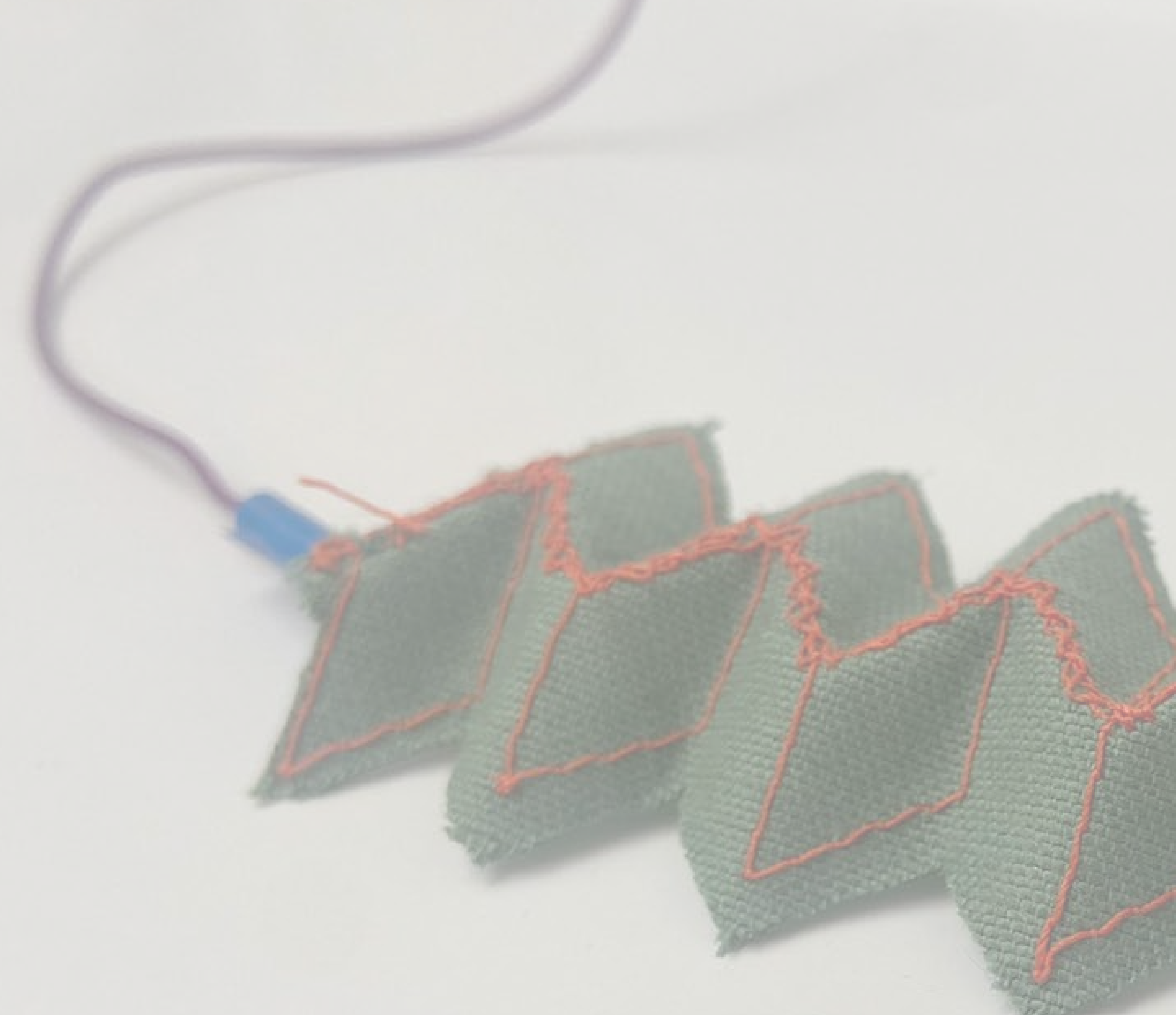

SHAPE MEMORY ORIGAMI FOR HAPTICS

Exploring the potential of a material system based on SMAs to generate haptic feedback for visually impaired people

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ABBREVIATIONS & TERMINOLOGY

VIPS	Visually Impaired People
SMM	Shape Memory Material
SMA	Shape Memory Alloy
SME	Shape Memory Effect
SE	Super elastic
As-Af	Austenite start - finish temperature
Ms-Mf	Martensite start – finish temperature
NiTi30	Nitinol wire with activation temperature of 30C
NiTi40	Nitinol wire with activation temperature of 40C

Passive feedback	Haptic feedback that is passively perceived such as a vibration
Active feedback	Haptic feedback that requires active exploration of a person
Counterforce	A force that is used to deform a shape memory wire in cooled state providing a two-way actuation
Grounded shape	The shape that is trained in the ceramic oven
Deformed shape	The shape that the SMA wire has in cooled state /martensite after it is deformed
Shape extension	The percentual extension of the SMA wire based on the initial shape trained length
Displacement	The percentual difference in shape change from the deformed state to the activated state: (L_deformed-L_activated)/L_deformed

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Additionally, I wish to sincerely thank the persons who participated in this project. It has been an honour and deeply enriching experience to have interviewed such inspiring persons with visual impairments. The openness of these participants in welcoming me into their homes and sharing their vulnerable stories has left an indelible mark on me. Additionally, I am grateful to those who tested my prototypes. Their openness and ability to empathize, examining the materials and envisioning potential applications greatly contributed to the project.

Finally, I would like to acknowledge my family, friends, the staff of the materials lab, and my fellow graduates. Their continuous support and encouragement were the foundation upon which I could rely throughout this project.

ABSTRACT

This project explores the potential of a material system based on SMAs that generates haptic feedback for Visually Impaired People (VIPs). Since VIPs rely more than others on tactile information, there is a need for more natural and unintrusive haptic devices as the commonly used electromechanical actuations are often perceived as intrusive and less acceptable than non-vibrating feedback. SMAs emerge as a promising solution to address these challenges effectively, due to their inherent ability to create silent, organic sensations, while being lightweight, thin, and flexible (Cruz et al., 2018).

The aim of this project is to investigate the unique characteristics of SMAs and translate this into an integrated material system that could inspire designers to adopt these materials and revolutionize tactile experiences. The process had an explorative nature and included a research, form configuration and embodiment phase. Most current haptic systems based on SMAs have the limitation of small actuation ranges and/or difficulties in integrating them in soft material systems. Therefore, in this project, a soft integrated material system is designed that shows the potential of incorporating SMA and SE flat springs into an origami-paper textile to create haptic feedback.

By using the combination of the SMA-SE flat springs, an easy integration of the wires in the paper-textile is enabled and a two-way actuation is created with a displacement of around 16%. Through the use of the origami structure, the two-dimensional shape change of the SMA spring is transformed in a three-dimensional shape change creating rich tactile feedback that can be perceived passively as well as actively.

The sensations generated by the material system were easily perceived with the hands and the movement was characterized as natural, calm and gentle by sighted participants. This demonstrates that there is a potential for creating an integrated material system based on flat springs SMAs that generated haptic feedback for VIPs in a natural and new way. Additionally, based on all these findings, a guideline was developed for SMA wires with the aim to give an overview of all steps involved when designing a material system based on SMAs.

CONTENTS

1 INTRODUCTION

1.0 INTRODUCTION

What if products could adapt to the environment, just like nature? Like a pine cone that folds together to protect its seeds from rain, and reopens when it is dry. Products around us are defined by the materials that they are made of. Imagine that these materials display dynamic behaviour as a result of surrounding stimuli to convey information.

That is what Shape Memory Alloys (SMAs) do. They change shape in an organic yet programmed way due to external stimuli such as heat (Bengisu & Ferrara, 2018). As such, these materials can be designed into structures to change the shape of an entire product while being thin, strong and lightweight which can be valuable in application areas that require integrated and compact actuators. Moreover, SMAs are not necessarily dependent on electronic actuators and sensors which gives this the potential to simplify systems. A good example of a shape memory product is the self-extendable stent implant made from an SMA for narrowing veins (Chaudhari, Vora & Parikh, 2021). Currently, these materials are mainly used in the aerospace and medical fields. However, one can imagine that these materials as well can be used for other purposes on different scales such as the field of haptics, which refers to the sense of touch.

In this project, the potential of a material system based on SMAs is explored for haptics. More specifically, this study targets the needs of Visually Impaired People (VIPs), since they rely, more than others, on tactile information. The most common way to convey tactile information is by feedback in the form of vibration, which has the limitation that it is not silent and depends on electronics. SMA material systems could provide new ways of generating haptic feedback as they tend to create a more organic and silent movement due to their shape changing ability. Moreover, due to their flexible and thin character, they have the potential of providing soft and integrated haptic devices which could be interesting for haptics for VIPs.

With a particular emphasis on addressing the unique properties of SMAs in a material system for haptics, this project tries to inspire designers to adopt these materials and revolutionize the tactile experiences of visually impaired people.

This report serves as a comprehensive account of the exploratory journey undertaken in this project, providing valuable insights for the field of haptics, VIPs and SMAs and serving as a roadmap for future development of integrating SMAs in material systems.

1.1 PROJECT INTRODUCTION

1.1.1 Problem definition

Assistive devices are gaining popularity for VIPs including haptic devices for tasks, navigation, and communication (Fact.mr, 2021; Sorgini et al., 2018). Haptic devices have the advantage of conveying information silently through touch which could be favourable in situations where audio feedback is not suitable (e.g overcrowded places or sensitive information). However, a common limitation arises when using vibration motors which is the most common used haptic feedback for VIPs. They often generate audible sounds and are perceived as more intrusive and less acceptable by VIPs compared to non-vibrating touch feedback (e.g. dragging and pressing) which propose a more natural and expressive alternative (He, Wang & Xu, 2020; Stanley & Kuchenbecker, 2011). The current non-vibrating feedback alternatives require bulky, rigid, and noisy electromechanical actuators such as motors, servos and pumps limiting their application scenarios (Pacchierotti et al., 2017). Thus, the need of having unobtrusive haptic devices is not met for VIPs in the current haptic technology.

By leveraging the capabilities of SMAs, it becomes possible to address these challenges effectively as SMAs offer the advantage of creating silent and organic sensations while being lightweight, thin, and flexible (Cruz et al., 2018). However, the complexity involved in working with SMAs poses an obstacle for designers, restricting their ability to develop innovative solutions tailored to the needs of VIPs such as less intrusive haptic technologies.

1.1.2 Project objective

To address this challenge, the primary goal of this project is to explore the potential of an SMA-based material system in generating haptic feedback for VIPs, showcasing the unique characteristics of SMAs. Through this exploration, I aim to enhance the understanding and usability of SMAs while providing valuable insights into the ways haptic feedback can benefit VIPs. To achieve this, the following objectives have been defined:

1. Investigate the unique characteristics of SMAs and explore their integration into a material system for haptics. Specifically, examine the extent to which SMA wires can be utilized with limited electricity and develop a comprehensive guideline for designers working with SMAs.
2. Design an integrated material system based on SMAs that generates haptic sensations, incorporating an integrated counterforce mechanism.
3. Identify the needs of VIPs where haptic feedback can assist in better understanding the world around them, and evaluate the potential value of the designed material system in addressing these needs.

