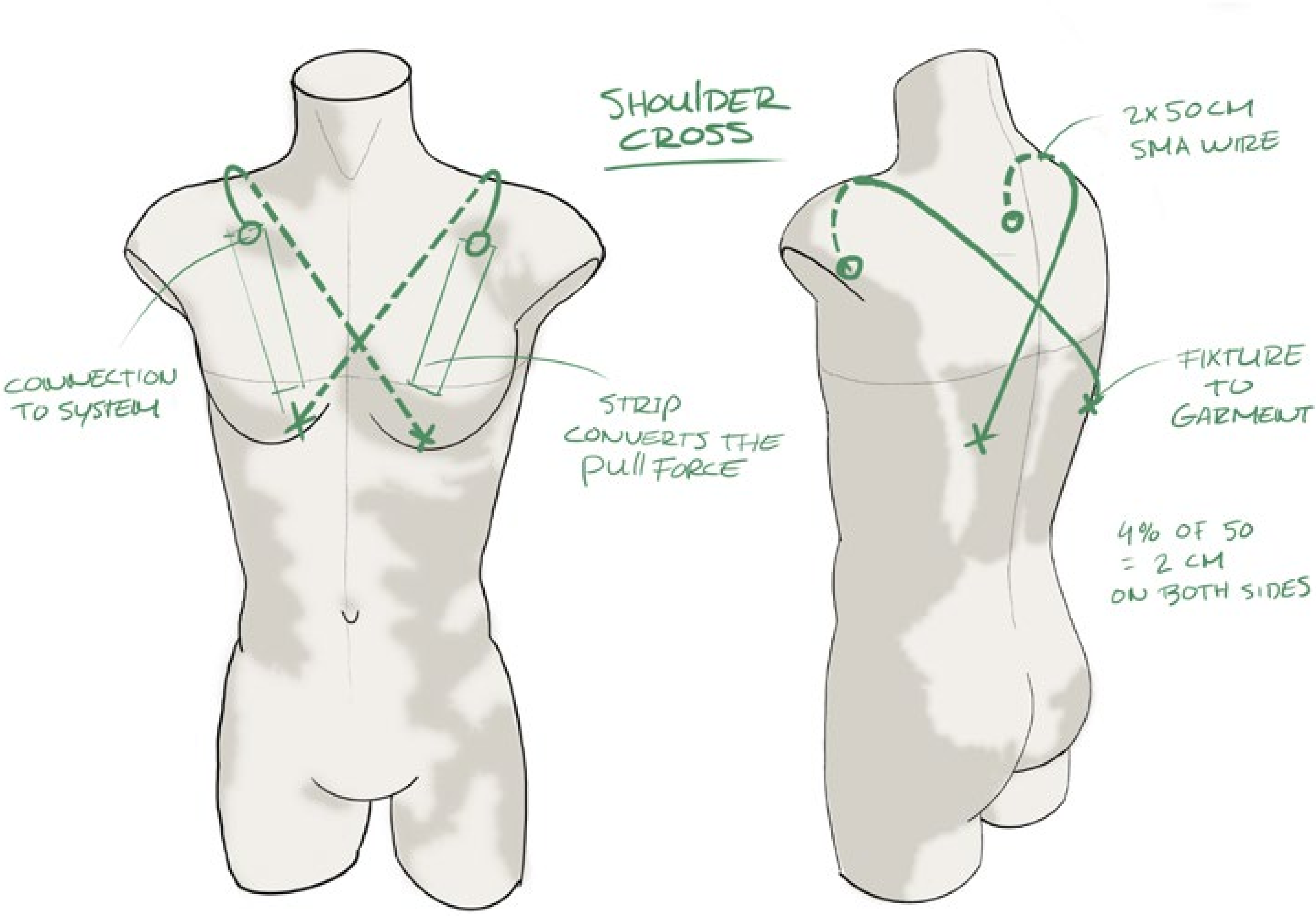


Figure 35 Wire concept 3

This concept makes use of two separate 50cm SMA wires that are guided over the shoulder and cross at the backside. Both ends of the wires are fixed at the back and the displacement is translated using the same non-stretchy fabric strips that are lifted from the top.

Test

A setup was built to test the three different SMA orientations with their corresponding lengths to see if they could generate the theoretically calculated displacement.

First, a wire was selected and tested while vertically suspended, to see if the orientation would have an effect on the performance. The wire that was used had a diameter of 0,125 mm and an activation temperature of 70°C. One metre wire was suspended and loaded with 85g (8,3N), which was the combined weight of the bolds used to fix the wire and the clamps that applied the electrical current. Also, a thermocouple was installed on the wire to keep track of the temperature when heated using an external power source.

At 35°C the construction started lifting up the bolds and at 70°C the displacement finished at 4cm difference in height. This means that the aforementioned theory is accurate. Also, the load was big enough to move the wire back to its starting position. This finding was unexpected because the maximum recommended recovery weight for a wire with this diameter is 230g.

To do a similar experiment, with a more organic wire orientation, small pieces of aluminium tube were used to guide the SMA wires over the profile of the human figure, using a dummy. All the previously discussed wire concepts were built and tested on displacement.

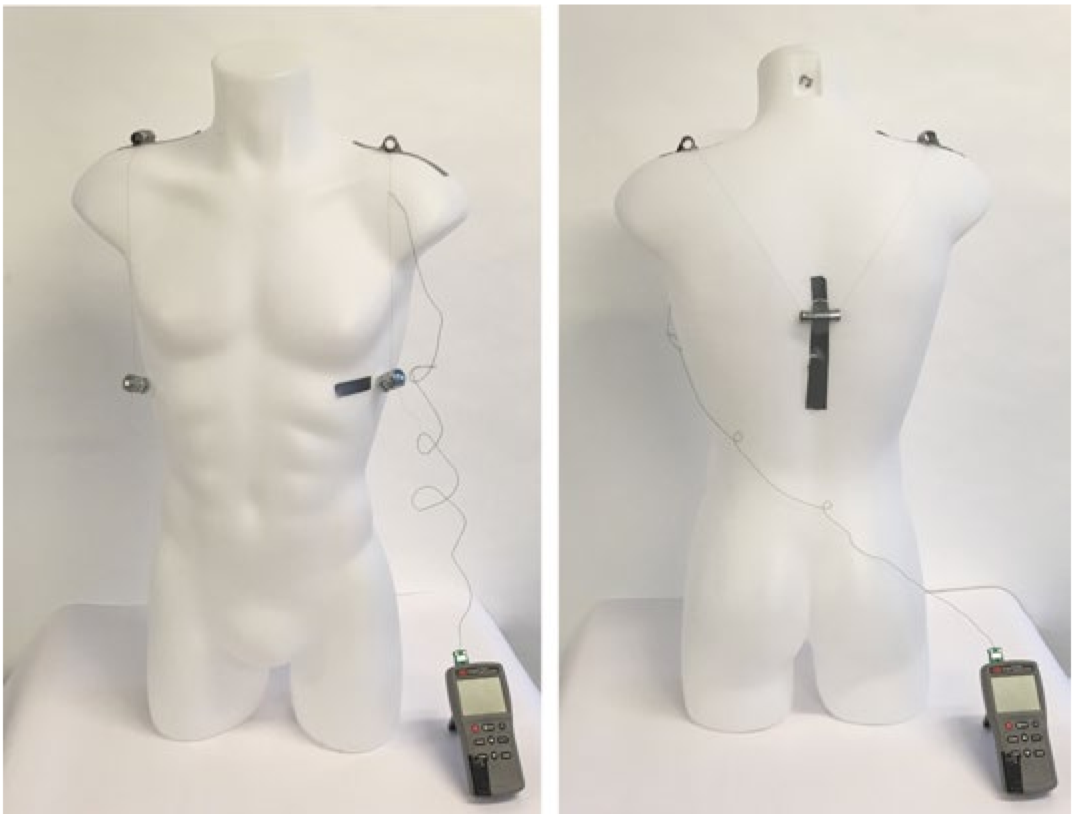


Figure 36 Wire test set-up

Results

The results for displacement are similar across the three concepts and therefore proven to be non-dependant of wire orientation. This means that the other criteria will need to support the decision on which wire solution is most suitable for the concept design.

Both the Break cable and the Shoulder cross concept rely on two additional fixtures on the garment. This influences the concept design in three ways, namely: it increases the chances of crease in the fabric, it increases chances of failure and it makes production more complicated. The results of the experiments are displayed in Table 12.

	Neck-loop	Break cable	Shoulder cross
Displacement (mm)	20	20	20
Additional fixtures	0	2	2
Displacement translation	Strip	Tube	Strip
Easy production (1-5)	4	2	3

Measured — Esimation on experience

Table 12 Wire solution results

Using a microtube to translate the displacement causes additional problems in comfort and system response. The tube is round and therefore more prominently noticeable by its thickness on the skin. Additionally, the tube creates an extra layer of insulation around the shape memory alloy wire, which decreases the systems response time to outside temperatures.

Additionally, the silicone has a large sliding resistance which prevents the SMA wires from sliding smoothly through it. For this test a silicone tube was used with a diameter of 5mm and wall thickness of 1mm. The path the SMA's need to be guider through is not jet tested with this experiment but is necessary to make the right decision on the wire solution.

SMA Passage

The silicone tube is too large for this concept design, because it hinders both the response time of the system and it is very noticeable for the wearer of the garment. However, a tube is necessary to create a path for the wires to slide through when the alloy is activated.

The SMA passage is a term used to describe the path through which the SMA wires are guided. Too overcome the downsides of the silicone tube, the tube is replaced with a PTFE (Teflon) tube with an internal diameter of 0.46mm and a wall thickness of 0.23mm. the small dimensioning of the new tube will improve the comfort of the garment and decrease the response time, due to its less insulating value. Teflon is one of the smoothest materials out there which improves the wire mobility.

A forth wire concept was created that incorporates the Teflon tube as SMA passage, using the best features of the tested concepts above. The first used concept is the neck loop, because it does not need additional fixtures as incorporates one single wire length. The second one is the break cable, because a tube was used as a force translation to the patch. In the break wire concept, the wire goes all the way down the patch and since the SMA just needs to be one meter in length the neck loop shifts upward in the fourth wire concept.

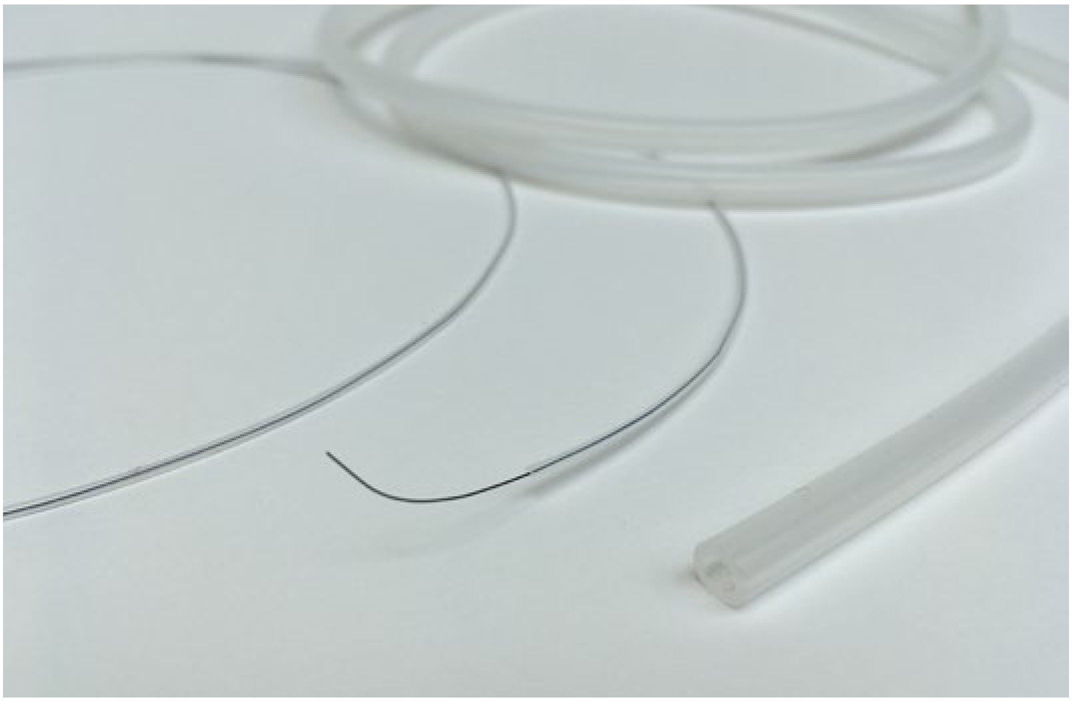


Figure 37 Teflon tube VS. silicone tube

Wire concept 4: High neck-loop & brake wire combined

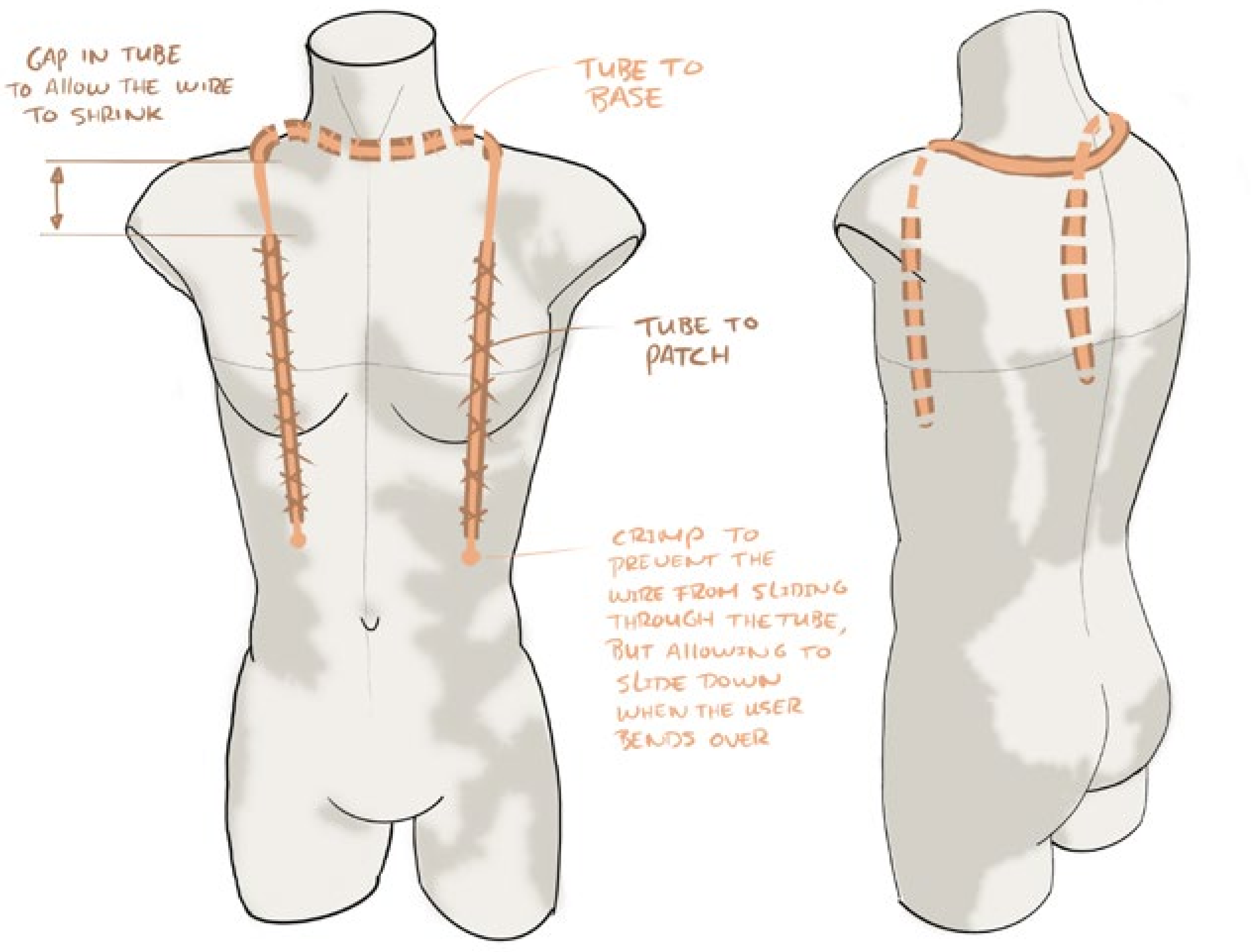


Figure 38 Wire concept 4

The neck-loop shows promising results due to the stabilising orientation of the neck. However, the neck-loop has just been tested in static situations, which means that the flexibility of the body was not taken into consideration for these tests.