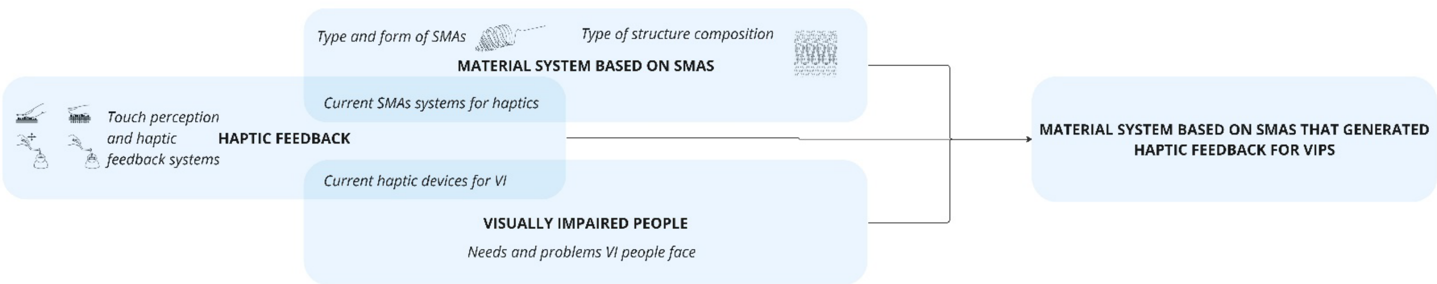


Figure 1.1 Overview of main elements involved in the project

1.1.3 Previous projects

This project relates to Sandhir's (2022) graduation and Liu's PHD projects from the TuDelft Faculty of Industrial Design Engineering. Sandhir (2022) investigated integrating SMAs into haptic technology for VIPs' well-being. She developed a wearable based on four SMA springs (0.5 mm diameter activation temperature of 65C) connected to an effector to generate stroking sensations on the forearm. When current is applied to one of the springs, the spring contracts and drags the effector to the corresponding side. Liu et al. (2022) developed a similar wearable system for navigation purposes using the contraction force of two straight wires each 50 cm long (0.2 mm diameter, 90C activation) as can be seen in figure 1.2. He embedded the wires in Teflon tubes to guide the long wires and account for safety issues.

In addition, he incorporated a counterforce mechanism into the system using Thermoplastic Polyurethane (TPU) to ensure that the end effector consistently returns to its central position. A remark is the amount of needed wire to enable a noticeable displacement of 2 cm which caused a slow response time of 10-30 seconds.

This project aims to explore a material system based on SMAs for haptics for VIPs, like Sandhir's graduation project, but having a stronger focus on showcasing the unique SMA characteristics to inspire designers. This means looking into the possibilities of using no or limited electricity, using the ability to design a memory and seeking ways to show SMA wires' flexible and thin characteristics by fully integrating the wire into the material system with an acceptable response time. Another difference with Liu and Sandhir's projects is that the project outcome will be a demonstrator that is not predominantly wearable but rather a modular unit that can be used in multiple ways.

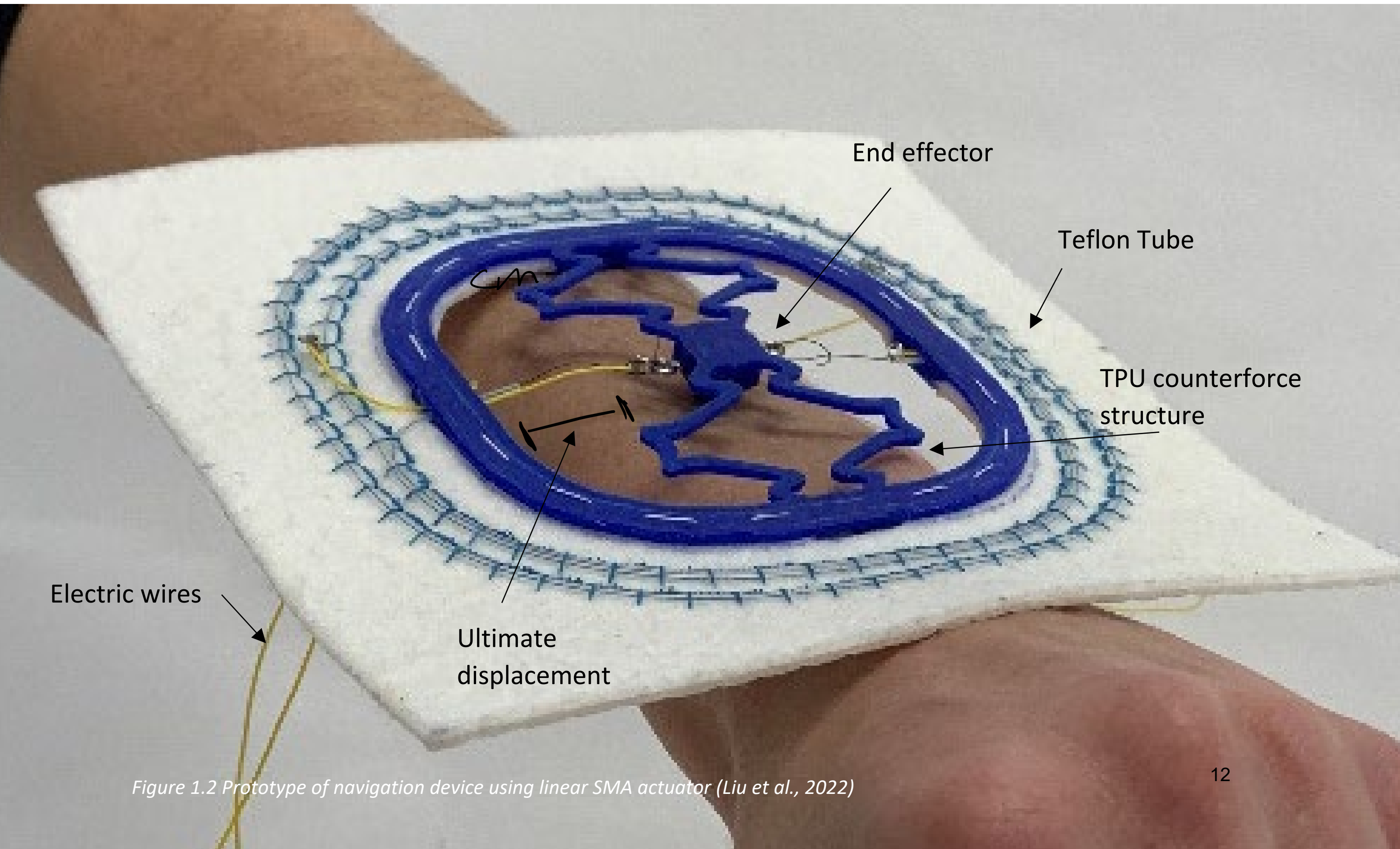


Figure 1.2 Prototype of navigation device using linear SMA actuator (Liu et al., 2022)

1.2 METHODOLOGY

For this project, two complementary methods serve as an inspiration: The material driven design (MDD) method and the basic design cycle (BDC) model. While the BDC method addresses the entire design process with the goal of fulfilling a need, the MMD method, conversely, uses the material as a starting point to generate knowledge and unveil new perspectives for designing applications.

1.2.1 Basic design cycle

The BDC, developed by Van Boeijen et al. (2014), outlines a design cycle involving analysis, synthesis, simulation, decision, and iteration (see figure 1.3). In line with this method, the project began with a comprehensive analysis on the literature, target group and SMAs from which design criteria and parameters are formulated. From there, multiple design cycles are employed in the material structure exploration, the demonstrator development and the concept development.

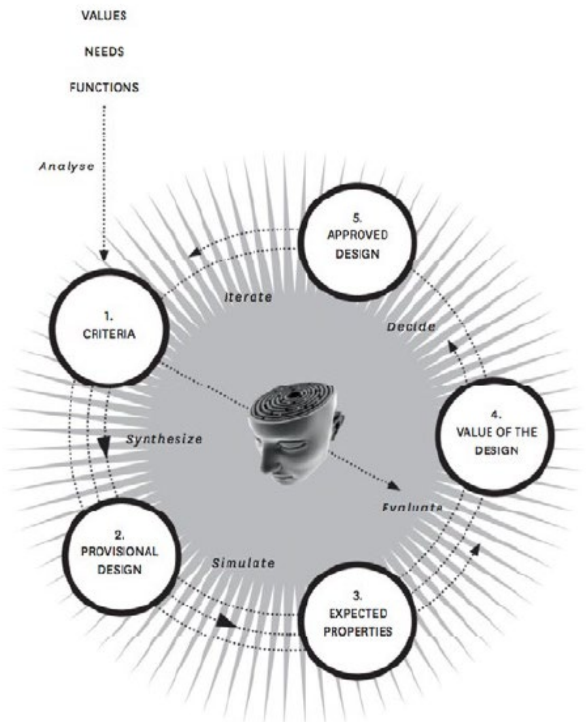
1.2.2 Material driven design method

The MDD method is developed in 2015 by Karana, Barati, Rognoli and Zeeuw Van Der Laan (2015) and aims to facilitate design processes in which the material is the point of departure. This method has been used in research of exploring emerging materials before and captures not only the physical properties of novel materials but also the experiential qualities (Barati, Karana & Hakkert, 2020). As visualized in Figure 1.3, the MDD method consists of four steps of which elements of the first step, named understanding the material to articulate the materials unique role, have mainly been used for this project. The elements that have been addresses are:

Material benchmark to understand its position in relation to similar materials and its potential application areas (paragraph 2.4).

Material taxonomy to systematically review and tinker with the material which means an explorative process of creation and evaluation of the material (paragraph 4 and 6).

Technical and experiental characterization to understand the technical and experiental mechanical properties (paragraph 7 and 8).



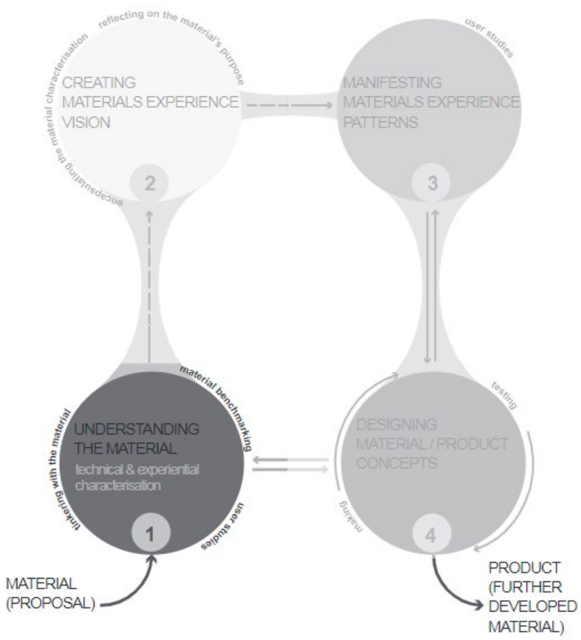


Figure 1.3 Basic design cycle (left) and material driven design method (right) highlighting the first step

1.3 DESIGN PROCESS

This project is of exploratory nature and aims to explore the potential of material system based on SMAs with a particular target group. This involves gradually exploring the material (MDD method) and the target group (BDC cycle) and identifying where overlaps exists. To do this, the project is divided into three phases: the research, form configuration and embodiment phase (figure 1.4).