On the other hand, the Teflon microtube is a very nice discovery that and addition to the system, which enables the wire to slide almost frictionless while contracting. By attaching the tube to the patches, the wire will still be able to move freely inside the tube.

2.5B **FORCE SYSTEM** COUNTERFORCE

Fabric or spring

The counter force is the force that pulls on the patches in the opposite direction compared to the SMA wires. In image ...the counterforce is displayed using red arrows. This force can be generated by making the edge finish out of stretch material that is that is tuned to be in the relaxed state when the structure is fully open.

By using a stretchy edge finish as counterforce, the recommended pull-force of the wire must be well balanced out with the amount of force the stretch fabric is able to generate. This can be finetuned by selecting the right wire and by adding layers of fabric to increase the elastic counter force.

The stretchy fabric does not exert a constant counter force over the length of the elongation and the exact modules of elasticity is hard to determine. If this gives too many problems during the prototyping phase, the option to use small springs must be considered. These springs can be attached to the end of the SMA wirers on one side and on the system fixture belt on the other.

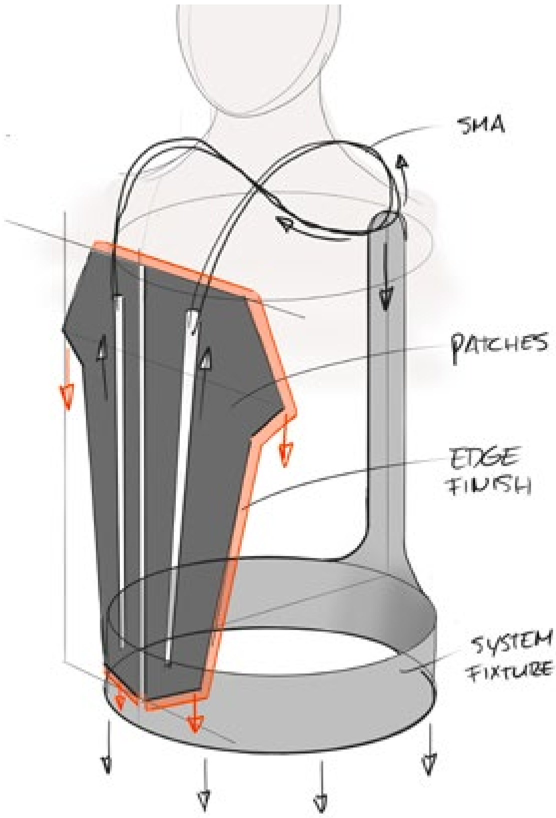


Figure 39 Force system

2.5C **FORCE SYSTEM** FIXTURE

Keeping the system in place

The system fixture is holding the entire system in place. This is needed to prevent the base from sliding up when the SMA wires are activated. When the SMA wires are activated they will exert an upward force on the patches which is larger than the counterforce. If the edge finish, which connects the patch to the base, slides upward, the mechanism will not open. To prevent this from happening the system fixture will need provide the necessary downforce to keep the system in place and function properly. two different versions of the System fixture belt were designed to match different wire solutions.

High waist fixture belt, with spine connection

On the back of the garment a long strip is incorporated that is attached to the system fixture belt to hold the low SMA neck-loop in place. If the SMA wires would be able to slide upward on the backside of the garment, the system will not open either. On top of that, there will be a lot of crease development if the system is not properly locked into place. This fixture belt fits the low-neck loop wire concept.

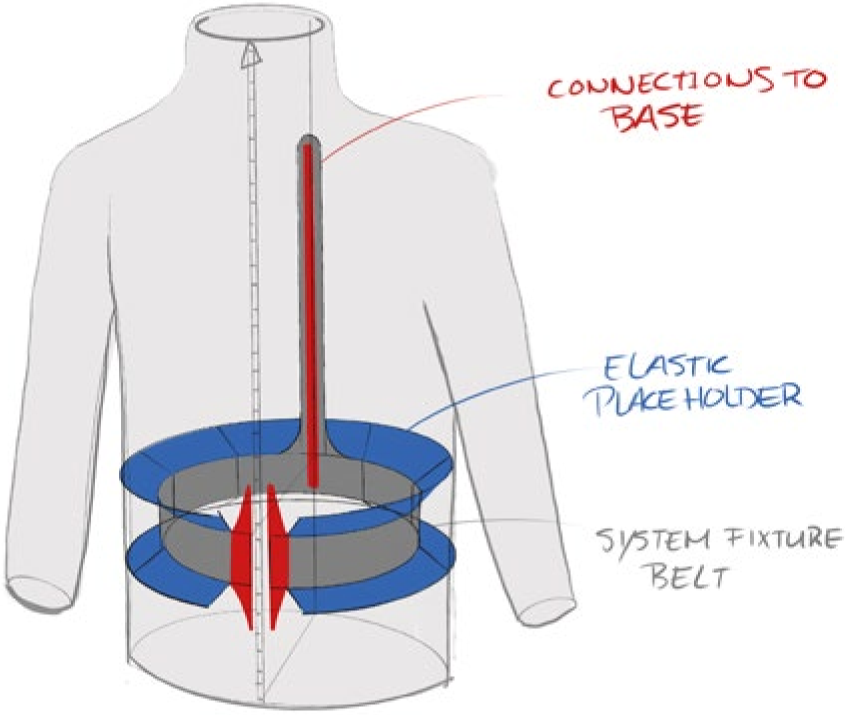


Figure 40 Fixture blet with spine connection

High waist fixture belt, no spine connection

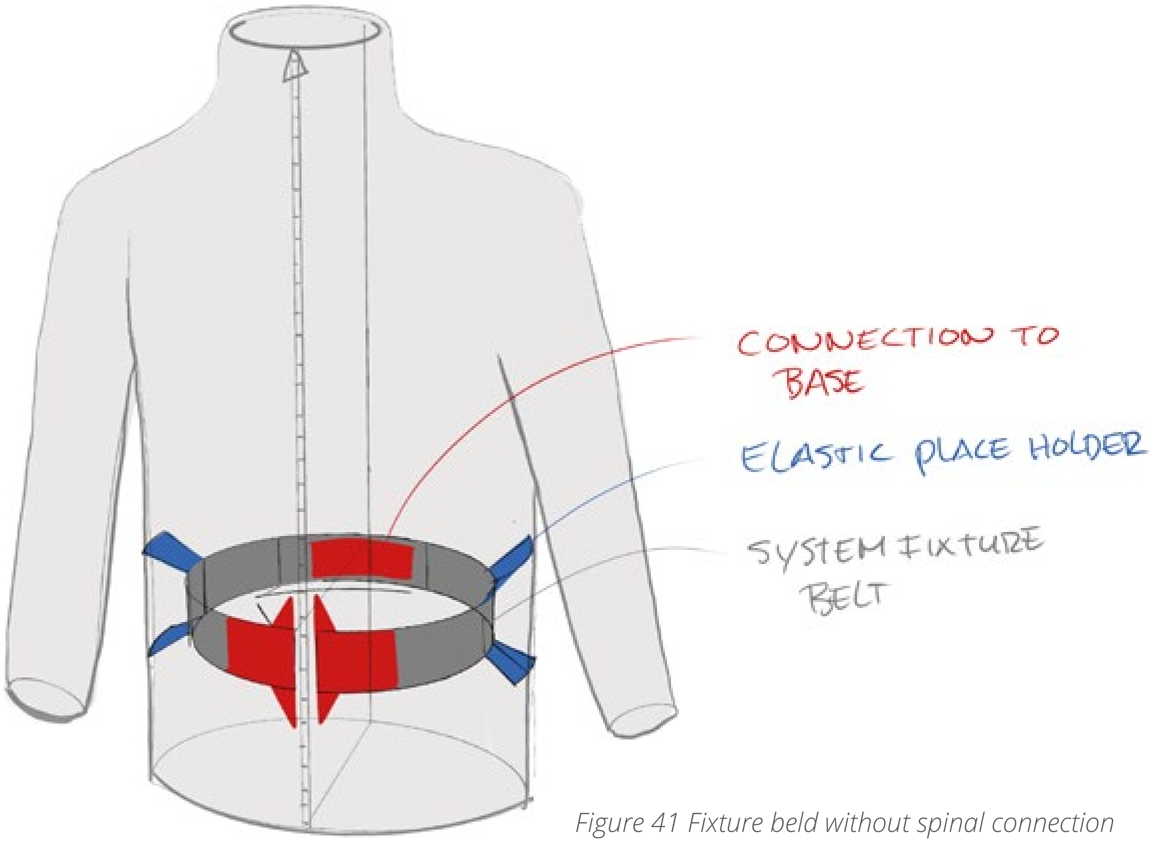


Figure 41 Fixture beld without spinal connection

This version of the system fixture fits the high neck-loop wire concept. The spinal connection is left out in this concept because the high neck-loop rests in the neck arch of the body and stays into place naturally when force is applied on the wires.

The rest of this fixture concept is about the same as the latter except that the placeholders have been reduced in size, instead of half a circle. This reduces the material use and simplfies production.

The system fixture belt must be made from a strong, yet elastic material that wraps around the body. The diameter needs to be smaller than the circumference of the body to clamp down nicely. The belt must be connected to the base three different points: next to both sides of the zipper and at the back. When the zipper is open the garment will be easy to put on or off. When the zipper is closed the belt will tighten up and keep the system in place. Elastic placeholders will keep the belt in the right position when the garment is removed from the body.

2.6 MATERIAL COMPOSITION

From fabrics to additional materials

The fabric composition is one of the most important and dominant factors of this concept design, because the most prominently present material of this concept design will be fabric.

The parts that will be made from textile are the base, the patches, the ribs, the system fixture and the edge finish. Apart from textile there are two parts that need to be enhanced using additional materials. The ribs and the SMA passage need reinforcing to properly function.