The aim of this phase is to understand the context of the project and the material to formulate design criteria and select relevant design parameters to focus on in the subsequent phase. The research phase consists of an extensive research about the target group and the literature covering topics about visually impairment, haptic feedback and shape memory materials (including a benchmark). In parallel, the material is explored to understand its fundamentals on what the material affords and how it can be shaped, following the MDD method:

*MDD encourages tangible interaction with the material in hand, from the first encounter through to exploring and understanding the material in detail with its unique qualities and limitations. – (*Karana et al., 2015)

In the form configuration phase, the selected design parameters are further researched and material systems are explored. In this phase the material system as a whole is tinkered with (instead of only the SMA). In addition, the designed SMA wires are technically evaluated to understand their core characteristics.

In the embodiment phase, the final concept will be presented -including an SMA guideline- and evaluated on its experiential characteristics (MDD method) and valuable addition for VIPs.

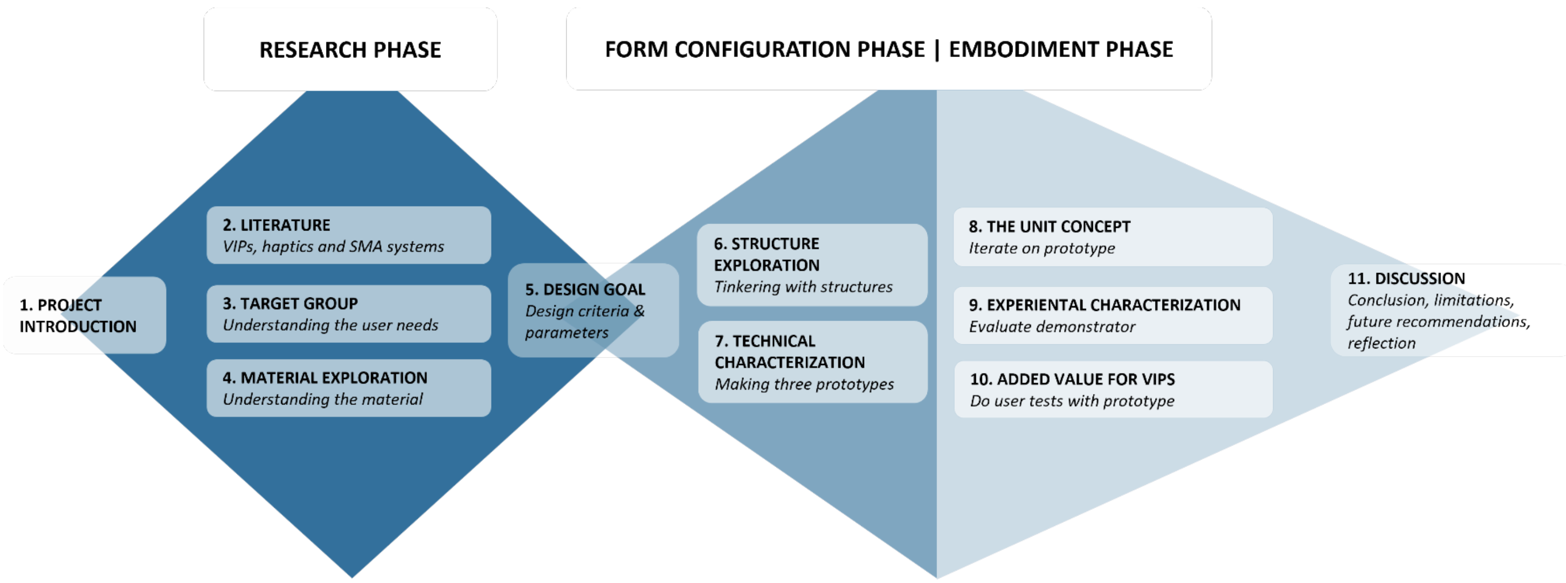


Figure 1.4. Illustration of design process of this project

2 LITERATURE

Figure 2.0 Homeastatic façade from Decker Yeadon architects (Bengisu & Ferrara, 2018)(left)

2.0 INTRODUCTION

The literature research for this project is divided into four paragraphs and a concluding paragraph. The goal of the first two chapters is to establish a comprehensive understanding of the background and context surrounding the project. Paragraph 2.1 'visual impairment and assistive devices' answers questions such as *What is visual impairment?* And *What types of assistive devices are currently on the market for visually impaired people?* Paragraph 2.2 'What is haptic feedback' addresses questions about the definition of haptic feedback from a neuro-psychological and design perspective and explores its various forms.

Paragraph 2.3 and 2.4 focus on the parameters involved in designing material systems with Shape Memory Alloys (SMAs) and investigates the existing developments in SMA systems for haptics. It begins by exploring the concept of shape memory materials and then delves into the elements of the proposed material system based on SMAs (paragraph 2.3 'Elements of a material system based on SMAs). Paragraph 2.4 'Benchmark of SMA systems for haptics' examines advancements in SMA systems for haptics to gain insights into the considerations and existing progress within the field. The concluding paragraph of this literature research (2.5) outlines relevant areas to focus on in the subsequent stages of the project.

2.1 VISUAL IMPAIRMENT AND ASSISTIVE DEVICES

2.1.1 Visual impairment

Worldwide at least 2.2 billion people have vision impairment and blindness of which the majority being over the age of 50 years (WHO, 2022a). The International Classification of Diseases - 11 (ICD-11) defines visual impairment as something that *´…results when an eye condition affects the visual system and one or more of its vision functions.´* (WHO, 2022b). In the Netherlands, a person is assumed to be visually impaired if the visual acuity with optimal eye correction is less than 30% and/or if the visual field is less than 30 degrees (moderate-severe vision impairment) (Bartimeus, n.d.; Oogfonds, n.d.; NVVO, n.d.). Visual acuity refers to detail perception and visual field refers to the area one can survey when looking at a single point (a normal visual field is 140 degrees). A person with severe vision impairment has a visual acuity between 5 to 10% and blind people below 5%. As Figure 2.1 illustrates, there are many ways to be visually impaired.

Causes & impact

The leading causes of visual impairment are age related macular degeneration, cataract, diabetic retinopathy, glaucoma, and uncorrected refractive errors. However, the type of cause depends strongly on socioeconomic and environmental factors such as the availability and accessibility of eye care services (Steinmetz et al., 2021). In high-income countries such as the Netherlands, ageing but also diabetes is the leading cause of the increase in the number of visually impaired people (Keunen, 2011). This project focuses on high-income countries, such as the Netherlands with moderate, severe visual impairment and blindness.

The absence of vision can have a great impact on people's livelihoods as 85% of the external world is perceived with vision that strongly influence our cognition and spatial perception (Gori et al., 2016). Young children that suffer from severe vision impairment may achieve lower levels of education with lifelong consequences (WHO, 2022a). Adults with visual impairment have lower work productivity and are more likely to suffer from depression: a meta-analysis shows that 25% of VI people report depressive symptoms, this number is increasing with more severe eye diseases (Zheng et al., 2017). Elderly with vision impairment are more likely to suffer from social isolation and have a higher risk of falling and fractures, leading to early entry into nursing homes (WHO, 2022a; Keunen, 2011).

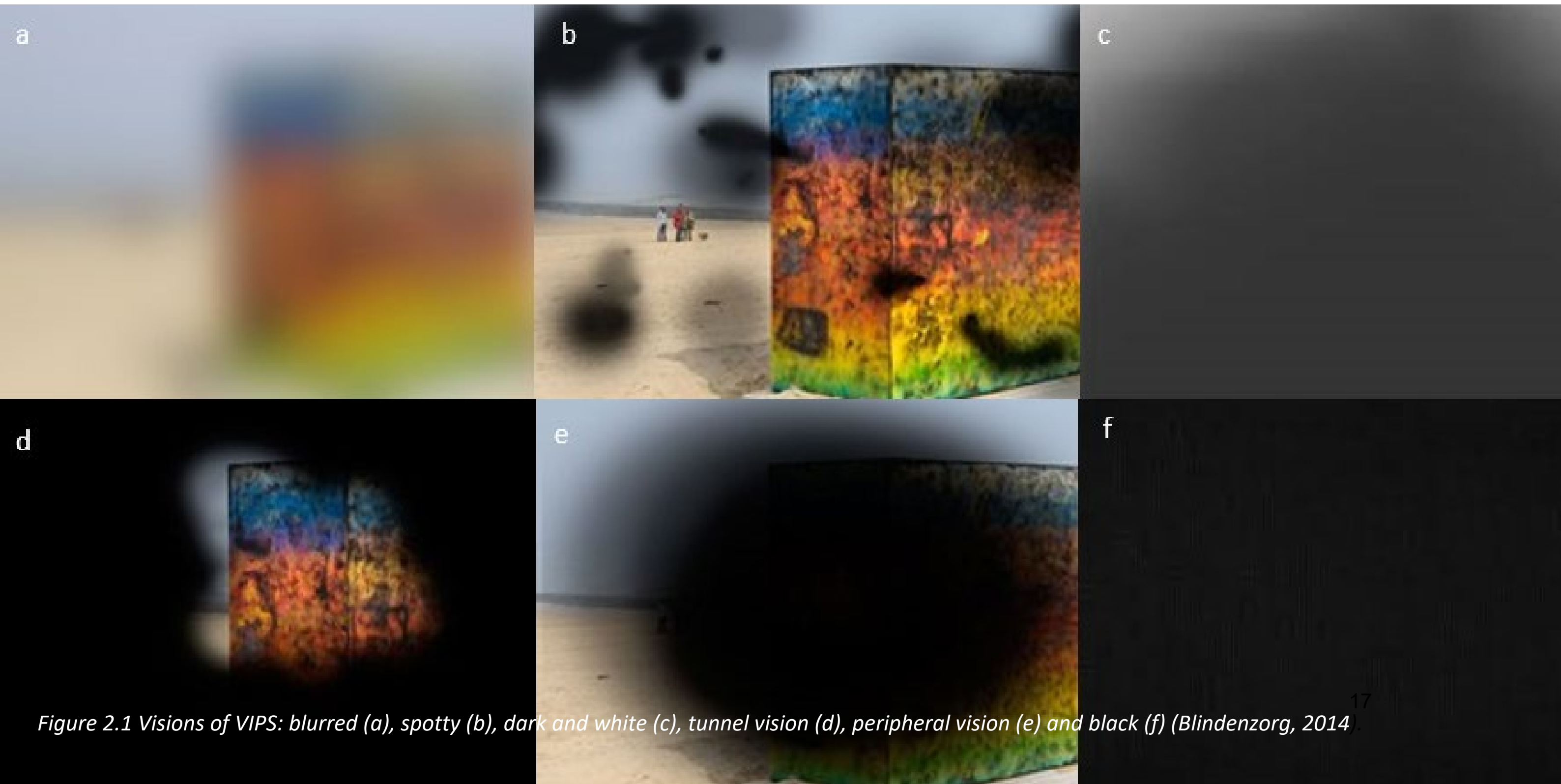
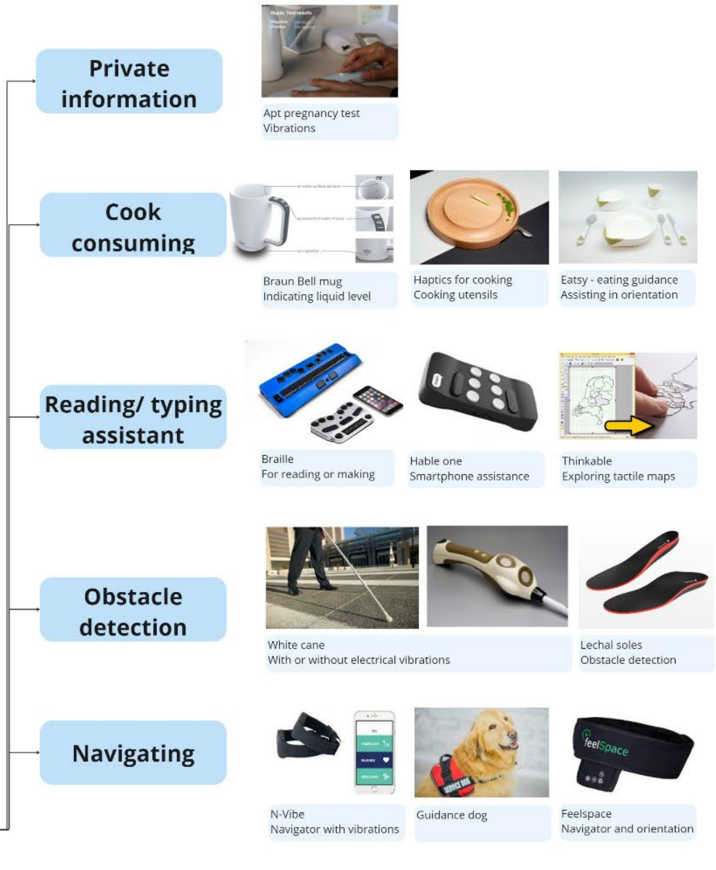


Figure 2.1 Visions of VIPS: blurred (a), spotty (b), dark and white (c), tunnel vision (d), peripheral vision (e) and black (f) (Blindenzorg, 2014

2.1.2 Assistive devices for VIPs

There is a wide variety of assistive devices on the market. These can be divided into vision enhancement, replacement and substitution (Hu, 2019; Elmannai & Elleithy, 2017). Vision enhancement- and replacement-based devices translate visual information respectively into display output and directly to the brain (e.g. prosthesis). Vision substitution-based devices refer to sensory substitution devices (SSD), which translate information to nonvisual senses, like audition and tactus. Based on an internet search, a literature review (Hu, 2019; Elmannai & Elleithy, 2017; Amemiya & Sugiyama, 2009) and a visit to the ZieZo-beurs (a fair for assistive devices for VIPs), a mind map is made of the currently available assistive devices on the market for VIPs, see figure 2.4.



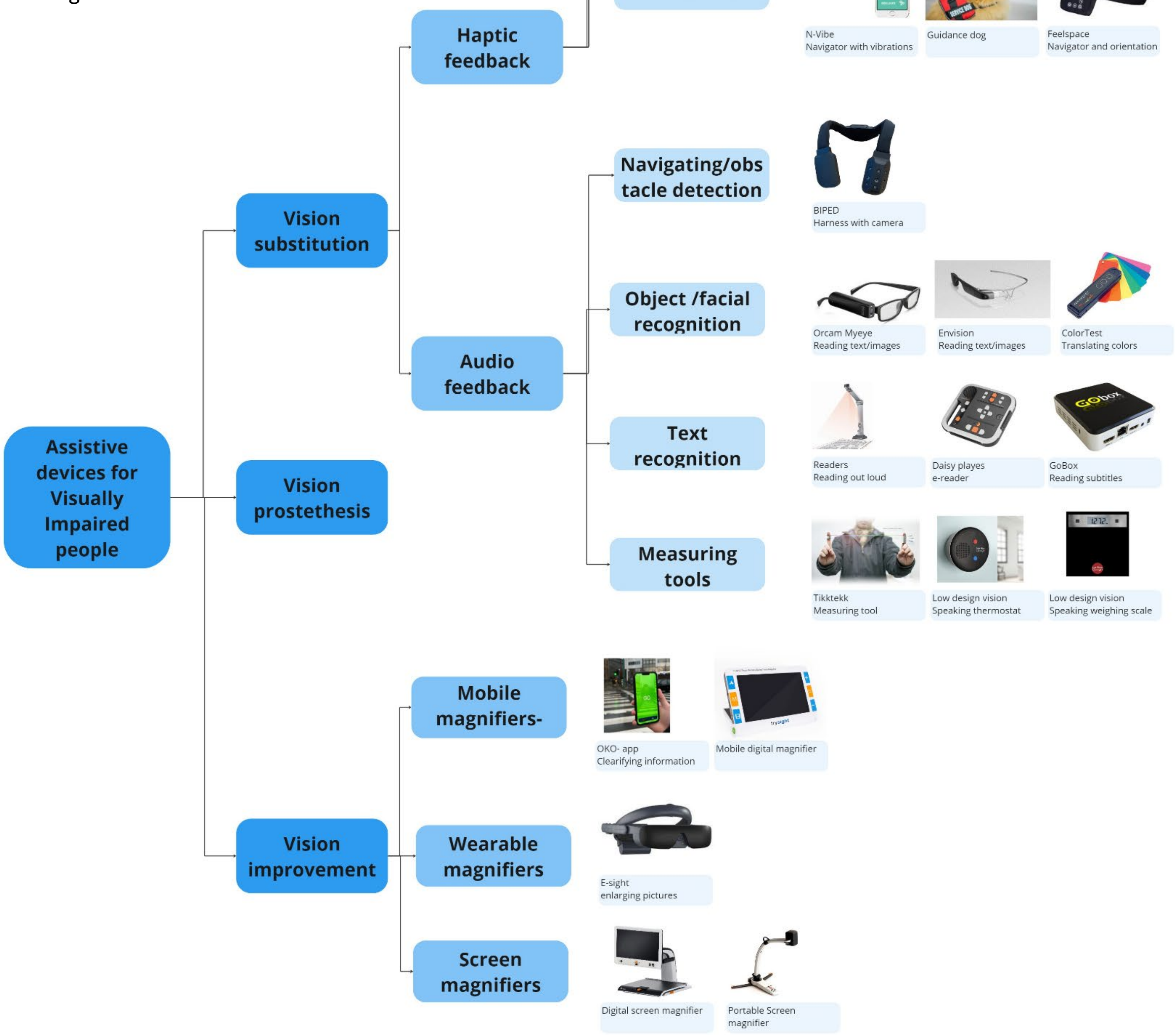


Figure 2.2 A mindmap of the market analyses of assistive devices for VIPs

Vision enhancement and audio substitution devices
The ZieZo-beurs mainly focused on vision enhancement tools like screen magnifiers and smart apps for those with some vision. For users with mild or severe visual impairment, most devices translated visual cues into audio feedback. Notable products are the Orcam MyEye and Envision glasses (figure 2.3 right), which recognize objects, text, and faces, providing audio feedback through built-in speakers. Another interesting development is the smart harness from Biped, an alternative to white canes and guide dogs, which uses 3D cameras and AI software to detect obstacles and provide sound warnings (figure 2.3 left). Paired with headphones or earphones, it connects to a phone's GPS for navigation. Biped aims to boost users' confidence through ergonomic and intuitive design. As Amemiya & Sugiyama (2009) suggest, the great advantage of audio feedback is the high resolution capabilities which is for example preferred in navigation and detailed information.

Haptic feedback devices
Popular traditional sensory substitution devices like guide dogs, Braille, and white canes, invented in 1780, 1820, and 1920 (IFDF, n.d.; Britannica, 2019; Strong, 2009), have seen many modifications. For instance, vibrating white canes detect knee-level objects and portable Braille displays use dynamic screens to reduce size.

A new haptic wearable device that focuses on navigation is the N-vibe (Figure 2.4a). It consists of two bracelets, one on each arm, connected to your mobile phone with an app that vibrates to navigate left or right. Feelspace uses the same principle in a belt (figure 2.4d). Through vibrations motors, along the belt, it vibrates in coordinated directions. Interestingly the belt always vibrates to the north to give the user an extra sense of orientation.

An interesting haptic assistive device for small tasks is the Apt pregnancy test (figure 2.4c). The Apt is a simple and affordable pregnancy test that vibrates one time for a negative result and two times for a positive result. In this way, private information is conveyed.

Furthermore, haptic feedback is used to assist in simple tasks such as cooking or consuming. An example is the ‘Haptic for cooking’ from Boey (figure 2.4b), which involves cooking products with tactile surface differences in height to guide the user. For example, a cutting board with a groove to guide the cut vegetables, or a measuring cup with a hole to know the height of the water.

2.2.3 Main insights
Based on this market research it was found that many haptic devices are designed for small tasks or basic navigation, using tactile distinctions and vibration motors. The benefit of tactile feedback is its subtle and private feedback due to its silent nature. SMA systems offer new methods for conveying tactile information due to their organic movement are potentially completely silent, in contrast to vibration motors. This could be a valuable addition to this expanding market. In order to grasp how this can be achieved, the upcoming paragraph will clarify the different categories of haptic feedback systems and the functioning principles of haptic touch.

Figure 2.3 Biped (left) and the Envision glasses (right)

Figure 2.4 a.The N-Vibe (upper left), b haptics for cooking (upper right), c the Apt pregnancy test (lower left), d the feelspace (lower right)

2.2 WHAT IS HAPTIC FEEDBACK

In contrast to the other four most recognised senses (sight, hearing, taste, and smell), the sense of touch is localised over the whole body and relies on the largest sense organ, the skin. To understand haptic feedback, the tactile sense, haptic perception and haptic feedback systems are described in this paragraph.

2.2.1 Tactile sense

The input to the tactile sense includes mechanical stimulation, heat, cooling and several stimuli that produce pain. Klatzky and Lederman (2013) distinguish three underlying sensory systems for the sense of touch: the cutaneous, kinaesthetic and haptic systems. They all receive sensory input through mechanoreceptors that convey signals via the neuron system to the brain. The cutaneous system receives sensory input from mechanoreceptors that are embedded in the skin, which refers to the perception of skin deformation (figure 2.6). The kinaesthetic system receives input from mechanoreceptors located in muscles, tendons and joints, which refers to the perception of movement and force (figure 2.7). The haptic system uses a combination of both the cutaneous and kinaesthetic sensory input systems, referring to active touch (figure 2.8): *the ability to experience the environment through active exploration, which relates to most of our everyday tactual perceptions (Klatzky and Lederman, 2013).*

Less sensitivity when getting older

The sensitivity, acuity and magnitude of tactile and thermal sensations decline with age due to a decline in density of certain mechanoreceptors (the Pacinian and Meissner corpuscles and Merkel's disc) in the skin (Wickremaratchi and Llewelyn, 2006). In this, the sensation of vibration is more affected by age than the sensation of light touch and pain. Furthermore, the spatial acuity decreases noticeably with age in the fingers, and less noticeably in the forearm. The notion of decreased sensitivity in certain body locations can be of importance for applying haptic feedback to visually impaired and blind elderly.