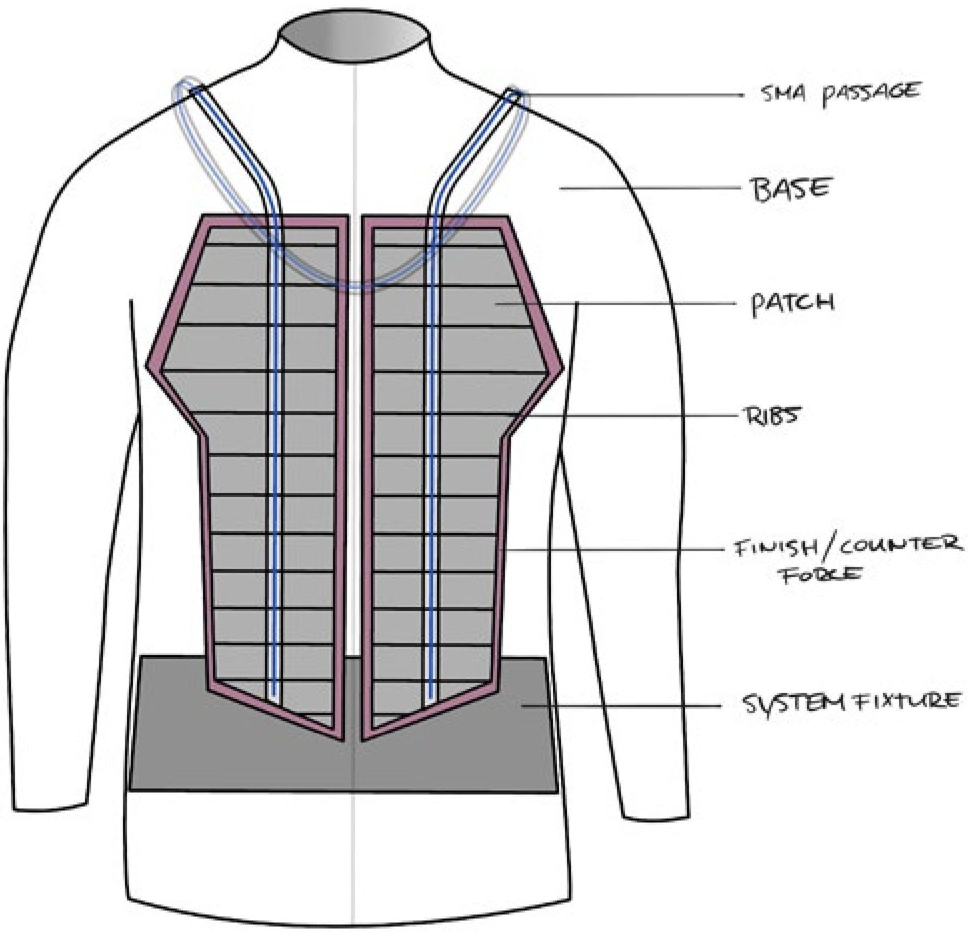


Figure 42 Fabric parts overview

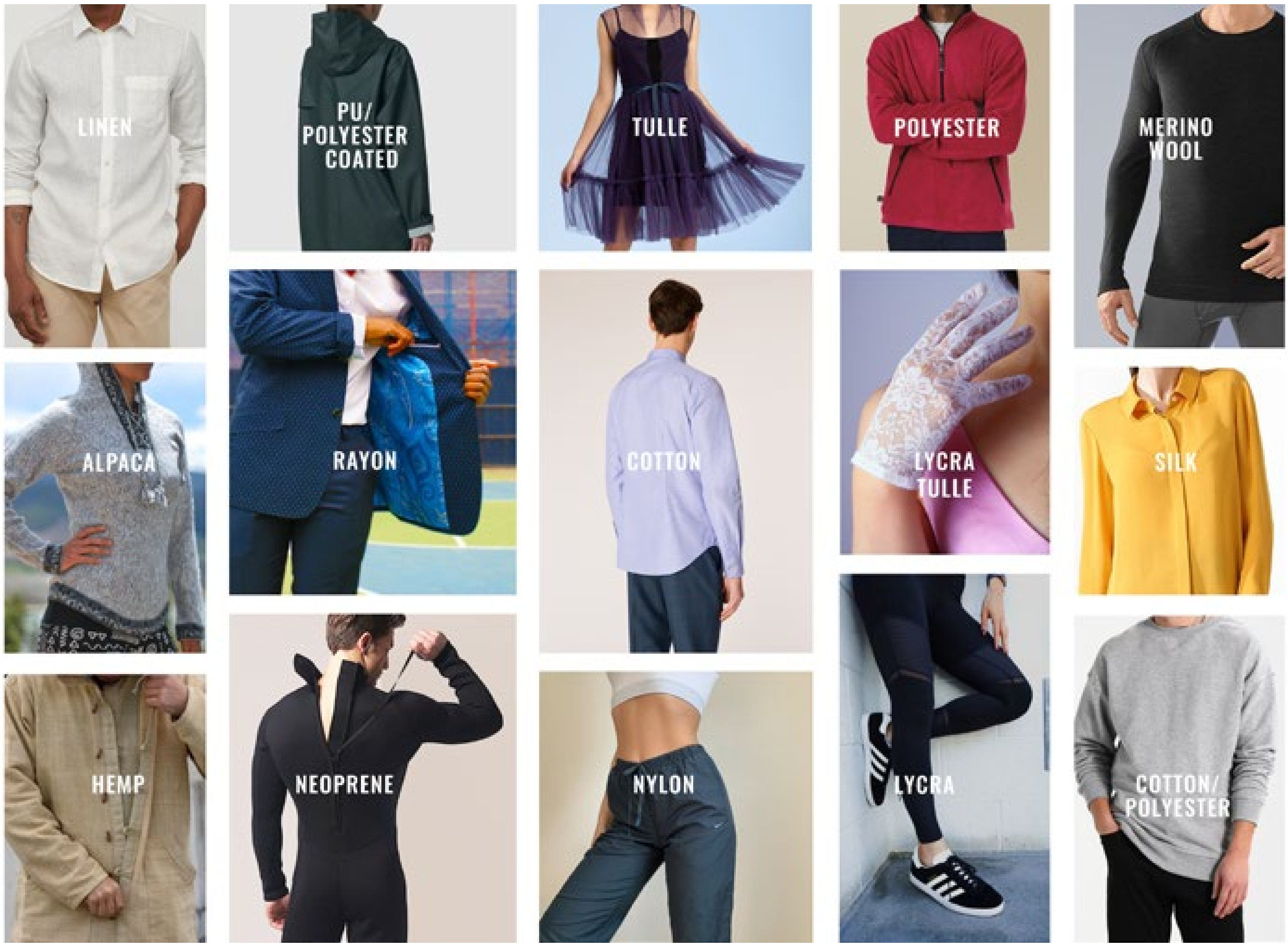


Figure 43 Composition of textiles and typical applications

A composition was made of all textiles that were used in former tests, with some additional ones that are slightly more focussed on the outdoor branch, like: PU/ polyester, cotton/polyester, merino wool. Additionally, some more exotic materials that were discovered during this research are added to the mix, just to see if they could be of any use for the concept design (silk, alpaca, hemp). In Figure 43 the various textiles are displayed to illustrate their typical use and the different characteristics pertaining to each material.

Base

The base is the is the largest textile part of the concept design. It needs to keep the user warm and dry. There are three different mid-layer insulation variants available on the market: down stuffed, fleece and merino wool.

Figure 44 Typical mid-layers

The down filled fabric is not suited for this design because it already traps a lot of air, which makes the system unnecessary. Merino wool is used to make super lightweight and thin insulation layers. Adding the system to this material will work but would be contradictory. Therefore, the most logical choice for this concept design will be a base of polyester fleece. The softness and thickness of the fleece will also help in preventing the user to experience any discomfort from the folding mechanism and the SMA passage.

Patch

The patches can be described as two moving chest panels that make sure that extra air is trapped by the garment. Therefore, the patches need to be wind-proof. An additional function of the patch is that it needs to transfer the force produced by the SMA to the ribs to put the system into motion. It must therefore not be made of a material that is able to stretch too much. The patches will be made from a synthetic material, like: polyester or nylon. These materials can be made non-stretch and wind-blocking. A coating can be added increase the dimensional stability of the shapes which will enhance the design aesthetics.

Ribs

The ribs are located in between the base and the patches. They make sure that the patches are lifted up when temperatures get lower. The ribs need to hold the structure open and by standing up straight. Therefore, they need to be reinforced using fleece liner, which is a more rigid textile that can be connected to another textile using heat (ironing). The other textile just needs to be flexible and dry quickly, preferably a polyester blend.

Edge finish

The edge finish is the border around the patch that makes sure that when the mechanism opens, the front of the garment will remain a closed surface. This fabric part will be connected to the base and to the patches, just like the ribs. However, the ribs use a rotating motion to open the mechanism, which means that the edge needs to be made from a stretchy material to cope with this expanding motion. The edge must also prevent wind from blowing underneath the patches and remove the stored warm air layer. Therefore, the edge finish must be made from a wind blocking Lycra. The stretch of the Lycra will also be used as a counterforce to create a two-directional force system.

SMA passage

The SMA passage will not be made from a textile but from a thermoplastic called Teflon (PTFE). Teflon is known for its low (sliding) resistance and can be produced in ultra-thin tubing with a wall-thickness around 0.2-0.3mm. This is ideal to house the SMA wires because, due to the low wall-thickness the tube has a low insulating value, which means the SMA's response time will be minimally influenced. The end of the SMA wire will be locked into the tube and the rest of the tube will be able to slide upward along the wire to guarantee an even displacement.

System fixture

The system fixture needs to be made from a stretchy, yet strong material to keep the entire system locked into place. For the system fixture belt neoprene will be a very suited material, due to its strength and stretch. The spine connection at the back of the garment that fixates the SMA neck loop, must be more rigid than neoprene. Nylon will be more suited for the spine connection. The elastic placeholders for the system fixture belt need to be stretchy and light and will therefore be made from Lycra.

Figure 45 Material overview of concept

2.7 MORPHOLOGICAL CHART

Forming concepts

All the sub-solutions discussed in the former chapters have been collected and displayed in a morphological chart. (Table 13) This chard gives an overview of all the options and by connecting sub-solutions concepts can be derived.

Three sub-solutions have already been tested or determined and the decision for best solution for these sub-problems has been made. The mechanisms that will be used is the Ribs mechanism and the patch design is limited by the backpack the user will be wearing. For the wire solution the neck-loop came out as the best option, however the decision has not yet been made if the high neck-loop or the low neck-loop will be used. The counterforce and the system fixture are both dependant on the wire solution, as these three sub-solutions together form the force system of the concept design.

By connecting the dots two concepts are can be formulated that merely differ in the set-up of the force system. The fabrics and the additional materials are the same for both concepts.

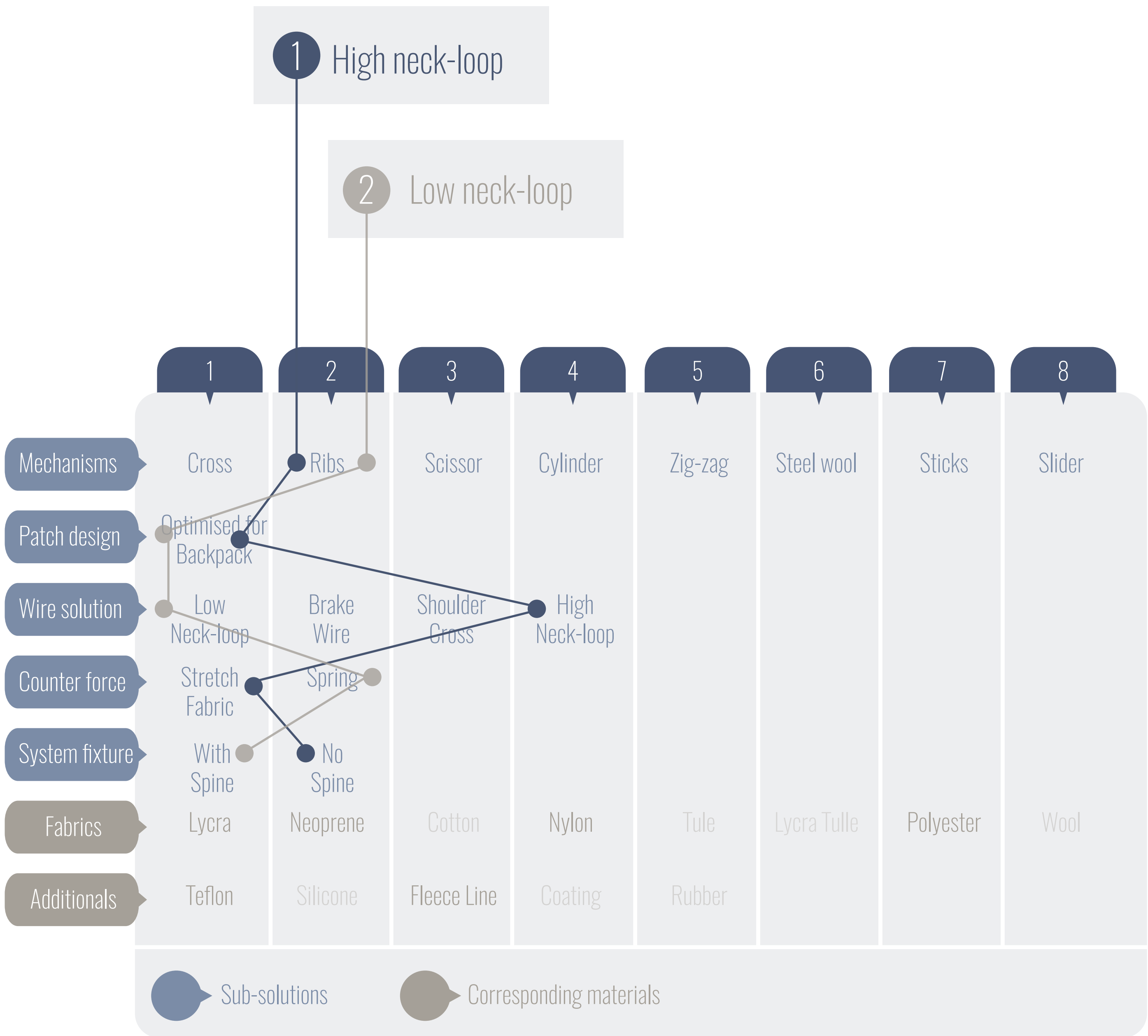


Table 13 Morphological Chart

Two concepts are designed according to the paths in the morphological chart, combining different sub-solutions. The concepts look pretty similar, but there are three essential differences between them.

The first difference is found in the path of the SMA passage. In concept one the SMA wires are guided very closely around the neck, in contrast to concept two. The wires in concept two show a wider shoulder passage and also bow downwards along the back of the garment.

This brings us to the second difference which is the SMA passage fixation. In concept one the wire passage goes all the way down the front of the patch, while in concept two the wire is connected on top of the patch. In concept two the force is distributed using a though textile strip that is attached to the patch. The fixation point creates the difference in the wire path for both concepts, as the total wire length needs to be 1 meter to generate enough displacement during activation.

Last but not least is the difference in the system fixation belt, visible in the two rear views of the garment. (Figure 47 & Figure 49) Concept two needs the spine connection to keep the force system in place, in contrast to concept one where the anatomic curve in the neck of the human body will be enough to keep the system in place during activation. However, coth concepts still need the waist belt to provide the necessary counterforce on the frontside of the garment.

Both concepts are rated on six design criteria that are ranked from most, to least important in a Harris profile. The Harris Profile helps to make the intuitive decision making more explicit, which provides the necessary guidance in choosing the right concept to further develop during the embodiment phase.

Concept 1 High Neck-loop

Figure 46 Front-view Concept 1

Figure 47 Rear-view Concept 1

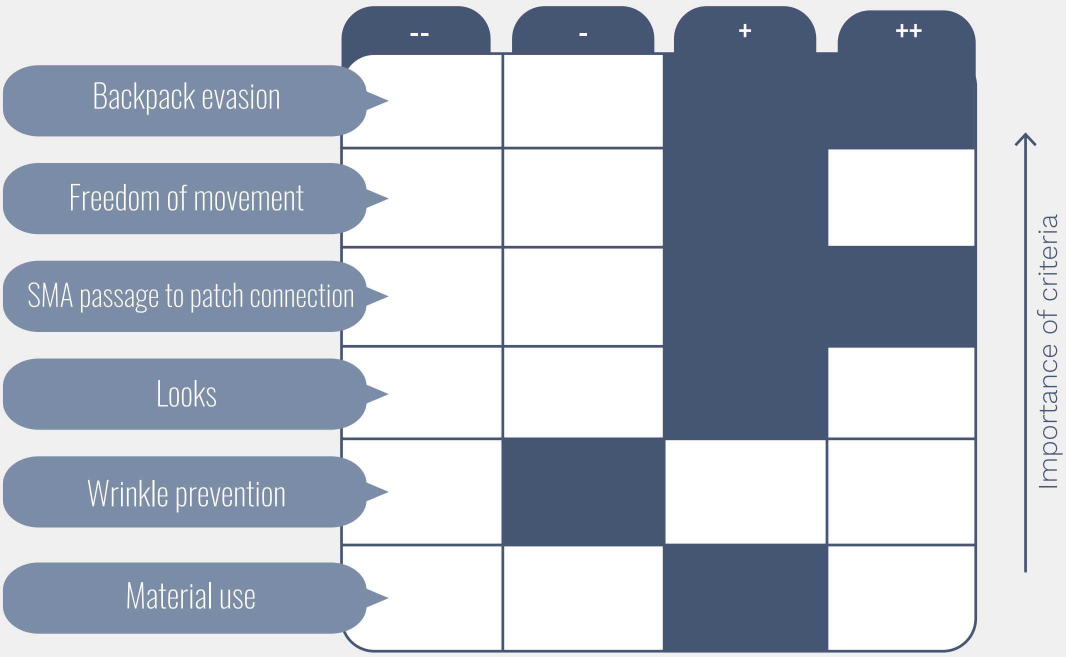


Table 14 Harris Profile Concept 1

Concept 2 Low Neck-loop

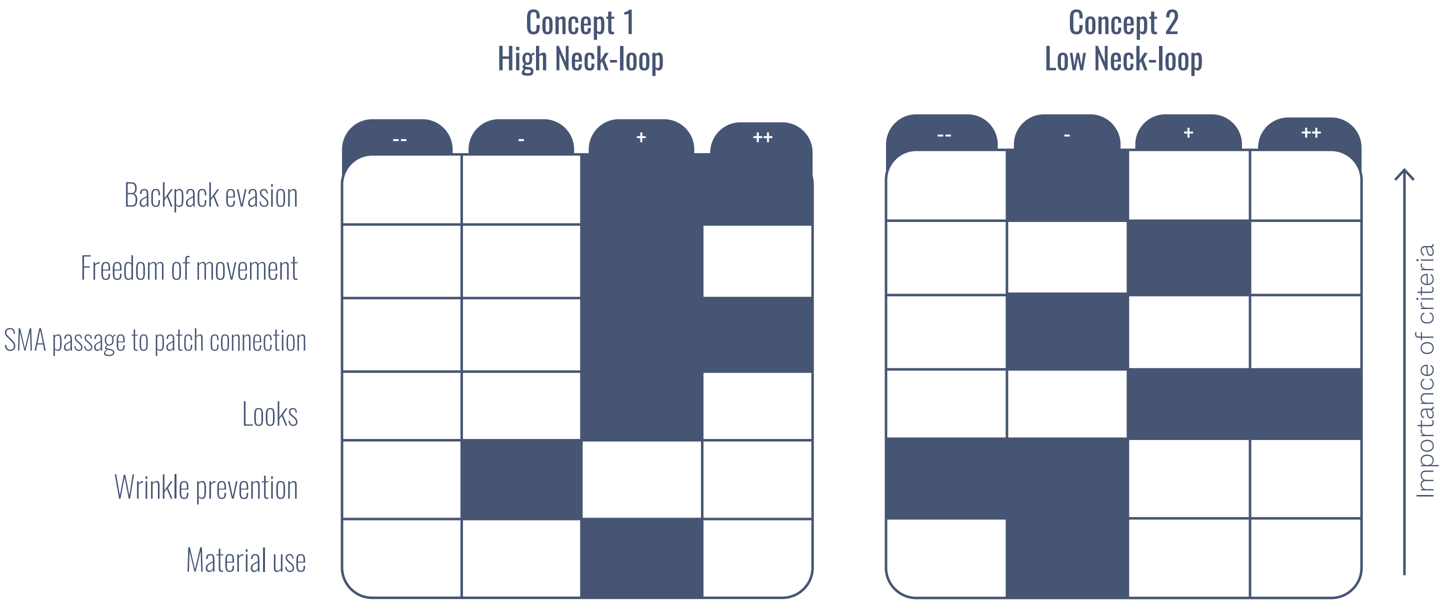
Figure 48 Front-view Concept 2

Figure 49 Rear-view Concept 2

	--	-	+	++
Backpack evasion		■		
Freedom of movement			■	
SMA passage to patch connection		■		
Looks			■	■
Wrinkle prevention	■	■		
Material use		■		