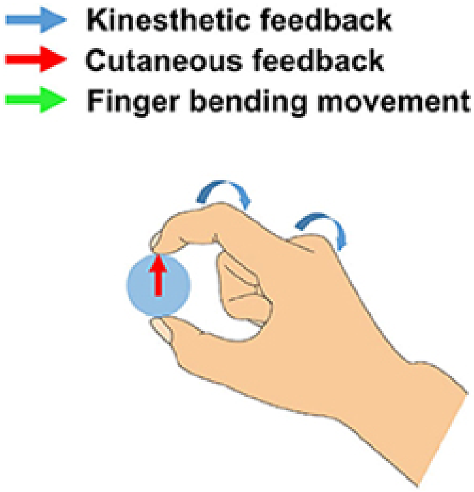


Figure 2.5 Example of the haptic system when squeezing a ball where sensory input is received from both the kinaesthetic and cutaneous systems (Klatzky and Lederman ,2013).

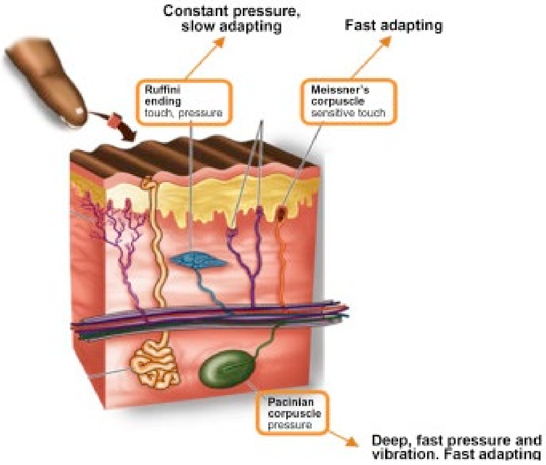


Figure 2.6 Mechanoreceptors in cutaneous system (Juo et al., 2020)

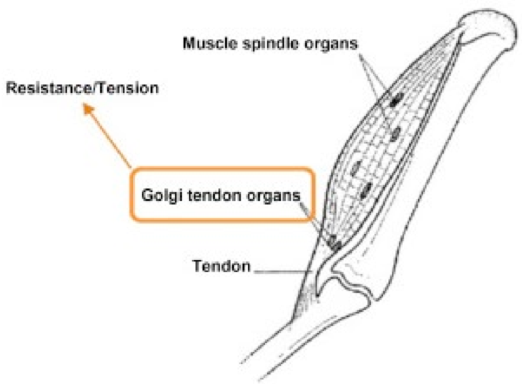


Figure 2.7 Mechanoreceptors in kinaesthetic system (Juo et al., 2020)

Impact of body location

The type and density of mechanoreceptors differ per body location which results in different sensitivity, acuity and magnitude of tactile and thermal sensations (Roudaut et al., 2012; Klatzky & Lederman, 2013). For example, the density of the Meissner and Pacinian corpuscles mechanoreceptors is high on the glabrous skin of the hands and feet, which makes it easy to localize pressure points in these areas (Culbertson, Schorr & Okamura, 2018). This is more difficult in hairy skin due to the reduced density of such receptors. However, the C-touch receptors, which detect slow-stroking touch, are more frequent in hariy skin. Another example is that the face (i.e., upper lip, cheek, and nose) is best able to detect a low-level force, whereas the fingers are most efficient at processing spatial acuity (Klatzky & Lederman, 2013).

Weinstein and later Mancini et al. (2014) mapped the spatial acuity on different body parts using the two-point threshold method: The minimal separation between two points needed to perceive them as separate points (see figure 2.9). Mancini et al. (2014) found that the spatial acuity is highest on the fingertip, hand palm, forehead and foot sole. In addition, Morrow and Ziat (2018) found that the spatial acuity in the neck is 13 mm, which is lower than the handdorsum (10-13mm) but higher than the forearm (16-20mm).

Interesting to note is that blind people have an increased tactile acuity compared to people with sight, independently of the degree of childhood vision or Braille reading (Goldreich and Kanics, 2003). Goldreich and Kanics (2003) concluded that the average blind subject had the acuity of an average sighted subject of the same gender but 23 years younger.

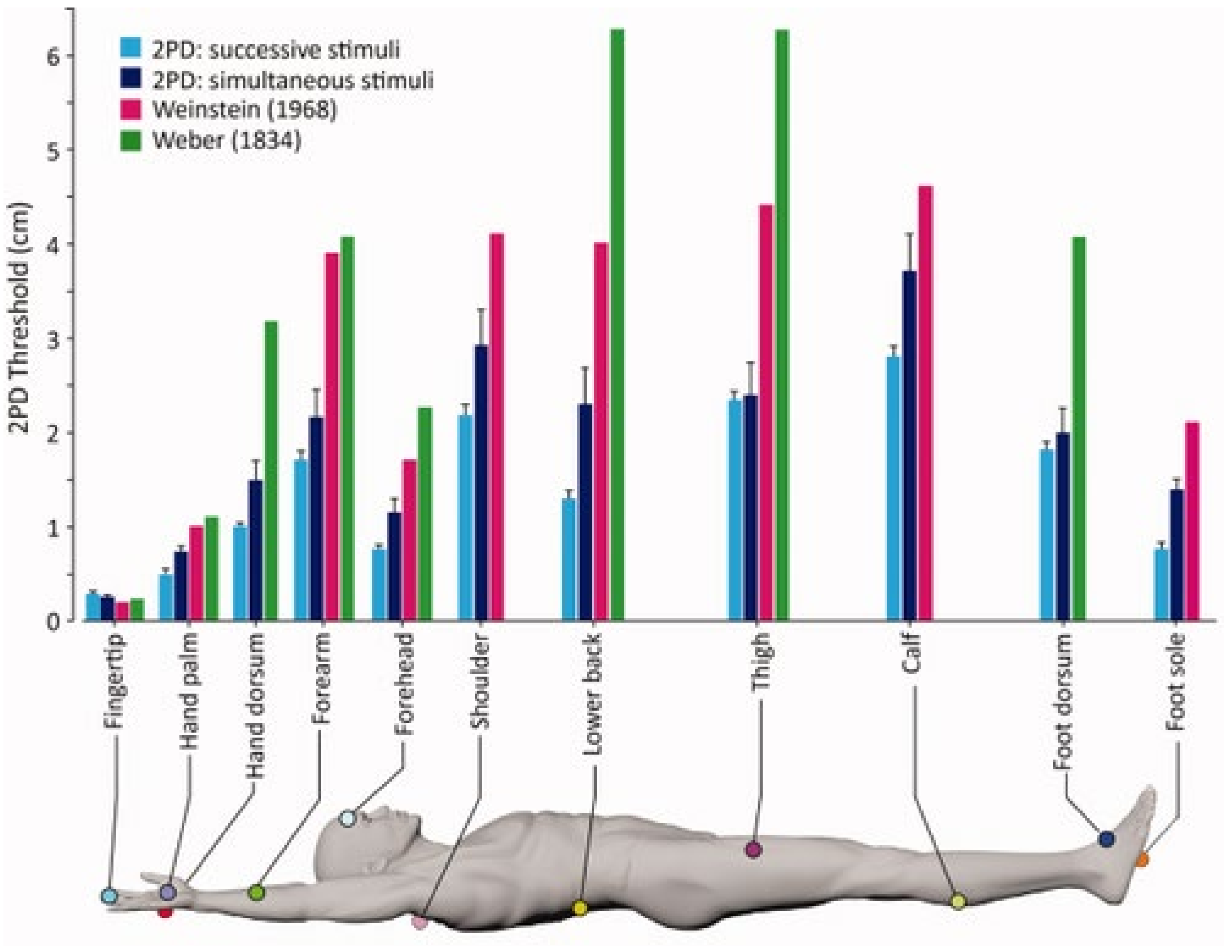


Figure 2.9 spatial acuity on different body parts using the two-point threshold method, comparing three different studies (Mancini et al., 2014).

2.2.2 Haptic perception

The touch sense provides the brain with information on material and spatial properties (Kappers & Bergmann Tiest, 2013; Klatzky & Lederman, 2013). These properties can be perceived through the cutaneous or kinesthetic systems, actively or passively (Rodríguez et al., 2019) (see figure 2.10). The most known material properties that humans haptically perceive are roughness, compliance, viscosity, friction and coldness (Kappers & Bergmann Tiest, 2013). Roughness refers to small-scale unevenness of the surface of an object which can be perceived actively (stroking with fingers) or passively (object is pressed to the skin). Compliance is the perceived deformation of an object, also actively (pressing an object) or passively (object deforms by an external force) perceivable. The most noticeable spatial properties are shape, curvature, size and orientation (Klatzky & Lederman, 2013). Curvatures can be small and perceived by a fingertip, or larger requiring movement of the hand or finger (Kappers & Bergmann Tiest, 2013).

Next to material and spatial properties, patterns can be perceived based on these properties (Klatzky & Lederman, 2013). The common stimuli for patterns are vibrotactile patterns and two and three-dimensional patterns. Vibrotactile patterns are formed by repetitive stimulation of a contact point with varying frequencies that are sensed by different mechanoreceptors. It is found that the discrimination of different patterns is more accurate when performed in the same place. Two-dimensional patterns are composed of raised lines or points, for example, braille text for visually impaired people. Small two-dimensional patterns that fit within the scale of one fingertip are more easily recognized than larger patterns that are felt with the fingers of one or more hands.

Illusion

Important to take into account is that haptic perception is subjected to illusions and therefore not always perceived right. For example, a curved surface along the finger feels more curved than across the fingers (Kappers & Bergmann Tiest, 2013). Another example is that the distance between two points is perceived as larger on skin areas with higher tactile sensitivity (e.g. the finger) than on lower tactile sensitive areas (e.g. legs) and vertical lines are sometimes perceived as larger than horizontal lines (Longo & Haggard, 2011). When designing a haptic feedback system, one should consider the ways of haptic perception that are subjected to illusions.

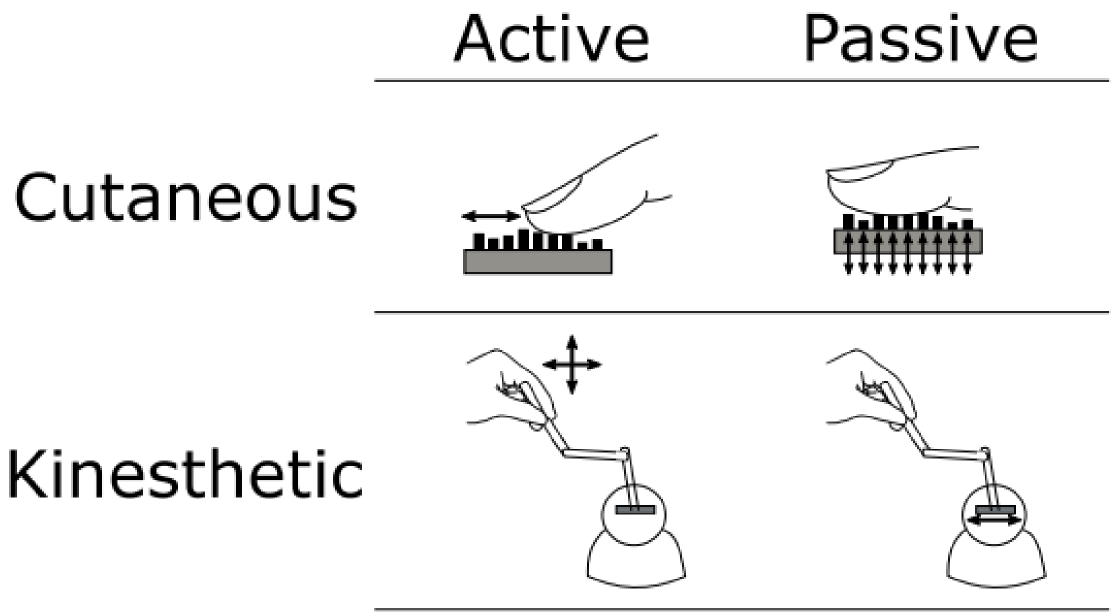


Figure 2.10 Classification of haptic interaction according to the exploration modality: cutaneous active, cutaneous passive, kinesthetic active, and kinesthetic passive (Rodríguez et al., 2019).

2.2.3 Haptic feedback devices

Haptic technology refers to 'a tactile feedback technology which takes advantage of a user's sense of touch by applying forces, vibrations, and/or motions upon the user.'(Yadav & Krishnaiah, 2013). Three categories are distinguished for haptic devices, each providing cutaneous and/or kinesthetic tactile information, actively or passively: graspable, wearable and touchable, respectively figure 2.11a, b and c.

Graspable

Graspable systems provide tactile information via a hand-held device mostly via the kinesthetic system (Culbertson, Schorr and Okamura (2018). The most prone example for graspable is the white cane which provides the user with information about objects via the cane by actively exploring the surrounding. Passive feedback via a graspable could be perceived when the cane vibrates when it comes into contact with an object.

Wearable

A wearable system is mounted to a part of the body and displays sensations directly to the skin by shear force (Culbertson, Schorr and Okamura (2018) (figure 2.11b). An example of a wearable device that generates passive haptic feedback is the N-Vibe, bracelets that triggers the cutaneous system by vibrations. A wearable that can be actively perceived is for example a glove that conveys vibrational signals when an object is explored about its details.

Touchable

Touchable systems allow users to explore surfaces actively -by stroking over the surface- or passively -when the surface moves-. The most known passive example of a touchable for VIPs is braille. The user actively explores the two-dimensional patterns on the pin-based tactile display. A touchable that generates passive haptic feedback would be the Apt pregnancy test as the skin is stimulated with vibrations without active movement of the finger.

2.3.4 Main insights

The tactile sense is unique due to its large sensorial area and varied possibilities of perceiving information. Material and spatial properties in different patterns can be perceived as well as active and passive feedback in a wearable, graspable or touchable system. SMA have the characteristics of changing its shape and generate a movement which enables them to comply to the wide variety of haptic feedback giving lots of opportunity for rich tactile feedback for VIPs. In this, the specific location on the body must be thoughtfully selected, as various locations exhibit different levels of sensitivity, with fingers demonstrating the highest sensitivity.

To design with SMA systems, a good understanding of SMAs and its accompanied elements is needed, which will be described in the next paragraph.

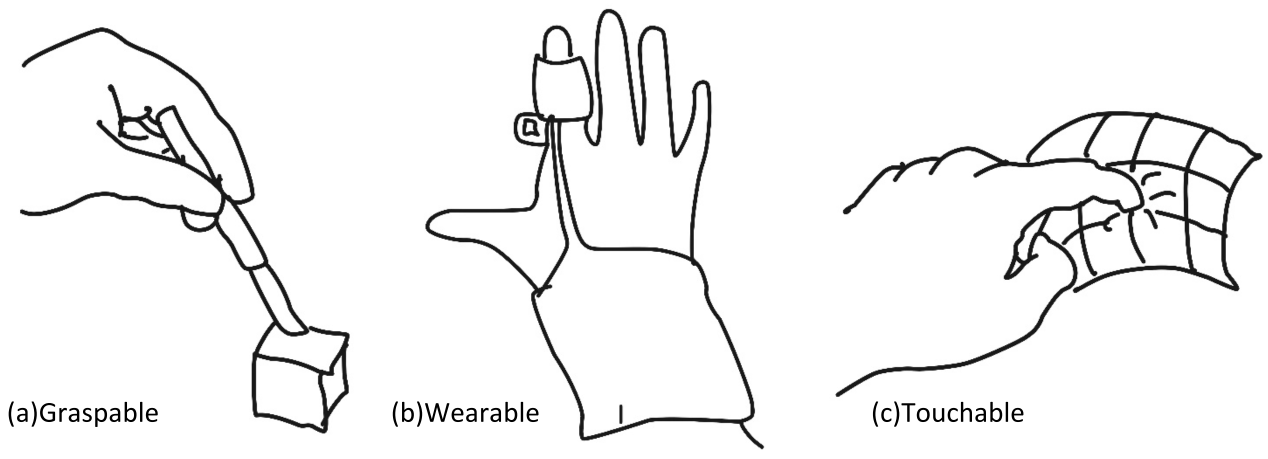


Figure 2.11 Classification of haptic feedback devices, graspable (a) left, wearable (b) middle and touchable (c) right.

2.3 ELEMENTS OF A MATERIAL SYSTEM BASED ON SMAS

The goal of this project is to design a material system based on SMAs that generates haptic feedback for VIPs. To create such a morphing object, one should design a composition of SMAs embedded in a substrate structure. In this paragraph, the different elements of the material system are described, explaining the working principle of SMAs, characteristics of possible SMA shapes and types of substrate materials that can be used to integrate the SMA.

2.2.1 General principles of SMMs

Shape memory materials fall under the umbrella term of the smart materials group, known for their changeable properties in response to external stimuli (Bengisu & Ferrara, 2018). Shape memory materials (SMMs) are defined as *´...smart materials that have the capacity to "remember" a certain shape they were "trained" to adopt´* (Bengisu & Ferrara, 2018). Most of these materials react to an external stimulus with a kinetic effect, enabling them to 'move'.

As shown in figure 2.3.1, SMMs can be classified in two ways, stimuli-based and material-based (Bengisu & Ferrara, 2018). External stimuli that can trigger a change in shape are for example light intensity, stress, pH, electric fields, magnetic fields or temperature change, of which the latter is most known. The type of external stimuli to trigger a shape change and the type of shape memory effect varies among the type of materials. The shape memory effect and types of materials will be explained further

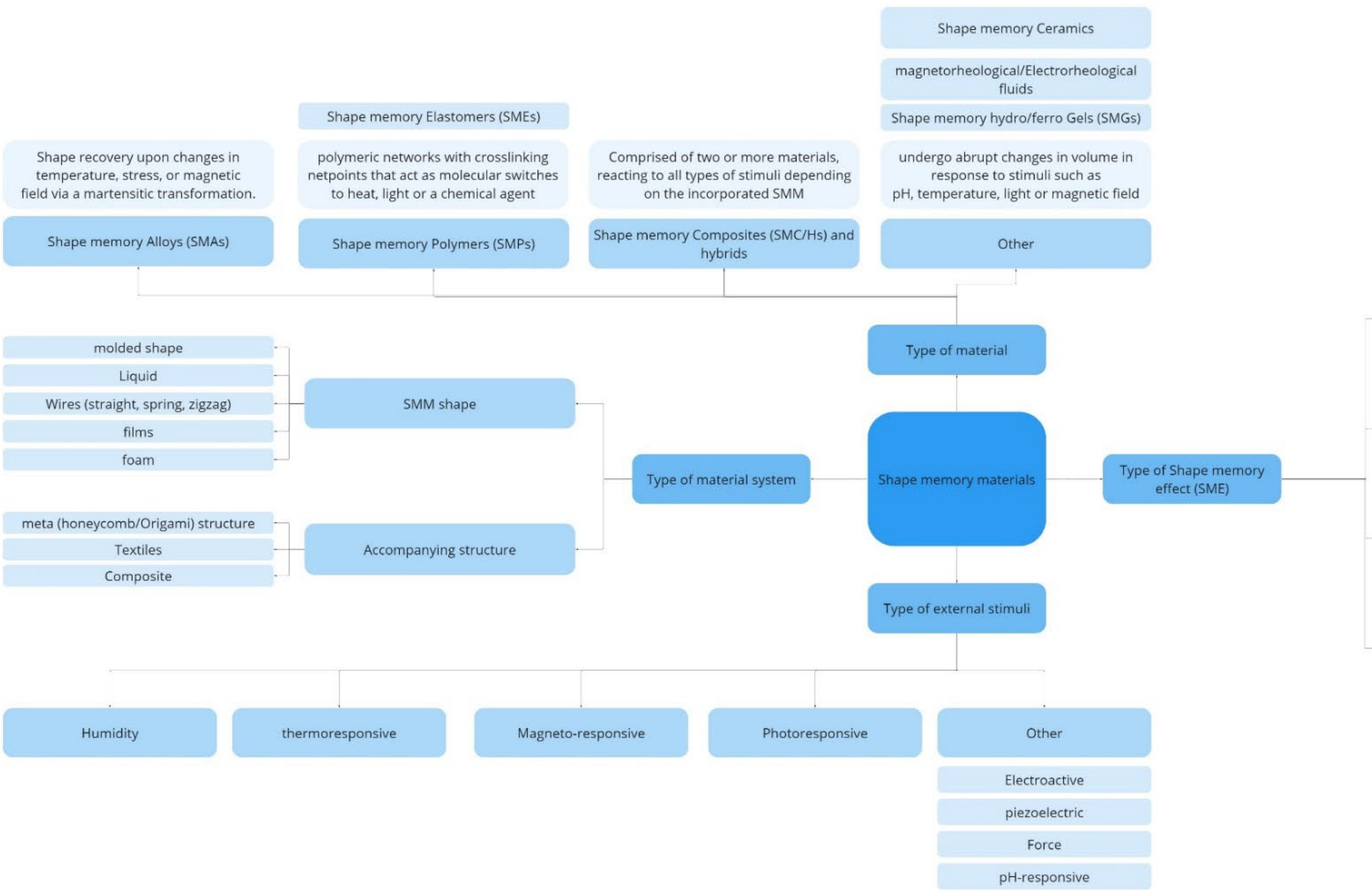


Figure 2.3.1 Mindmap of all related topics regarding shape memory materials (SMMs)

Shape memory effect

All Shape memory materials are featured with the shape-memory effect (SME). This is '...the ability to recover their original shape from a significant and seemingly plastic deformation when a particular stimulus is applied' (Huang et al., 2010).

A shape memory effect (SME) is characterized as a one-way, two-way or multiple-shape memory effect, depending on the type of material and stimuli, see figure 2.3.2 (Bengisu & Ferrara, 2018; Rao, Srinivasa & Reddy, 2015). In a one-way SME, the material is trained to a predetermined form. When it is deformed it can reverse to its predetermined shape by applying an applicable external stimulus, for example, heat. The deformation can be achieved by applying force through human involvement, through a counterforce created by the structure, or by using an opposing SME. In a two-way SME, the material is 'trained' to have two predetermined shapes, for example, a high-temperature and a low-temperature shape. When cycled between these two temperatures, the material can shift between the two shape states, without the use of externally applied force. Accordingly, in a multi-way SME there are multiple predetermined 'trained' shapes and the material can shift between the multiple shape states. For example, a multi-SME in polymers can be achieved by setting several shape transitions at different temperatures such as glass transition and melting points.

A phenomenon commonly observed in shape memory alloys is Pseudoelasticity or superelasticity. Superelastic alloys undergo large amounts of elastic deformations (up to 8%) when stress is applied. When the stress is removed the material transforms back into its predetermined shape. An application that relies on this phenomenon is orthodontic braces and highly flexible glasses. The phenomenon of superelasticity is not the same as the response of a spring. The difference is that superelastic alloys, unlike conventional spring wires, undergo a so-called martensite phase transition, which is characteristic of SMAs and will be further explained in paragraph 2.2.2.