↑ Importance of criteria

Table 15 Harris Profile Concept 2

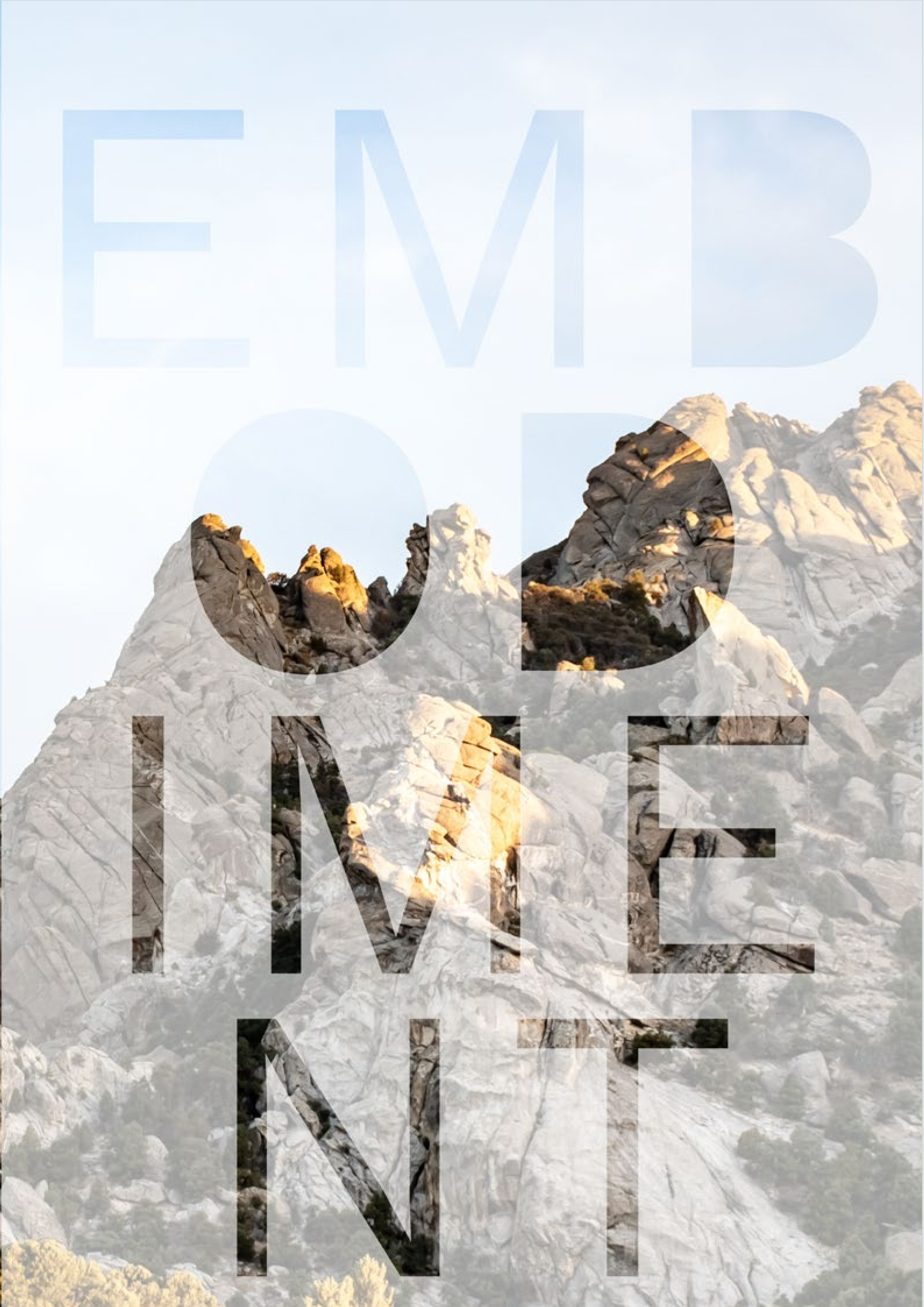


Concept one clearly shows a better result when comparing the two tables since it has more blocks on the positive side. This method is greatly based upon designer intuition and the decision is very personal. I need to trust my gut feeling and pick concept one, high neck-loop, for further product development during the embodiment phase of the project.

END OF CONCEPTUALIZATION PHASE

The concept choice is the closing milestone for the conceptualization phase. This means it is now time to start the embodiment phase in which the concept design will be further developed. This will involve a lot of prototyping and detailing. The prototypes will be used as a means to perform user- and thermal tests. Most results will be used to fine-tune the design to a the furthest extend, the remainder will lead to recommendations for further research and development.

CONTENTS


EMB
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INTRODUCTION
Embodiment phase

During the embodiment phase the concept will be brought to life by making a working prototype. Building the prototype will involve an iterative process to determine the right building strategies. Additionally, all parts need to be finetuned to properly work together as one system. To get this right every connection and tension needs to be tested and adjusted where needed. Furthermore, more elaborate specifications for each part of the concept will be described. When the prototype is finished it will be subjected to user testing to discover flaws and gather data on desirability. The results of the user tests will either lead to minor adjustments of the final design or be processed as recommendations.

Considerations

The concept design incorporating the high neck-loop was chosen to undergo further development during the embodiment phase. However, some parts of the concept have not been tested yet. Moreover, the concept as a whole has never been made yet. The problem points that are expected to cause difficulties in either production, comfort or functionality are:

Neck-loop: The neck-loop has only been tested in static situations, ignoring the flexibility of the human body in the neck and shoulder region. When the user would lift his/her shoulders when the SMA is suspended around the neck the patches might unintentionally open.

Edge finish: The concern regarding the edge finish is mainly about the surface finish. When force is applied on the patch it will move upward causing the edge to stretch out. The problem here is that the stretching motion is not a rectilinear motion, instead it is a tilting motion to one side. This might cause the fabric in between the two edges to wrinkle, which is not desirable for the final model.

Round ribs: Rounding the ribs to fit the curves of the human body can cause issues regarding smooth opening and closing of the patches, because the curves affect the symmetry of the connecting edges from ribs to patch.

Fixture belt: The fixture belt is needed to prevent the fabric from sliding up when force is exceeded by the SMA wire. The belt might be uncomfortable to wear and cause the whole garment to slowly crawl up when the vest is worn during activity.

3.1 INITIAL CONCEPT

Building the prototype

To gain more understanding about the cohesion of materials and the potential unexpected building challenges, a prototype is made of the chosen concept. This prototype is used as a means to evaluate the design choices that were made during the conceptualization phase.

The first preparation for building the prototype is determining all the connections between the different parts. Some connections need to have different properties compared to others, and some materials require different bonding methods than others. Therefore, an overview is made to keep track of all the connections that are present in the concept design. In Figure 50 all parts are separately displayed, and the arrows show to which other parts they are connected. The number behind each part represents the number of interconnections that part has to the other parts. For example, the SMA passage is connected to: SMA (wire), patch and base, which makes three.

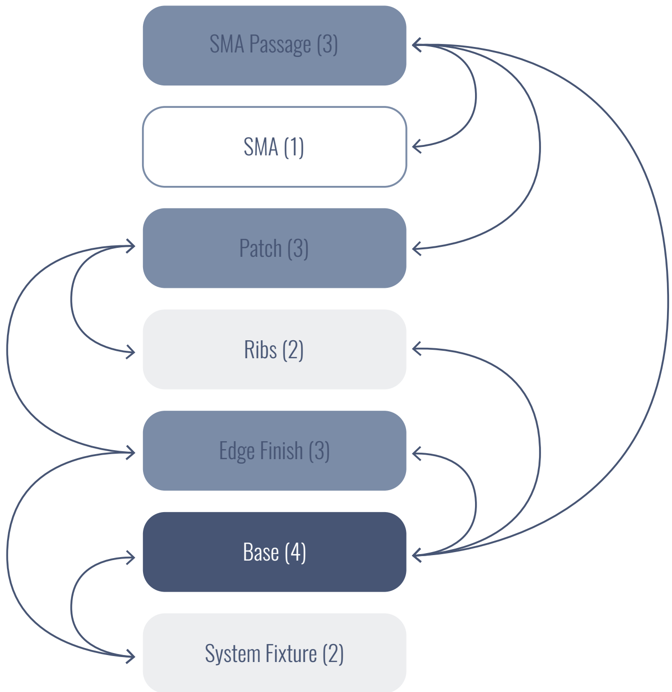


Figure 50 Interconnections

Figure 51 shows all connections on their designated location in the concept design. Each connection is named after the two parts it is fixing together. Most connections are established by sewing the parts together using the right stitch, either a zig-zag for stretch materials or a straight stitch for the remainder. However, the tube, the wire and the ribs need extra attention, due to their important role in making the concept work.

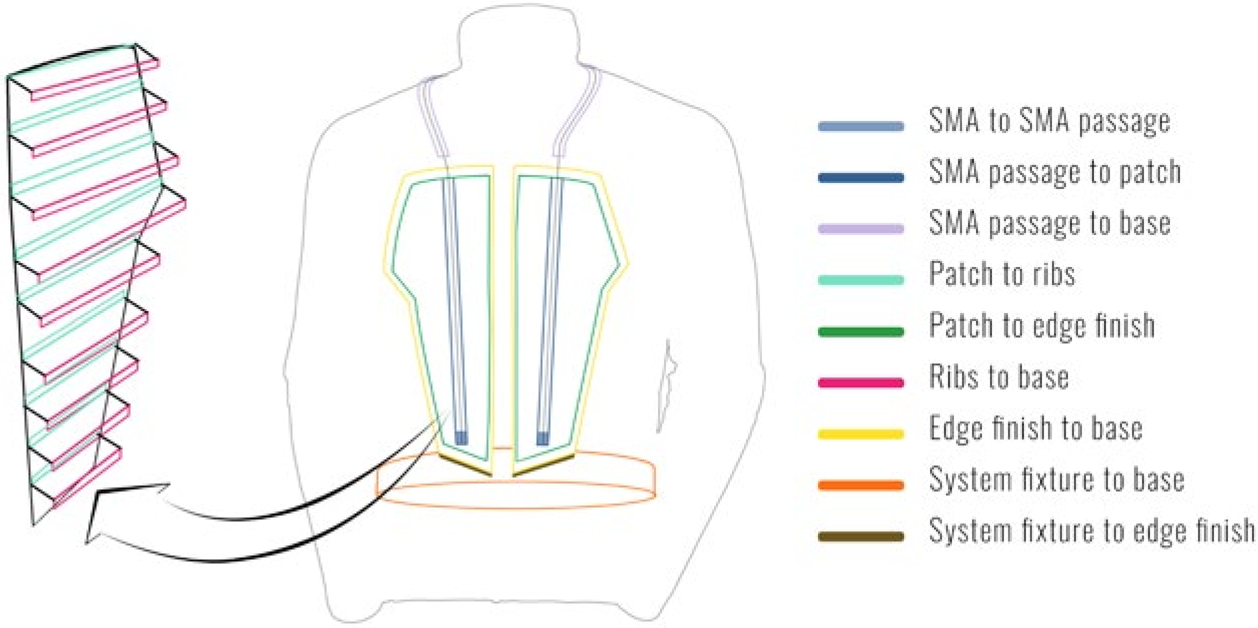


Figure 51 Connection location

The tube needs to be connected to the patch while still allowing the wire to slide through. It is very thin and has a low sliding resistance and trough this it is very hard to fix it without crushing the inner diameter of the tube. Three different methods are examined to fix the tube to nylon: Zig-zag stitch over tube, cloth tunnel and a two-layer laminate with stitches over the top. The latter bonding method is the only that really fixes the tube to the patch securely. Surprisingly the stitches did not go through the tube, enabling a clear passage for the SMA wire to slide through.

Figure 52 Bonding tube to patch

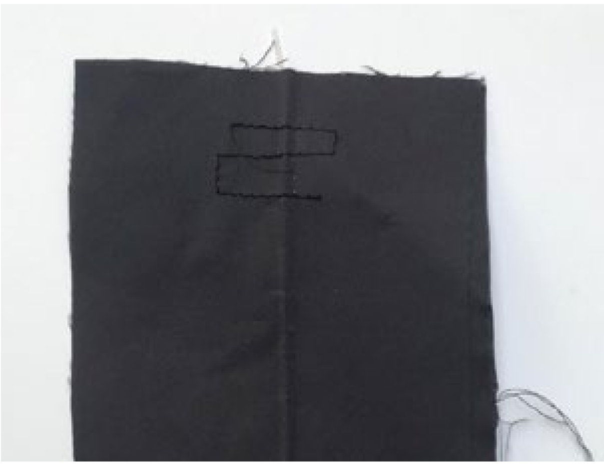


Figure 53 Laminate with stitches

Still in preparation for the built of the prototype the next step is to take a closer look at the construction one single patch unit, incorporating both the tube and the ribs. For this test two versions of the patch unit are made, one with straight ribs and one with round ribs. The round ribs idea was mentioned earlier in chapter 2.4 (Patch design process) and has not yet been tested on full scale.

The tube is first laminated between two layers of nylon. In-between, a layer of Vlisofix is applied to glue the two halves together using a hot iron. After that the patch is attached to a larger piece of Lycra with the same contour, which will be used as edge finish and as the rotating parts of the ribs. Fleece liner is attached as reinforcement and the Lycra behind the patch is cut open to enable the ribs to tilt.

With the selected bonding methods and the order of making of the patch established, the rib shape can be analysed. Figure 55 and Figure 56 show the two patch units with opened ribs. The straight ribs test opens up very smoothly without any resistance, in contrast to the round rib version. Due to the round rib, the connecting stitch needs to follow the contour making the rib as well as the patch curve in open position. The best solution is the one with as little resistance as possible, therefore the straight rib version is the way to go for the prototype.

Figure 54 Patch unit model

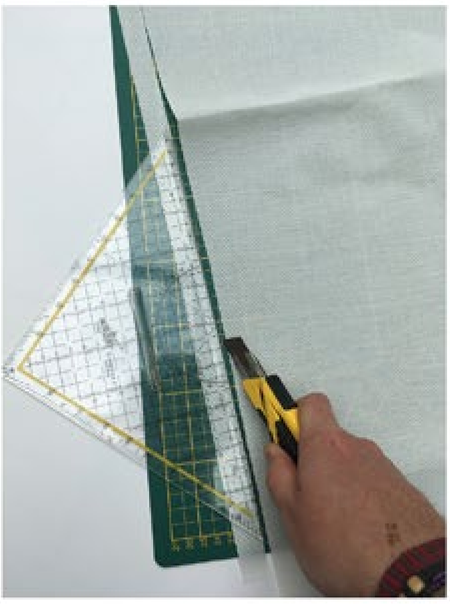
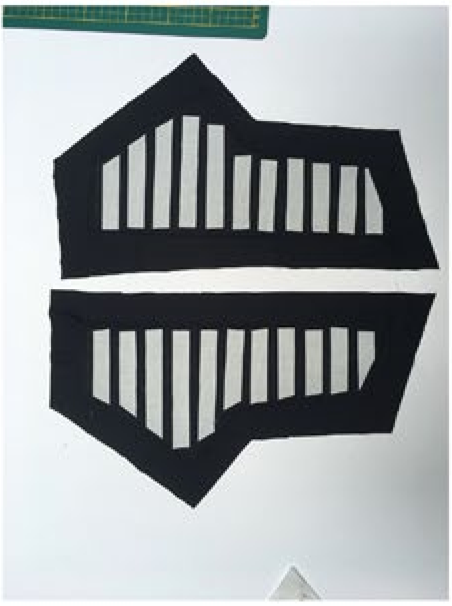
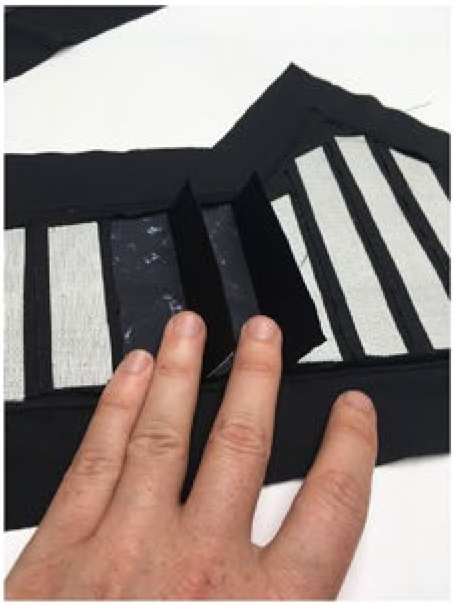
Figure 55 Open straight ribs

Figure 56 Open round ribs







On these two pages a photo report is displayed showing the building steps of the first complete prototype from start to finish. It is very cool to finally be able to wear you have thought about for such a long time! However, some major challenges were discovered that either need to be adjusted or completely redesigned. On the following page the prototype evaluation will explicate all flaws and imperfections that were discovered.

Wire path
The neckloop only works for static situations, because when the shoulders are lifted, or the neck moves forward the wire loop causes the patches to react to the body's movement. This can lead to unintentional opening and closing of the structure which is undesirable.

Force distribution
When force is applied in the by the wire, inside the tube, on the patch, the patch wrinkles a bit on the point the tube fixes for the first time (depending on from which side force is applied). This is because the tube is singular and is attached in a parallel fashion in the middle of the patch. The problem is that the force is too large for the small contact surface the tube has with the patch.

Edge finish
The edge finish simply does not work the way it was envisioned. Two different versions of the edge were experimented with and both did not work. In the first patch the edge was sewed onto the vest while the ribs were flat (Figure 57). With the edge being only 20 mm larger all around the patch this causes so much counterforce that the ribs are not able to tilt up. Therefore, the second edge was approached differently by cutting the edge on the corners to be able to create an in-going fold to create extra space (Figure 58). The ribs are able to tilt by this solution, but the edge is no longer completely sealing. Additionally, when the ribs are opened up the edge creases by the tension which creates a sloppy finish.

Shape and size of patch
The shape and size of the patches are off. Firstly, they are too large to fit in between the sternum strap and the waist belt of a backpack. Secondly, the widest point is right on the chest area, where the body is curvier. This creates problems when using a straight rib, because it is unable to fold properly around the curve of the body. Due to this the ribs will encounter difficulties when opening.

Vest type
The vest that was used for this test was a cheap fleece that has does not have a tailor fit, which makes the ensemble look a bit dowdy. Naturally, this is not the look that is aimed for by this concept. The vest needs to look more high-tech and futuristic. Also, the material of the vest looks very warm, which makes the application of an added insulation system on the vest less powerful, because it already looks very warm on itself.

Stitches through the tube
Another problem was discovered when feeding a through the tube. At a certain point it would not go any further. The problem turned out to be a stitch that was blocking the way. The needle from the sewing machine had penetrated the tube at this point, something was deemed impossible. Luckily it was easy to repair by removing the thread.

Sma distance and total wire length

Up till now the imagined wire foreshortening needed to completely open and close the patches has been 20 mm. However, when looking at the model I realised something. The height of the ribs is 20 mm and the wire is attached to the patch and the base (vest), this means that that the actual length the wire needs to bridge is larger, because it is the diagonal of a 20X20 mm square. The shrinking distance needs to be 28 mm and the total wire length either 707 mm for single use or 1414 mm for use on both sides (Figure 59).

Figure 57 Edge finish 1

Figure 58 Edge finish 2

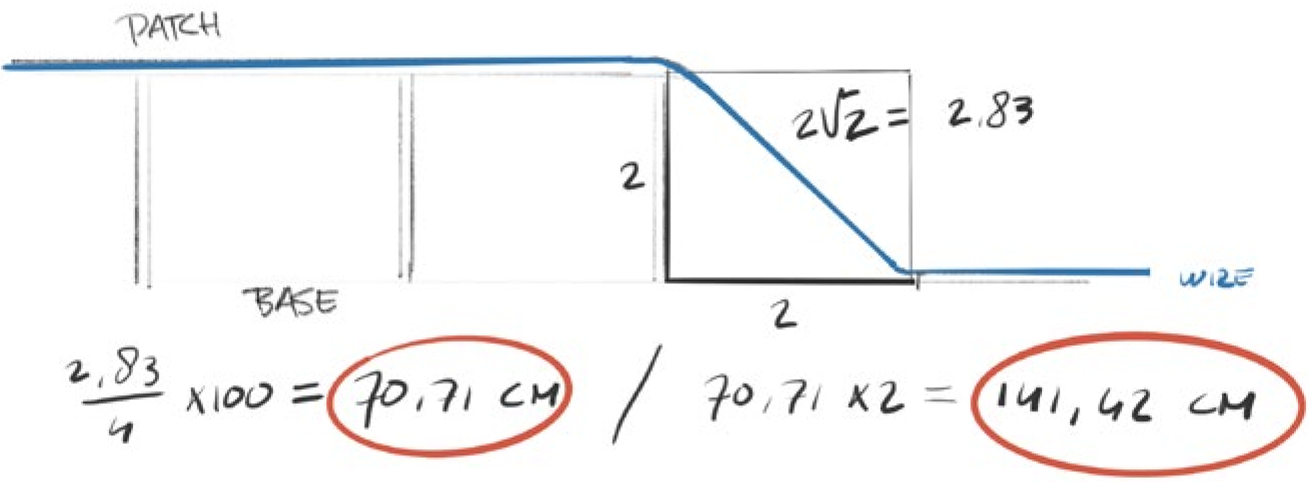


Figure 59 SMA length calculation

The first prototype is never the last, because by actually building a concept for the first time, so many unexpected things can happen and always do! This means it is time to head back to the drawing board and try out some different solutions. The biggest and most radical change that needs to be redesigned is the wire path, because all other parts are dependant on it.

The new wire path needs to prevent the body from influencing the patch movement, distribute the force more evenly over the patch and generate enough movement to fully close the patches by being longer.

Furthermore, the edge finish needs to be redesigned to enable the patch to move without too much counterforce and its wrinkling needs to be prevented while doing so.

Also, the shape of the patch needs to be revised to perfectly fit in the design area (between the straps of the backpack). Additionally, the patch must not be at its widest point in the chest area because the body is curvier in this region, which will create problems when tilting when using straight ribs.

Lastly, a vest needs to be found that gives a lighter and more futuristic impression, to better match the design vision and make the concept stronger as a whole.

3.2 DESIGN ITERATION

Solving the issues

Wire path

The wire path needs to be redesigned to prevent the flexibility of the body from interfering with the movement of the patch. Therefore, it is necessary to distribute the total length of the wire over the front side of the garment, instead of making loops around the body. Figure 60 shows two different solutions that were prototyped that keep all the forces close to the patch.

In the left solution the wire is guided in a straight line over the patch and when it gets to the end it loops back underneath the patch. It continues all the way to the top of the patch where it is connected to the same point as the counterforce.
In the right solution the wire makes a loop on the patch itself to get enough length. Both ends of the wire are connected the base on the same side of the patch with a nice spread. This spread makes the force more evenly distributed over the patch. The counterforce is connected to the base at the other end of the patch.

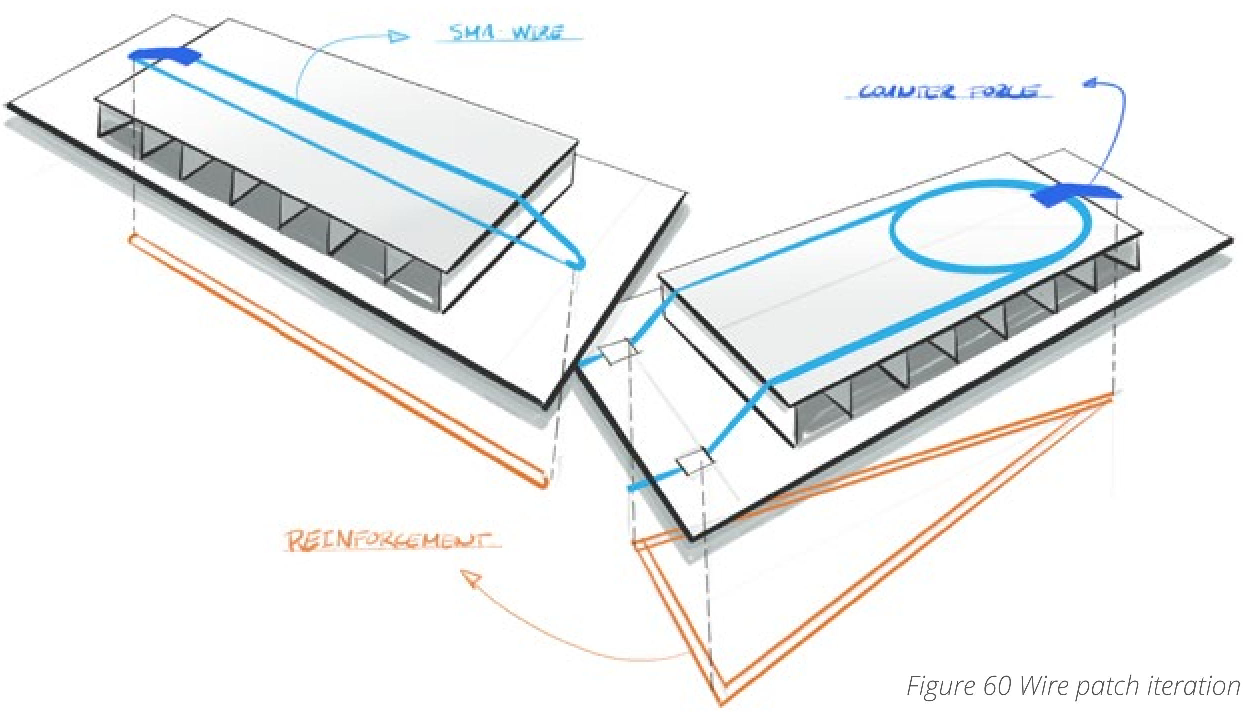


Figure 60 Wire patch iteration

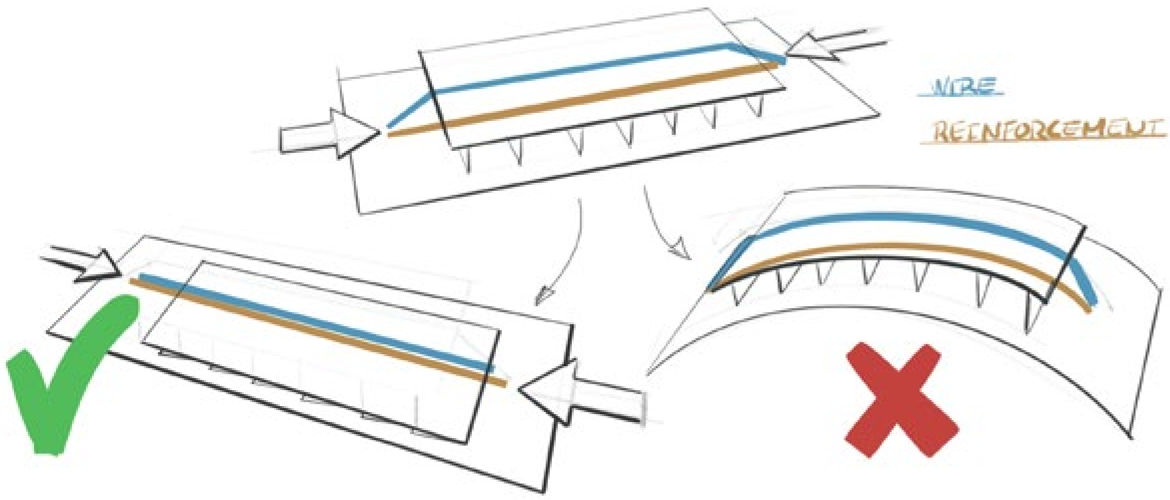


Figure 61 Buckle explanation

The orange reinforcement is necessary to prevent the connected fabric points to slide towards each other (Figure 60 & Figure 61). In the former concept the fabric connections that were attached to the counterforce and the force applied by the SMA wire were kept in place by a combination of the neck- and the fixture belt. In the two new configurations these forces have to be countered with a more rigid material that is able to undergo a compression force without buckling. Different materials were tried out, choosing the best one is a way off between rigidity and comfort. The plastic/fabric whalebone were considered to be the best option to prevent buckle underneath the patch (red circle Figure 62).

Also, for the counterforce multiple variants with different strength are selected to make adjusting possible in the future. For the two following prototypes the soft green elastic is used, which is most flexible (red circle Figure 63).