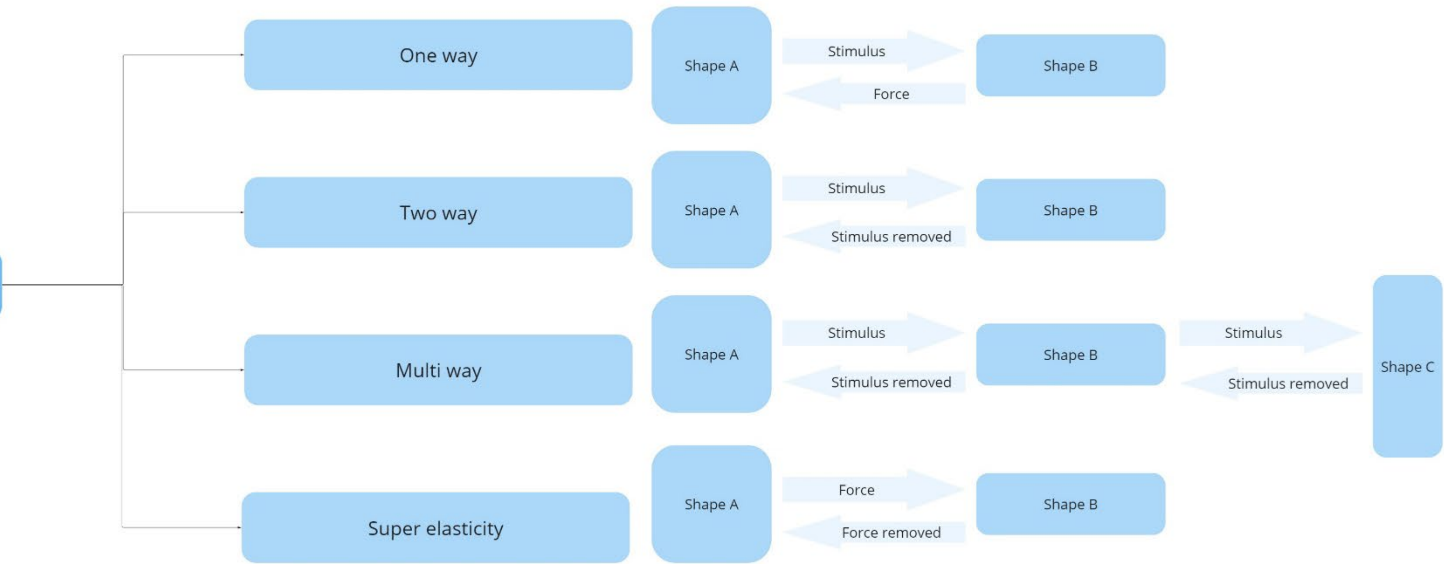


Figure 2.3.2 type of shape memory effects

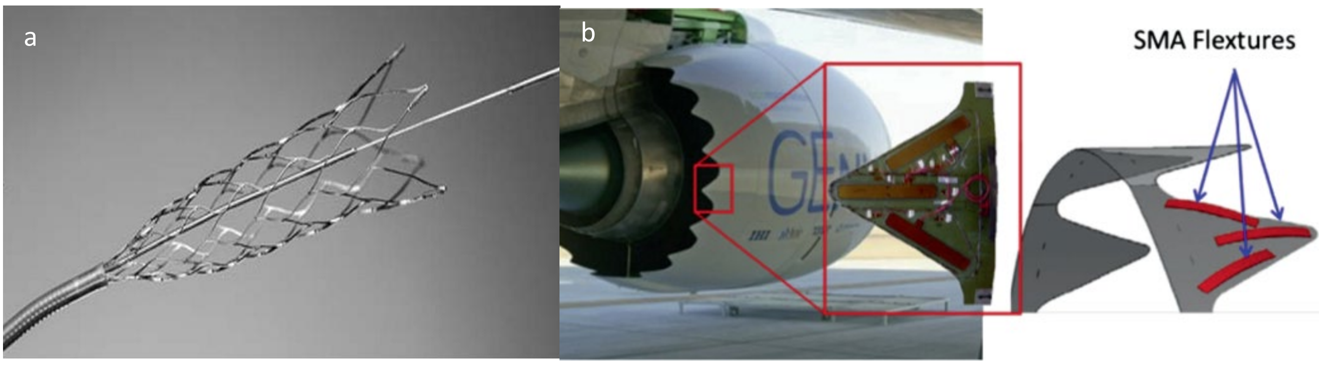
Many different shape-memory materials (SMMs) are discovered over the years. The most known and distinguishable groups are shape memory alloys (SMAs), shape memory polymers (SMPs) and shape memory composites and hybrids (SMCs and SMHs).

Shape memory Alloys

Shape memory alloys (SMAs) are metals that undergo shape change due to temperature or magnetic field (Bengisu & Ferrara, 2018; Rao, Srinivasa & Reddy, 2015). The first discovered SMA was in 1932 by Örlander, who found a 'rubber-like' behaviour in the gold-cadmium alloy. Various SMAs are being developed, of which alloying elements of Nickel (Ni) and Titanium (Ti) are the most affordable, reliable and biocompatible ones. The mechanism behind the shape memory effect is the martensite transformation, a change in the structure of the cubic arrangement, this will be explained more elaborately in paragraph 2.2.2. Shape memory alloys are generally characterized high power-to-weight ratio, biocompatibility, high wear resistance and the ability to react directly to environmental stimuli (Bengisu & Ferrara, 2018; Rao, Srinivasa & Reddy, 2015). The most common application fields for SMA systems are in aerospace, automotive industry, appliances, robotics and medical fields (Bengisu & Ferrara, 2018; Chaudhari, Vora & Parikh, 2021). An example is the self-extendable stent implant for narrowing blood vessels, see figure 2.3.3 (a). The SMA stent implant is pre-compressed and widens -due to a shape memory effect- when it comes into contact with body temperature (Chaudhari, Vora & Parikh, 2021). Another example is the SMA-based variable geometry chevron (VGC) in the aerospace industry, developed by Boing. It is an SMA actuator that enables a noiseless and cruise-efficient chevron deflection during take-off, see figure 2.3.3 (b).

Shape memory polymers

Shape memory polymers (SMPs) are polymeric networks with cross-linking netpoints that can undergo shape change due to heat, light, magnetic or a chemical agent. SMPs were an important contribution to the field of shape memory materials as they are characterized by low densities, large strains, low manufacturing temperatures and pressures and easy shape programming (Bengisu & Ferrara, 2018). The most known mechanism behind the shape memory effect (SME) of SMPs is the dual-segment system, consisting of the elastic and transition segment (Sun et al., 2012). The elastic segment is highly elastic during the SME cycle whereas the transition segment changes its stiffness when exposed to an applicable external stimulus, enabling a shape change.



2.3.3 Self-extendable SMA stents to widen blood vessels (a) and a variable geometry chevron (VGC) based on an SMA actuator to reduce noise (b) (Chaudhari, Vora & Parikh, 2021)

Just like SMAs, SMPs are covering a wide range of application fields, such as aerospace engineering, biomedical devices, flexible electronics, soft robotics and 4D printing (). An example is the biodegradable SMP surgery fibre that shrinks and tightens a wound after suturing, see figure 2.4 (a).

A subcategory in SMPs is shape memory elastomers (SMEs), which are featured with the ability to undergo large elastic deformations under stress. A recent field of development with SMEs is in Magnetorheological elastomers (MREs) (Bengisu & Ferrara, 2018), also known as magneto-responsive soft materials (MSMs) (Wu et al., 2019; Kim, 2018). This type of material consists of an elastomeric matrix with magnetic particles inside and undergoes a shape change when an external magnetic field is applied. The mechanism behind the shape change is due to a reorientation of magnetic domains in the matrix: the magnetic poles align with the externally applied magnetic field which achieves strain in the material and deforms it. The advantage of this material is a fast, complex and remote shape change. An example is the structure developed by MIT which is a 3D printed structure that can be used for functions such as reconfigurable soft electronics or drug pill delivery (see figure 2.3.4,b) (Kim, 2018).

Shape memory Composites and hybrids

Shape memory composites (SMCs) are composed of at least two materials, a reinforcement and a matrix (Bengisu & Ferrara, 2018; Rao, Srinivasa & Reddy, 2015). SMCs contain at least one material that has a shape memory effect, either based on the martensitic transformation (in SMAs) or the dual-segment system transformation (in SMPs). The shape memory hybrids (SMHs) are also composed out of at least two materials, but without an individual shape memory material. The mechanism behind the achieved SME is comparable with the dual-segment system of SMPs: It is the interaction between one material that represents the elastic domain and one material that represents the transition domain.

Choice for Shape memory alloys

In this project, thermally activated shape memory alloys will be explored. The reason for choosing SMAs over other SMMs is that they have a high load-bearing capacity, reliable shape recovery, quick response time and the ability to work on electricity (Bajpai et al., 2020). Besides, SMA wires are widely available in a wide range of geometries and temperatures, which is needed for this project. In addition, the type of shape memory effect will be one-way as two-way wires are expensive, less reliable and hard to train and therefore out of the scope of this project. The next paragraph delves into the working principle of SMAs.

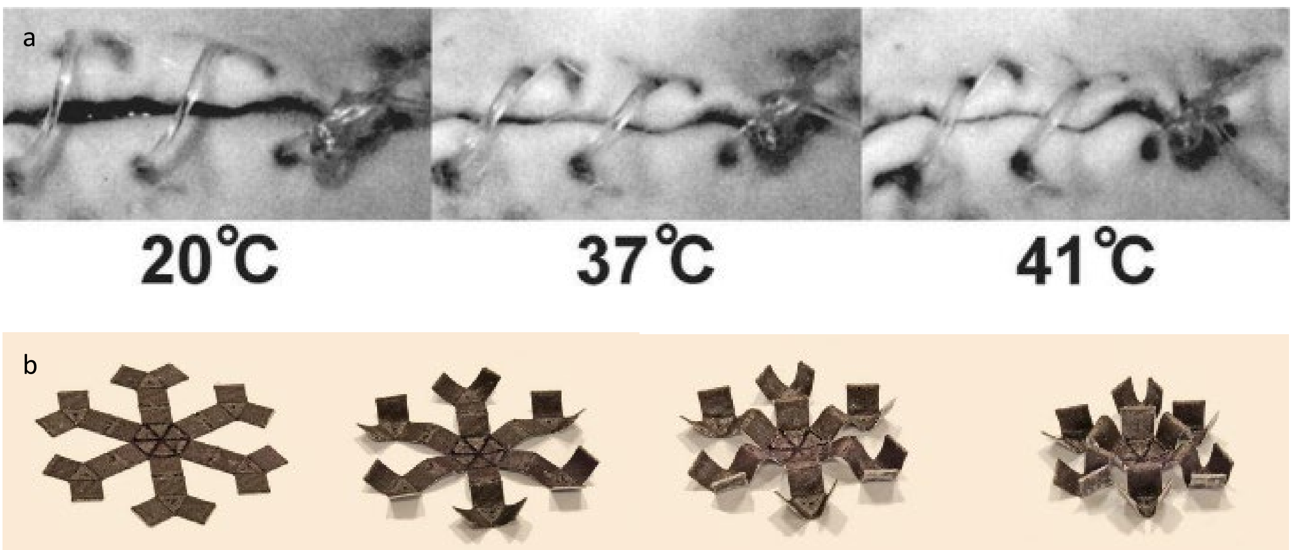


Figure 2.3.4 biodegradable SMP surgery fibre (a) and 3D printed Magnetorheological elastomers (Kim et al., 2018) (b)

2.2.2 Working principle of SMAs

To understand the working principle of SMAs, the underlying mechanism is described and its main components such as alloy composition, manufacturing process, force and displacement, cycle time and fatigue.