Figure 62 Counter force materials

Figure 63 Wire patch iteration

Figure 64 Solution 1 wire loop

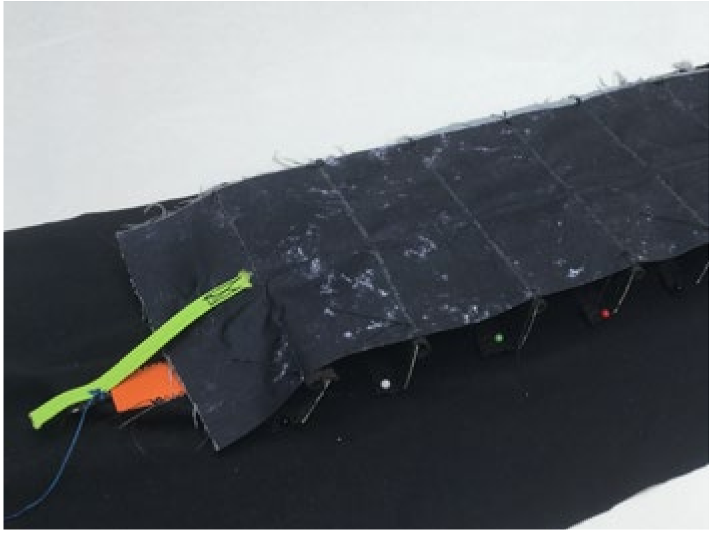


Figure 65 Solution 1 counter force

Two prototypes are made of the exact same dimensions and materials to analyse the behaviour of the two new solutions. Solution one (Figure 64 & Figure 65) uses a single beam of reinforcement on which the wire loop is attached to one side of the beam and the counterforce and the wire end to the other. The wire loop in this concept is not ideal because when force is applied to the wire the tube tends to nod on the last stitch, which makes it less durable. Also, the single line of tube on the patch does not distribute the force over the patch well enough to neatly close.

The second solution however performs very well on every aspect in a horizontal orientation, accept on buckle prevention. It is less noticeable compared to the former solution, but not yet perfect. Figure 66 & Figure 67 show the movement of the patch. What can be seen here is that the force distribution on the patch is even, which makes the patch close completely. The big advantage of this configuration is that both ends of the wire debouch from the tube on the same side of the patch, making them easily connectable to the electrical current which will be used to heat the wires in the final model. Note that this solution needs a double wire length (1414 mm) compared to the former solution, because both ends of the SMA wire are utilised to overcome the distance of 28 mm.

Figure 66 Solution 2 open

Figure 67 Solution 2 closed

Figure 68 Solution 2 on vest

To test the performance of the second solution in the intended orientation, the prototype is pinned to a vest. This way the prototype can be tested on functionality, buckle and comfort. Surprisingly the buckle did not show in this orientation, presumably because the whalebone is slightly bended in the opposite direction by the shape of the body and the vest provides more support than a loose piece of fabric. Additionally, the movement of the patch is not limited in any way and is able to close perfectly. The reinforcing whalebone were expected to be disruptive for the experienced comfort of the vest, but in fact they are hardly noticeable.

Edge finish

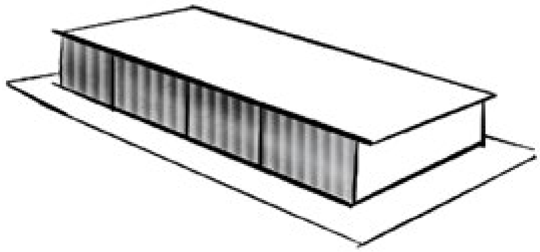
The challenge that was discovered regarding the edge finish, during the build of the initial prototype, was that it complicated the opening of the patch because of its large force. Additionally, the edge wrinkled when the patch opened due to the tilting motion.

This part needs to be completely redesigned to make the prototype work. Therefore, three different solutions were contrived and prototyped to evaluate the working.

Fringe band

This solution makes use of multiple small strips that are able to tilt just like the ribs. The encountered problems with this solution are:

- The strips amass and create a bulge
- No complete seal
- Looks messy



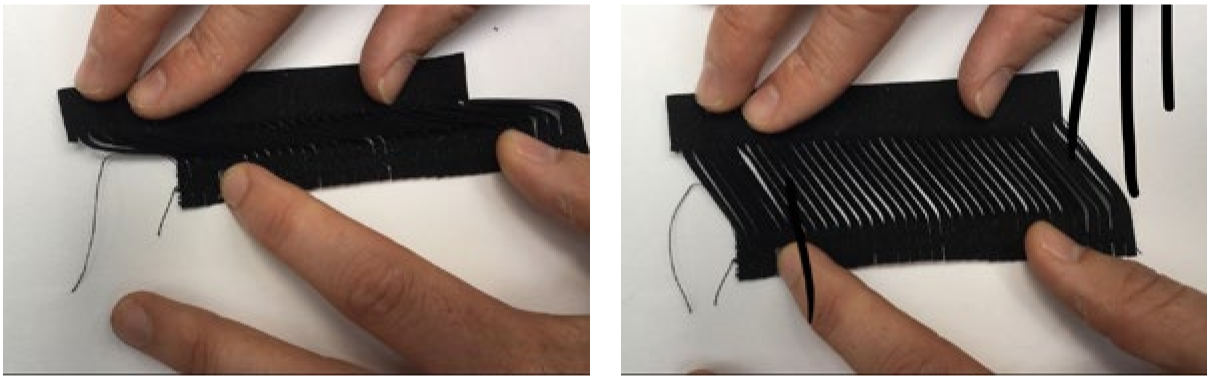
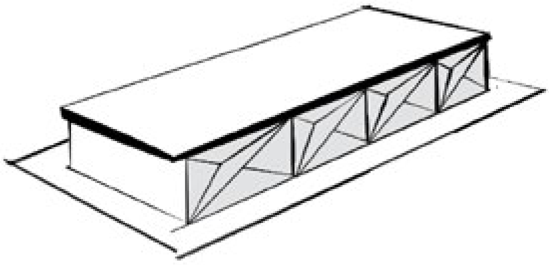


Figure 69 Fringe band edge

Origami cover

This solution uses special folds that are able to keep one opening sealed over the entire range of movement.
The problems encountered with this concept are:

- Hard to produce (Two covers per air-chamber)
- While folding down the cover needs to pop inwards, which demands more force.



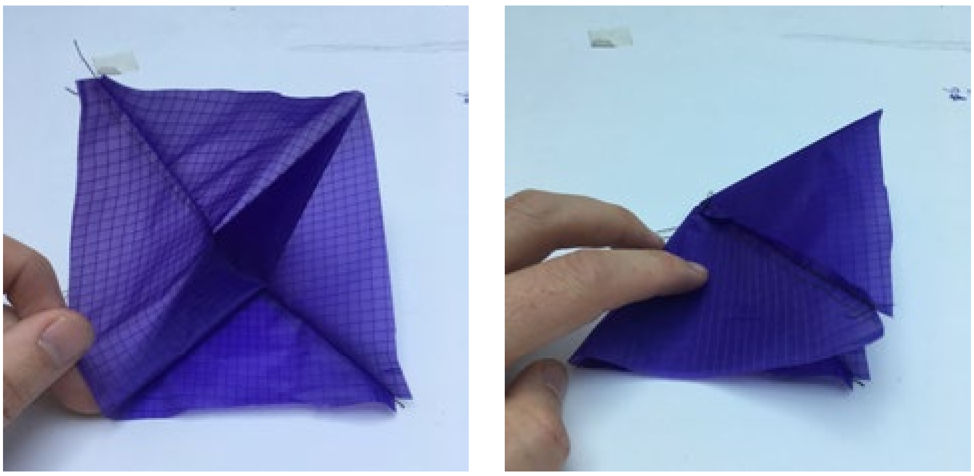
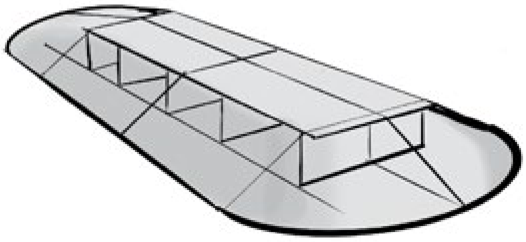


Figure 70 Origami edge cover

Flexible over-patch

This solution is very similar to the former solution. However, the surface-area is increased which makes the fabric way more flexible and capture more air. Creases in this solution are prevented because the patch is able to slide underneath the over-patch, which gives a more finished look.
The problems encountered with this concept are:



- Still much force needed
- The working element of the prototype is no longer visible

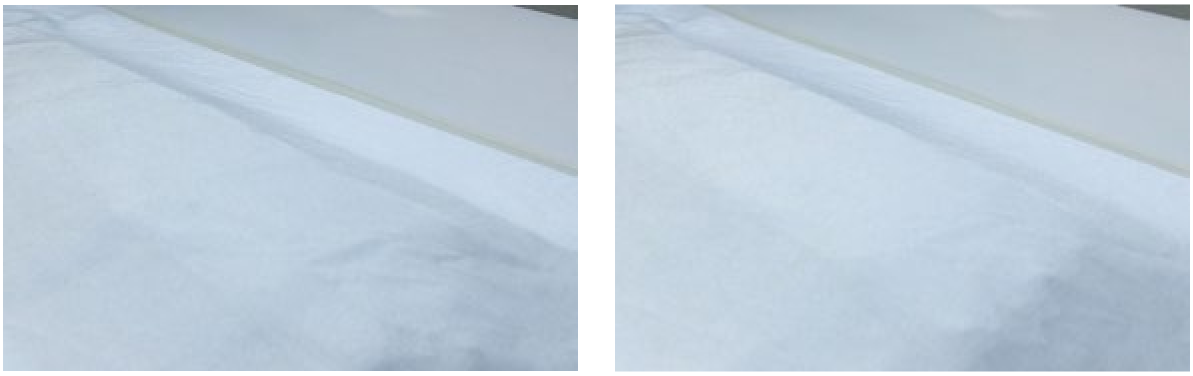


Figure 71 Flexible over-patch

The solution in which the problems are most surmountable is the over-patch. To make the working element visible again, a zipper will be incorporated in the over-patch. This is also convenient when the counterforce needs to be adjusted or the wire needs maintenance. To decrease the opening force a fold will be made along the middle edges of both over-patches to give the system more room to move.

Figure 72 Zipper test

Figure 73 Over-patch shape

Finding the right vest

The new vest was found at Decathlon. Compared to the old vest it looks way more futuristic and suited for the concept. The vest is also more tailored and not as thick as the old one. All together the total picture of the prototype will make more sense and look way better on this vest. A nice detail is that the side pockets are inserted backwards, which leaves the front plane of the vest completely untouched, with lot of room for the addition of the insulation system.

Figure 74 The prototype vest

Shape and size of the patch and over-patch

The shape and the size of the patch were found to be incorrect. The patches were too large to fit between the straps of the backpack. With the new vest obtained a drawing is made using transfer paper to analyse the dimensions on which the patches must be placed. Beforehand the vest was put on together with a backpack to mark the borders of all the straps, to define the design space. The shape of the patch is drawn into the design space ensuring a minimum distance of 25mm to each strap. This distance is necessary to make sure the over patch does have enough room to allow expansion, even when the backpack is worn on top. The maximum width of the patch is 120 mm, because if its larger the curvature of the body will counteract a smooth rotation of the ribs. Additionally, a small test is done to determine if the new tube length (1414 – 2*28 = 1358 mm) is able to fit inside the patch (image). To fit the length the tube needs to make three loops.

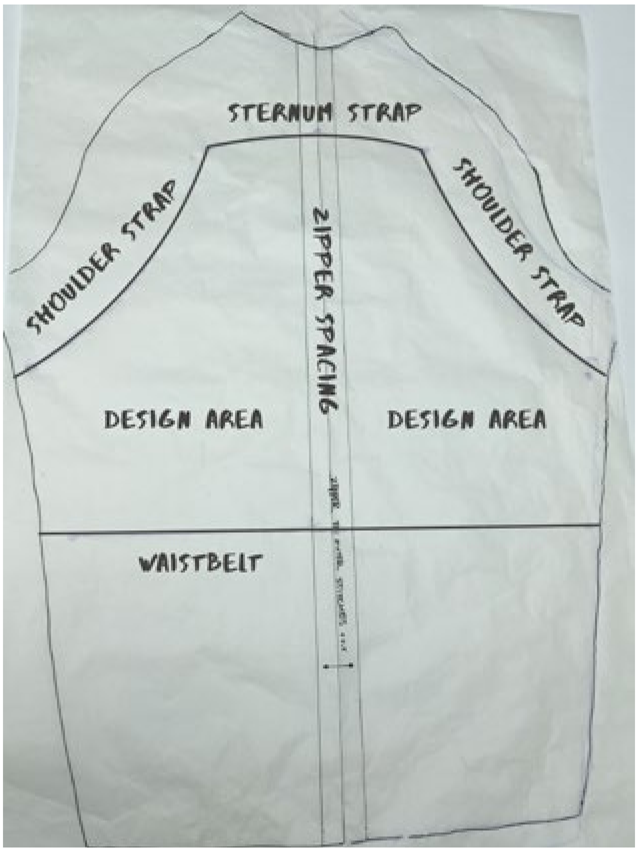


Figure 75 Transfer paper mapping

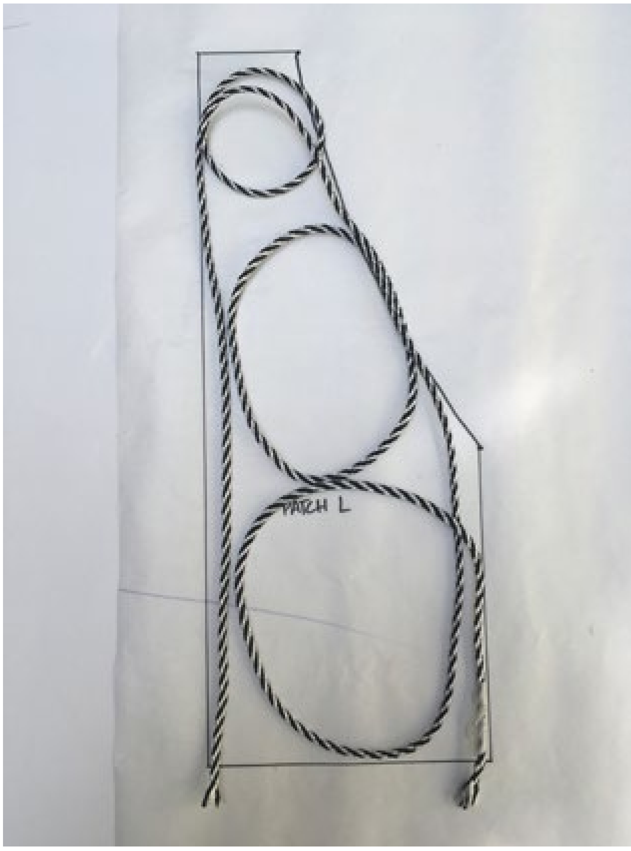


Figure 76 Wire length in patch

Figure 77 The new pach shape

The shape of the patch has changed drastically and also became smaller in surface area. However, the newly designed over-patch makes up for the lost space by creating a chamfered border around the patch that is also able to trap air inside. The shape of the over-patch was designed in such a way that it flows with the lines of the vest and while leaving enough room for the patch to tilt. In the new prototype the patch will tilt down to close, due to the new wire-path. Therefore, the over-patch has a larger spacing with the patch at the bottom of the shape, compared to the top. The over-patch steps outside the designated design area, however this does not lead to any problems because the patch is designed to always keep at least 25mm off the straps of the backpack. As a result, the over-patch always gets enough wiggle-room to allow the patch to open.

Proof of concept

The moment we have all been waiting for, where all the pieces of the puzzle need to come together has arrived. The system can finally be tested to see if the SMA wire is able to close the patch by contracting. The two big questions that are still unanswered are: Does a single wire provide enough force to overcome the counterforce? Is the sliding resistance of the wire inside the tube low enough to make the patch move?

For this test one of the earlier produced patches is used in combination with a 0,25mm SMA wire with an activation temperature of 70 degrees Celsius. The wire is guided over the top of the patch, through the Teflon tube. The wire is kept in place by two small pieces of tube that are connected to the ground plane and both ends of the wire are connected to a DC power supply. This is where the magic happens.

By applying an electrical current to the wire, it heats up because of its resistance. When the wire is hot enough it starts to contract about 4% of its total length. The tube makes sure the maximum displacement is converted to the patch in order for it to close.

I am very proud to conclude that the test was successful on the first try. The patch closed very smoothly and opened back up again when the wire cooled down. The opening motion was a lot slower than the closing motion, which is because the wire cools down slowly after heating. The higher the activation temperature, the faster it cools down, because of a larger difference with the ambient temperature. To speed up the reaction time of the system a wire with an activation temperature of 90 degrees Celsius will be implemented in the final prototype.

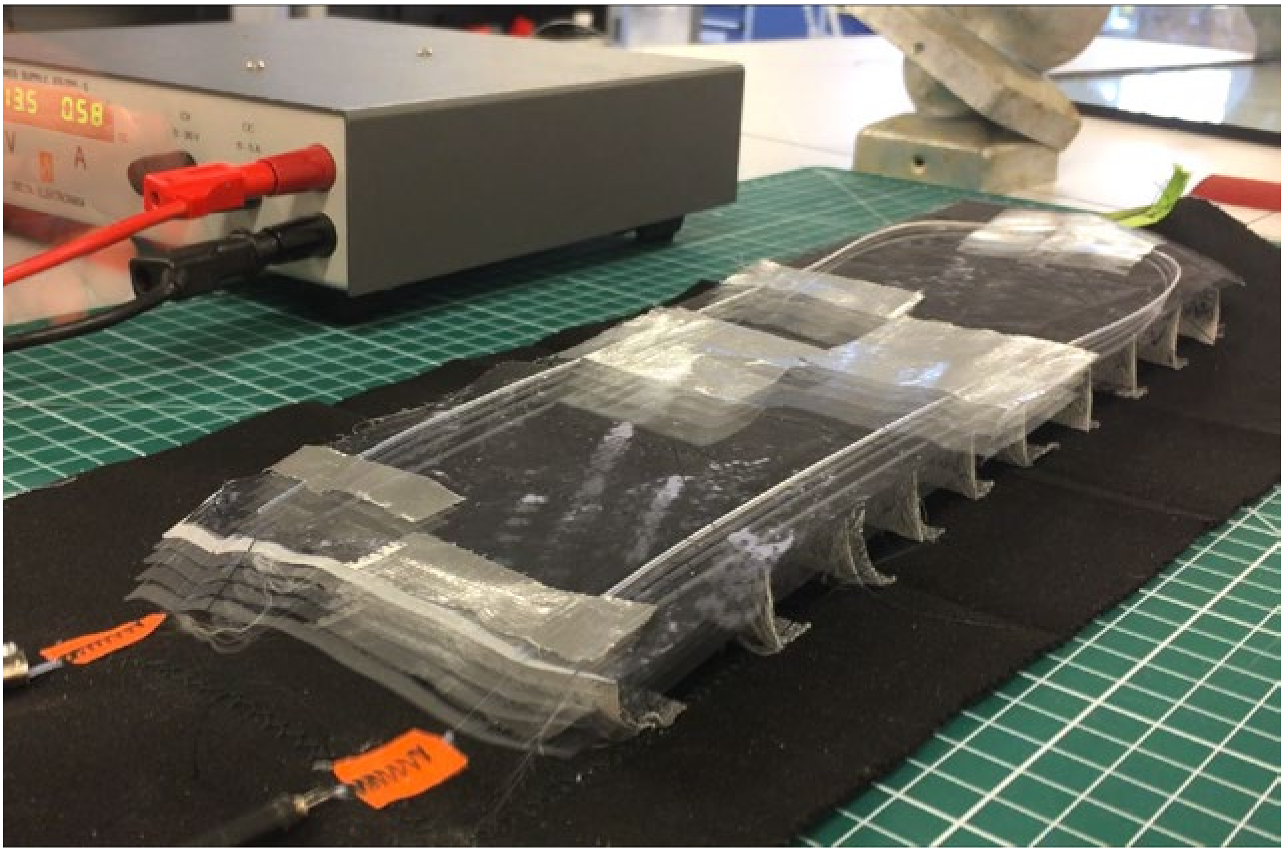


Figure 78 Patch in movement

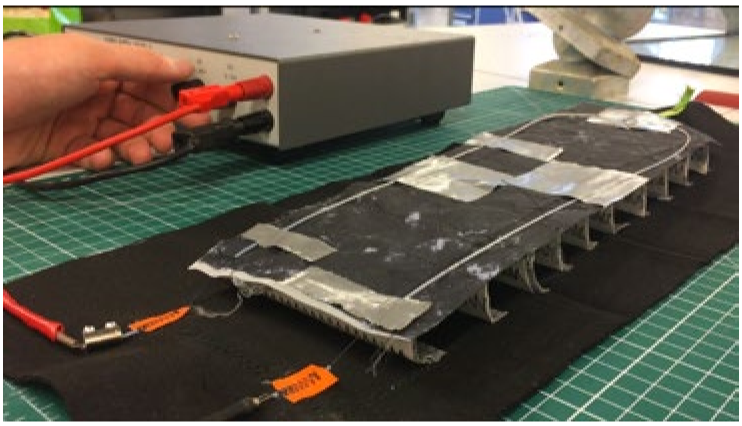


Figure 79 Start position

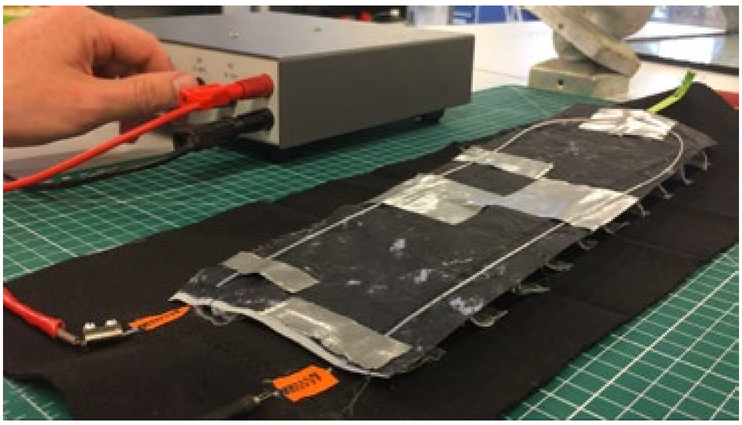


Figure 80 Closed position

3.3 BUILDING THE PROTOTYPE

Steps and specifications

In this chapter the building of the prototype will be described as a visual story. A photo report is made of the building steps from start to finish. When the prototype is complete the dimensions and materials of each part that is used to build this prototype will be illustrated in a drawing.

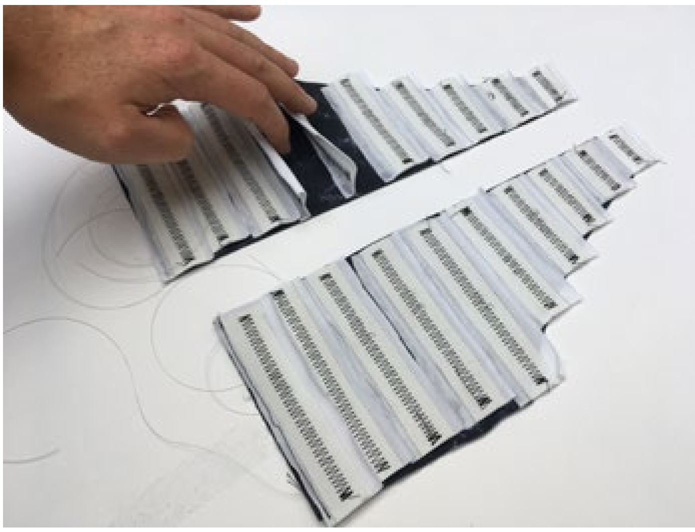







Figure 81 Finished patches

Figure 82 Patch placement

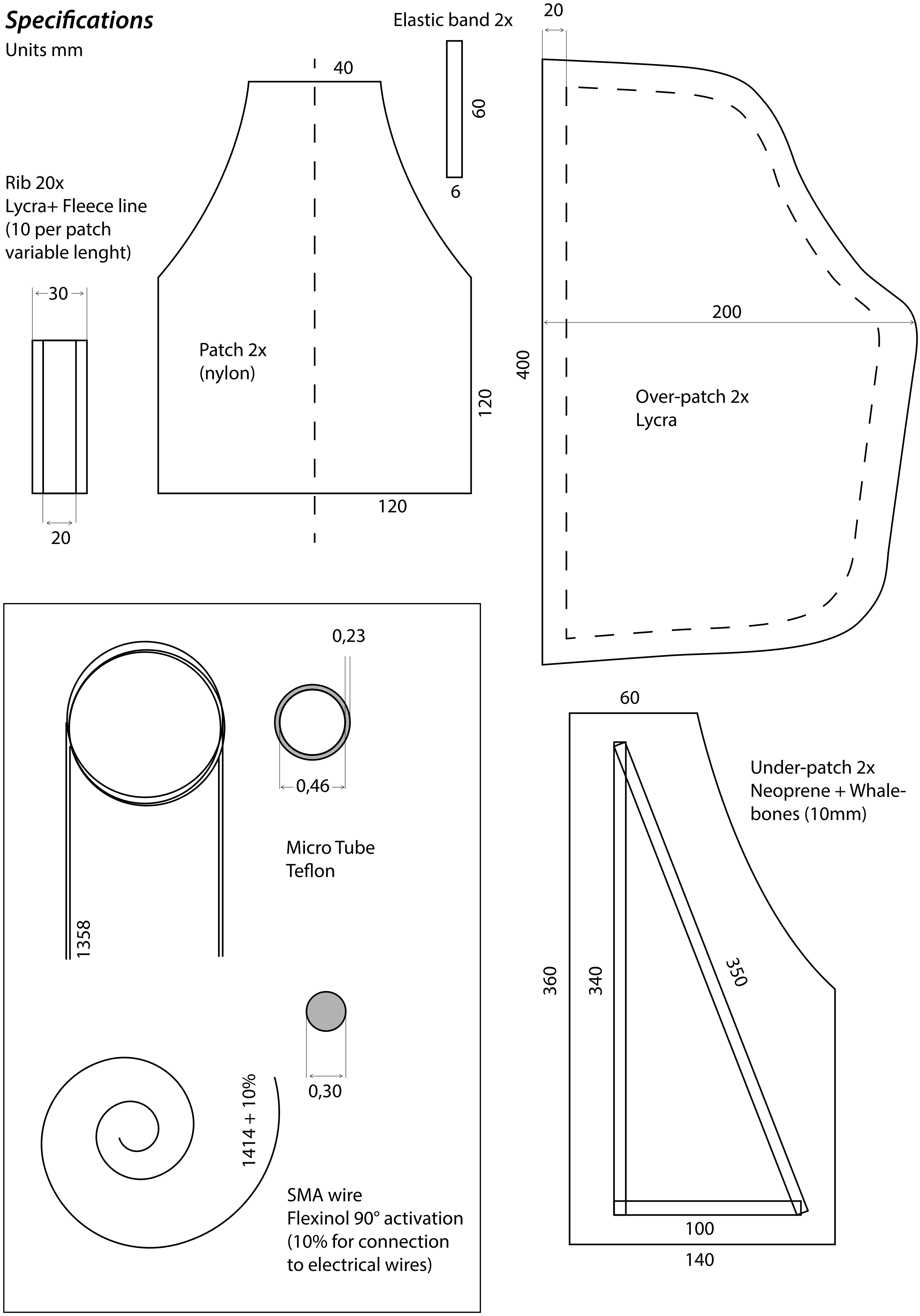
Figure 83 Patch fixed

Figure 84 The result

Figure 85 Zipper opening towards patch

Specifications

Units mm



3.4 USER TESTING

Into the lions den

Two user tests are conducted to get feedback on the design and to study the needs of the intended target group to a more extensive level. The first user test is conducted at the Bever, a famous Dutch outdoor store.

The second user test is set up via a popular Dutch, online hiking forum. The approach of both tests will be explained in this chapter, after each explanation the most important outcomes will be summarized.

What I want to learn

Is the product desirable?
What are the main concerns?
Is the prototype comfortable to wear?

Figure 86 Bever store

Bever, the outdoor store

For the first user test I went to the city centre of Rotterdam to get first hand feedback from the outdoor enthusiast. There is no better place to find these people than in the Bever, a popular outdoor chain that is located in the Netherlands.

Approach

The day before the research the store manager was asked for permission to interview people inside the store on the condition that I would inform them the research was not linked to the store in any way. With permission granted I went there the next day with my prototype and my questions prepared. I used a very open approach and tried not to stick to the questions so much, to really give the people the idea and the space to speak out their thoughts. After a brief introduction the prototype was explained and I asked each participant for their initial reaction, which worked great as a starting point for conversation. During the conversation the participants were asked to try on the vest and move around a bit, to be able to give comments on the comfortability.

After having interviewed two people in the store of which one was a tree sawer and the other an outdoor enthusiast, the employees from the store started to get curious about my concept. I seized the opportunity to get some more information from the real gear experts. Eventually, I managed to interview four different Bever employees. During the last two conversations I noticed some reoccurring comments, so the decision was made to leave it at six interviews. After each conversation notes were taken to keep track of all the thoughts and ideas.

Overall the reactions on the concept were very positive. However, I also found out about the concerns the target group has about the concept design. What was nice to see is that the model of the concept really evoked the imagination of the participants. They even started dreaming about other possibilities and came with suggestions for additions and even other applications. Table 16 shows the clustered positive points and the major concerns the target group has about the concept. It also shows multiple suggestions that were made by the participants during the session.

Positive	Concerns	Additions	Other applications
No discomfort while wearing	Temperature range is personal	More pockets	Professional working gear
Less is more (2 in 1)	Wear resistance by movement of patch	Button to adjust working range	In the hardshell
Low weight	Compression by gear worn on top	Colour changing fabric	Ski-gear
Works when wet	Difficult to cramp up in bag		

Table 16 Results interview

Hiking forum

To get more information from experienced outdoor fanatics a concept description was posted on the forum of Hiking-site.nl, in the material discussion group. After the description four questions were asked to the reader to stimulate reactions and fire up a discussion. This is a great, low effort method to immediately reach the right kind of people.

Questions

- What is your first reaction on this idea?
- Does this product catch your attention as an outdoor enthusiast?
- In what way can this be an addition to your gear?
- Is there something you would like to add/change about the concept?

Time to go

Reactie van de ervaringsdeskundigen gewenst.

Momenteel ben ik bezig met het ontwikkelen van ThermoTilt, een smart-isolatie systeem voor de middenlaag van de hiker outfit. De isolatielaag, bestaande uit luchtkamers, reageert op de buitentemperatuur en vouwt uit over een gebied van 10 graden (12-22). Bij 12 graden zijn de kamers volledig uitgevouwen en zorgen zo voor een beter isolerend geheel. Word het warmer dan 22, dan zullen de kamers volledig gesloten zijn.

De beweging wordt mogelijk gemaakt door een geheugen metalen draad die reageert op temperatuurverschillen.

De uitvouwende vlakken zijn zo ontworpen en gepositioneerd dat het dragen van een rugtas met beide straps (heup en borst) vast, het systeem niet zal hinderen.

Mijn vragen aan jullie:

1. Wat is je eerste reactie op dit idee?
2. Wekt dit product jouw interesse als outdoor fanaat?
3. Op wat voor manier zou dit iets kunnen toevoegen aan jouw gear?
4. Wat zou je anders zou doen?

Bij voorbaat dank voor je reactie!

Groet,
Tijmen (student TUDelft)

vrijdag om 15:40 Meld #1 Reageer

Figure 87 Forum post

The first reactions on the idea were very positive, but they were followed up by interesting comments and tips. Strangely, no-one was very keen to adopt the system in their current hiking gear.

The problem of this research is that the description was not covering all points, because this would lead to an uninterestingly large text that no-one likes to read. Also, I was unable to post pictures on the forum, that would have been able to explain a million words. These limitations made it very hard to get my fully get my idea across.

The concerns the people on the forum had about the concept design mainly are about the temperature range and the weight. All the Bever employees, which are all outdoor fanatics themselves, also mentioned the importance of being as light as possible. They called hikers: 'Grammenjagers' (Gram-hunters), who always want to be packed as lightweight as possible. table summarises the main findings that were derived from the reactions on the forum.

Positive	Concerns
Caught their attention	Temperature range
Evokes curiosity	Weight
Interesting concept	Walking and rest state are not noticed by smart system

Other applications
Wetsuit for sea kayak
Proffesional preformance gear (when important not to loose any time)

Table 17 Results forum

To conclude, after having spoken to multiple people with of outdoor experience and knowledge about hiking gear, it is safe to say that the product can be desirable. Although many people had their concerns about the weight and the temperature range, I think the product has a chance in the market. The reason for this is that everyone reacted very enthusiastic about the concept and it triggered their imagination of other application opportunities in the field.

Regarding comfort, the prototype was received very positively. While wearing the prototype and moving around the participants did not experience any discomfort. The main reason behind this turned out to be the central placement of the patches that have the exact right size not to hinder when bending forward.

With new products that can not relate to something the users know, the same problem always occurs. People tend to be affright for new developments, especially when it contradicts with the way they are used to. Designers should not be put off by these initial reactions, instead they must try and find a way to gradually introduce their advanced concept for it to be accepted among the public. The MAYA (Most Advanced Yet Acceptable) principle explains this theory. According to Raymond Loewy a famous designer and futurist who came up with the theory;

"The adult public's taste is not necessarily ready to accept the logical solutions to their requirements if the solution implies too vast a departure from what they have been conditioned into accepting as the norm."

Innovative products always need a certain amount of incubation time to be accepted among the large public. When the product lives up to the expectations of the early adopters and shows clear benefits over more traditional products, it will eventually find its way and become successful.


SALE
HEREN

3.4

ThermoTILT

SMA embedded thermo-responsive insulation technology

Summarizing, during the embodiment phase the teething troubles of the concept were tackled, which lead to a redesign of the initial concept. The final model is an accurate representation of the current status of the product's development. The intended goal of making a prototype that both works and also looks professional is reached. However, there are still a lot of steps that need to be taken towards further development of this product.

User testing helped to discover that the comfort of the vest is not badly influenced by the application of the patches. The reactions also pointed out the most important qualities hikers are looking for in their gear. Weight is the biggest decisive factor for a true outdoor fanatic. Additionally, many concerns people have regarding the concept are about either temperature range, durability or packability. Ideas to solve these potential issues will be discussed in chapter 4.2 "Recommendations".

END OF EMBODIMENT PHASE


CONCLUSION

CONTENTS

This final chapter reflects upon the concept design "ThermoTILT" by discussing the limitations of the research and development done so far. Specific aspects that still require improvement will be discussed accompanied by recommendations and advice for the further development of the concept design. Furthermore, an estimation will be provided that indicates the current stage of the product development track relative to a finished product. Lastly, a brief evaluation of the design vision will be provided which reflects upon the concept design.

4.1 **LIMITATIONS** AND DISCUSSION

To evaluate the proposed concept design in terms of desirability and comfort a user test was done using the final prototype. However, at the time of the test the SMA wires were not yet incorporated in the system. Therefore, it was not possible to show the automated opening and closing of the patches. The participants were asked to put on the vest and move around, to give feedback on comfort. This test proved that the patches did not limit the movement or had a negative effect on comfort. To further research the comfort a test can be set up with a focus group that goes on an actual hike with the prototype.

The ultimate goal for this project is the creation of an independent system that just needs temperature fluctuations to activate, without the support of an external power supply. Due to the limited availability of shape memory wires of different activation temperatures I was unable to obtain the perfect wire. Therefore, this part of the concept is still only grounded by theoretical proof. Obtaining the right wire is for this project is application, but it would require the order of a large batch, which would be very expensive. Due to a limited budget and the large risk involved, this was impossible.

Finally, the time limitation that every graduation student in the new system has to deal with plays a big role in the achievable level of thoroughness of the project. Officially the board only offers twenty weeks to complete the thesis. Depending on the starting point of a project, which is either a detailed brief or an open assignment, the end result of the project is already determined. With the former starting point, the end results usually consist of a detailed design that is close to a final product. With the latter, however, a proof of concept is usually the norm, given that more time is invested in establishing a solid foundation.

4.2 RECOMMENDATIONS

The steps toward further development

The user tests as well as the limitations of the project point out the way for possible further development tracks of the product. Also, personal ideas that are worth exploring and could possibly improve the concept are mentioned.

To discover the impact of the insulation system **Thermal testing** can provide useful insights about patch size, -thickness and -placement. This was very high on my list, but it required too much time to plan-in and a required a finished prototype. Unfortunately, I could not make this within the given time.

Durability of wire and fabrics have not been analysed. The movement of the patch creates a friction between the patch and the over-patch. Endurance testing can be valuable to determine and optimise the lifetime of the system.

Packability (volume when stored) must be looked into because it is very important for the target group to be able to pack the garment in a small volume. The whalebone that are used as a reinforcement to prevent the patch from wrinkling might need to be redesigned or adjusted to allow more flexibility.

Make the Temperature range adjustable to fit personal preference. Every person produces heat when the body is active, but some people produce more heat then others.

From the reactions on the forum research I learned that everybody has his/her own preference in in insulation adjustment. Therefore, it could be a large asset for the product if the activation range is manually adjustable.

To convince the user about the true potential of this concept design, advertising should incorporate **Comparisons to traditional insulating layers** like the fleece and the down jacket. By doing so, comparison material is provided to the target group which could help them in decision-making. The fields that must be covered in this comparison are: weight, durability and packability.

An interesting option to further research is the implementation of multiple thin tilting layers stacked on top of each other. The SMA in each individual layer must react on a slightly different temperature range to create a self-regulating system with an **Increased thermal precision.**

Production and automation are not yet tackled, it can be very useful to analyse the building steps to **Optimize the concept for production.**

The Sustainability of the system can be optimised by experimentation with single material application. Polyester is a very versatile material which can be produced in many different thicknesses and finishes. Clothing that is build up from different fabrics is very hard to if not impossible to separate and recycle. Designing every part from the same material will drastically lower the product's carbon footprint.

Round ribs offer a new world of possibilities to the concept, because it will improve the drape of the garment as well as the comfort. To correctly execute this a body scape analysis needs to be done with 3D scan technology. The scanned body surface will allow computerised cutting machines to perfectly cut out the (tilting) ribs along the contour-lines of the body. It would be interesting to discover the differences for male and female bodies and create optimised versions for both sexes.

Getting the right wire will be a big and expensive challenge. Nevertheless, if it succeeds, it will have a positive impact on the design. Without the addition of any external power source the user will experience an all-natural reaction that will feel magical.

So far, the concept has only been tested by users during an interview that took place indoor. It would be a nice experiment to find outdoor enthusiasts and ask them to wear the vest on one of their hikes. **User testing in the field** on the location the product is designed for can lead to many new insights.

Exploration of other possibilities to implement the ThermoTILT system can lead to many new designs. I have the feeling that the system in general can be of great use in all sorts of applications. The only thing it needs to work is a temperature fluctuation, for example think of moving architectural surfaces that can be aesthetically pleasing, but at the same time regulate the insulation of a building.

4.3 **PRODUCT** DEVELOPMENT TRACK

Estimation of design costs

In this chapter a brief evaluation of the progress I have made so far is explained. The reason for this is to show how much work is involved in developing a product from design vision until the delivery. I will also make an estimation of the design costs this would involve.

The graph in figure... shows the usual development track a product has to go through before it can actually be manufactured. The light blue area in the graph is an estimation of how far I got in the development track. The arrow splits up three of the realisation stages: design, production planning and production. The design is almost finished, it just needs to be optimised for production. The early stages of the production planning and production are covered by the build of the prototype. The prototype allows for testing and optimization to take place. Additionally, the prototype can be used as a means to facilitate discussion between design and production, which will help converting implicit ideas to explicit knowledge more quickly.

It took me 22 weeks to reach this point. The arrow in the graph is at about 3/8 of the total project time. If this was a project I would be working on for a company as a Junior designer my monthly salary would be € 2865, - on average (WO Monitor, 2016) I got a prototyping budget of €500, - which was sufficient for 22 weeks.

The calculation of the estimated design costs is displayed below Figure 88.

Design costs estimation

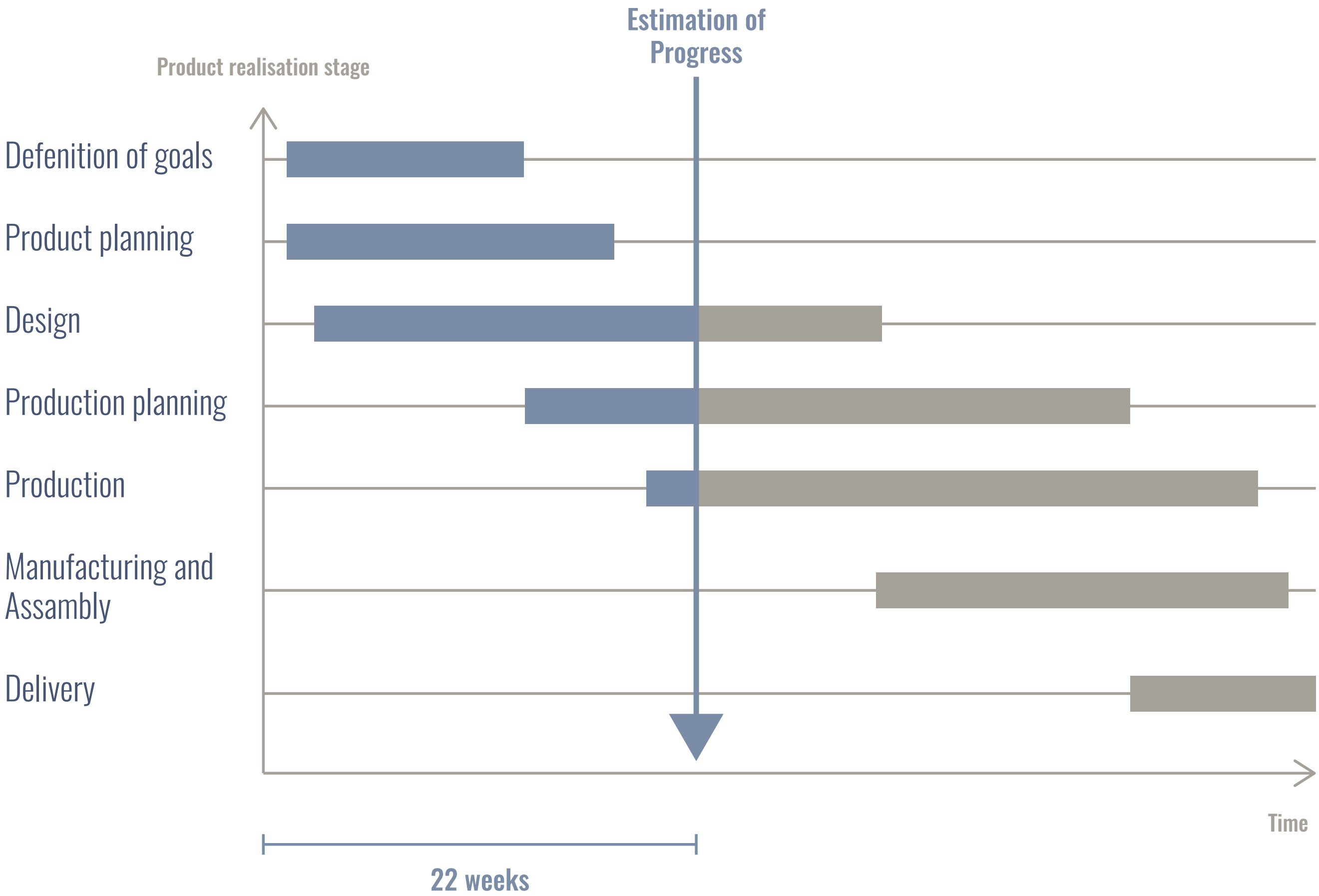


Figure 88 Progress estimation

22/4*2.865 = 15.757,50 (salary 22 weeks)
15.757,50 + 500 = 16.257,50 (salary 22 weeks + proto budget)
16.257,50/ (3/8) = **43.353** (Entire project length + proto budget)

€ 43.350, -

This calculation does not include production costs.

4.4 CONCLUSION

Using material as the starting point of this project, has forced me to approach the design process in a different way compared to the more traditional way, which centres around finding a solution to a problem in society. Shape Memory Alloys have unique properties, singular to this type of alloy and which cannot be found elsewhere. The value of these properties and how it could benefit a product came to light, not just through extensive research but more importantly by tinkering and experimenting with them first hand. Each experiment and test performed in the Analysis, Conceptualization and Embodiment phase show this systematic step by step approach, which has educated me about the possibilities this material has to offer by getting to know its properties and behaviour through and through.

Central to this project has been to create a final prototype that could demonstrate the SMAs potential and illustrate how it can contribute to make a more meaningful design. However, this project goes beyond merely showcasing the alloys functionality, but also attempting to inspire designers and users alike by proving how it can be incorporated in something we use in our daily lives. Therefore, this project tried to present SMAs in a new light by discovering a new field for its application, breaking away from its traditional high-tech environment which is almost invisible to the eye and unbeknownst by most designers. Bearing in mind these predefined objectives, the following design vision was formulated:

Integrating shape memory alloys and textiles to create a thermally self-regulating garment that increases in thickness when exposed to cold temperatures and decreases in thickness when exposed to warm temperatures.

This led to an interesting system which combined the alloy with a Teflon microtube to form a brake cable mechanism that has the ability to open air chambers. By incorporating this system in an insulating layer for hikers, the earlier stated design vision was successfully achieved. Despite only resulting in a working prototype with still room for improvement, it has revealed to have the ability to match the current market alternatives (e.g. fleece) and might even outshine its competitors in some ways, given its smart use of SMAs and air to maintain the user's thermal equilibrium. Additionally, this system not only showed great potential in the current application as insulation layer, but also suggests promising applications in other fields of design, such as architecture. I came to the realization that the system I designed actually is the main product and the vest is just a way of applying the system. There are so many other possibilities in which this system can be applied, the only thing it requires are temperature fluctuations to work.

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