Underlying mechanism

In thermally responsive SMAs, the mechanism behind the Shape memory effect (SME) is the martensitic transformation of the crystal structures in the metal (see Figure 2.7) (Bengisu & Ferrara, 2018; Rao et al., 2015). When a shape memory alloy is deformed, its structure changes from a twinned martensite phase to a detwinned state martensite phase. Consequently, when the SMA is heated above its austenite start temperature (As), the detwinned martensite phase starts to transform into the austenite phase (Af). When cooled again the austenite phase (Ms) transforms into the twinned martensite phase (Mf). To minimize internal stress different twinned martensite variants arrange themselves, also called 'self-accommodated martensite variants' (Sun et al., 2012). Martensitic transformations are reproducible and a completed cycle -the transformations from deforming, heating to cooling- refers to the shape memory effect SME. Good to emphasize is that As and Af temperatures can differ.

To program and control the shape change, SMAs are 'trained' -shape setting is performed- by applying high temperatures far above Af, also referred to as the annealing temperature. For example, a shape memory alloy wire is shaped in a coil and heated to its annealing temperature while fixating the coil shape. Consequently, the SMA wire in spring shape is cooled below the martensite temperature (Mf) preserving its spring form. After training the SMA wire 'remembers' the spring shape. When the spring is deformed and heated again above (As-Af), it will reverse its shape again to its predetermined spring shape.

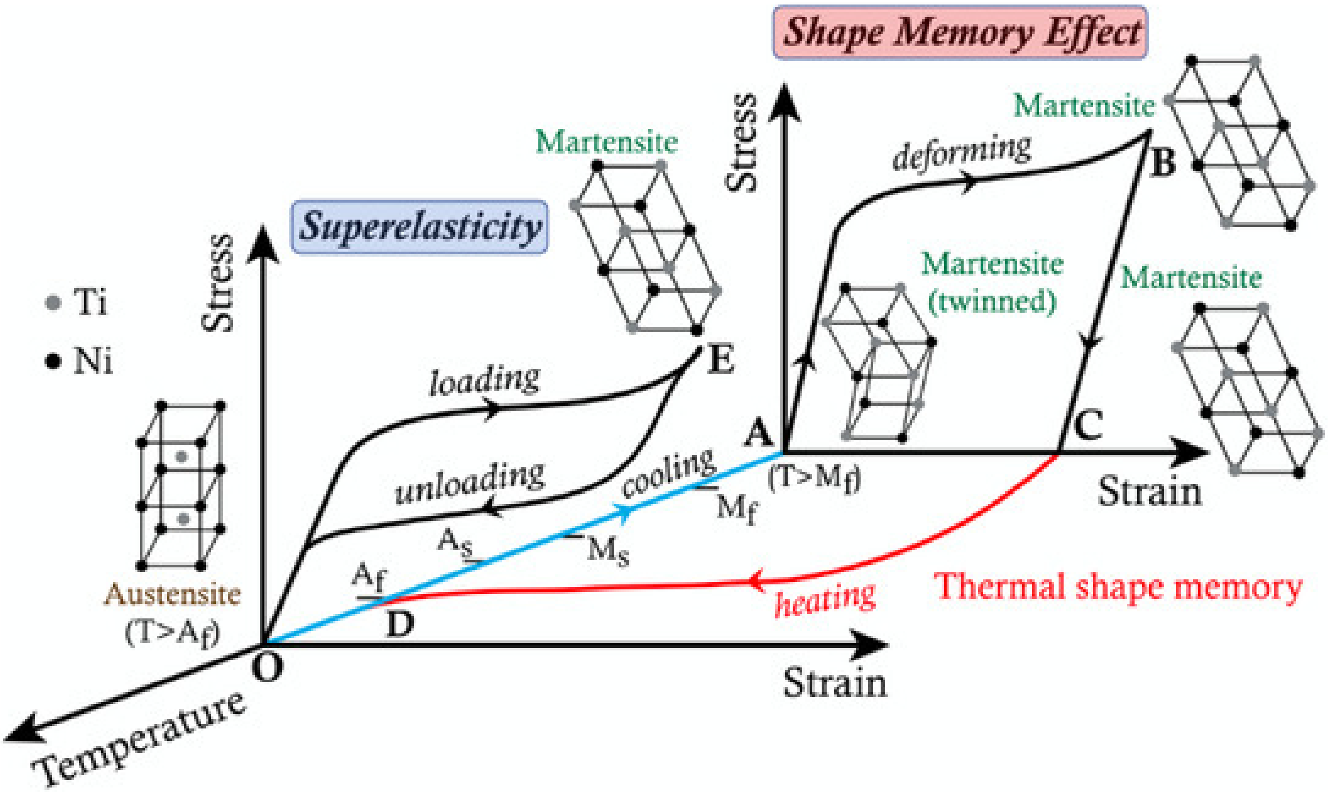


Figure 2.7 Visual representation of martensitic phase transformation of an SMA (Abdelrahman & El-Hacha, 2021).

Hysteresis is the difference between the forward and reverse transition paths (Sun et al., 2012), for heating (Af) and cooling (Mf) (see figure 2.8). A short hysteresis is desirable when a fast actuation cycle) is required whereas a large hysteresis is desirable when one wants to keep a certain shape over a large temperature range (Jani et al., 2014).

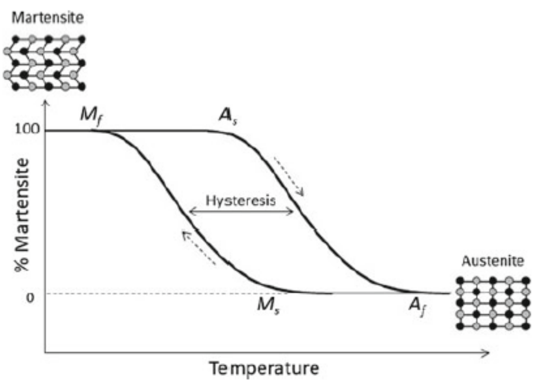


Figure 2.8 hysteresis in martensitic phase transformation (Rao et al., 2018).

Alloy composition

Common commercial SMAs include Ni-Ti-Cu, Cu-Zn-Al, Cu-Al-Ni, and Ni-Ti alloys, with Nitinol (NiTi) being the most popular due to its affordability and reliability (Bengisu & Ferrara, 2018). Nitinol's shape-setting temperature range is 500-550°C and its transformation temperatures range from -200 to 100°C (Rao, Srinivasa & Reddy, 2015), with some NiTi alloys regaining shape at body temperature, while others require boiling water. Nitinol's Ni and Ti content varies around an equiatomic composition (50% Ni and 50% Ti) and is closely related to the martensite transformation temperatures (Rao, Srinivasa & Reddy, 2015). Adding an atomic percentage of Ni above the 50% will result in a decrease of its transformation temperature and increases the yield strength of the austenite phase. Copper (Cu) additions decrease the hysteresis which can be favourable when a quick SME cycle is required (Bengisu & Ferrara, 2018). Iron (Fe) addition increases the yield strength and is commonly used for superelastic wires.

Manufacturing process

The manufacturing process is critical in achieving desirable material properties, as slight deviations can significantly impact thermomechanical properties (Bengisu & Ferrara, 2018). Nitinol manufacturing involves melting, casting into ingots, and hot or cold forming, followed by annealing wires or shaping them into springs. Purity and homogenization in melting are essential for a reliable alloy, while forming type influences material properties. For instance, cold forming is preferred for wire diameters below 4 mm to prevent surface oxidation and roughening. Consequently, wires with identical alloy composition and geometry may still vary between manufacturers.

Force and displacement

SMA wires are favoured when a high power-to-weight ratio is needed, often used in tension due to their actuator efficiency and energy density (Jani et al., 2017). Commercial NiTi generates 25 times higher work density than electric motors (Jani et al., 2014). Wire strength depends on composition, training, diameter, and its phase state, with NiTi SMAs Young's modulus being 28-41 GPa in martensite and 75-83 GPa in austenite. To provide a perspective on the forces involved, the pull force of a 0.3 and 0.5mm nitinol wire when heated is respectively 12N and 35N while the cooling pull force is 5N and 14N (Rao et al., 2018).

A limitation of SMA wires is the allowed strain of approximately 5%, leading to limited displacement (Mohd Jani et al., 2017). In addition to tension, loading configurations include torsion and bending, which can potentially yield larger displacements but at the expense of decreased actuation efficiency and energy density.

Cycle time

SMAs have the characteristic to have a relatively low cycle time compared to alternative mechanisms such as vibration motors which also gives them organic-like behaviour. Cycle time refers to completing the whole martensite transformation including heating up and cooling down the wire (Bengisu & Ferrara, 2018). To ensure reliable results, reactivation of the wire should occur only after the entire cycle has been completed. Heating up the wire can be done by contact heating through ambient or internal heating through the passage of an electrical current, joule heating.

A way to decrease the cycle time is to select thinner wires due to their higher resistivity and surface-to-volume ratio (Jani et al., 2014; Bengisu & Ferrara, 2018). For example, a Flexinol wire (Trans = 90C) with a 0.5mm wire diameter has a cooling time of 14s while a 0.05mm wire diameter takes 0.3s (Jani et al., 2014). For heating up the wire the rule of thumb from Kelloggs' Researchlabs can be used (Kelloggs' researchlabs, n.d): a Nitinol wire with 0.25mm diameter heats up 40C per second, 0.5mm 10C per second and 1 mm 3C per sec. More specific is the formula from Rao, Srinivasa and Reddy (2015) that describes the required current (a) and response time (b) needed for specific wire properties:

a. $$I = \sqrt{\frac{(T - T_{amb})}{4\rho} \times (\pi^2 d^3 h)}$$

In formula a, I is the current, T is the target temperature, d is the wire diameter, ρ is the resistivity and h is the heat transfer coefficient.

b. $$\Delta t = \frac{\rho_m (C_p \Delta T + L)}{-\frac{4h(T_{avg} - T_{amb})}{d} + \frac{16 I^2 \rho}{\pi^2 d^4}}$$

In formula (b), t is the time, ρm is the density, Cp is the specific heat capacity and L is the latent heat.

*The heat transfer coefficient (h), specific heat capacity (Cp) and latent heat (L) can be calculated using the thermal wizard website (Maya HTT, 2014). The resistivity (ρ) for NiTi wires differ in martensite and austenite (higher) state and is approximately around 0.5–1.1 *10−6 Ωm (Rao et al., 2018). To resistivity can be calculated using formula c where R is the resistance and l is the wire length.*

c. $$\rho = \frac{R\pi d^2}{4l}$$

As can be derived from the formula, a smaller diameter wire will significantly decrease the amount of current (a) and the response time (b). To give an order of magnitude, Rao, Srinivasa and Reddy (2015) describe that a 5mm wire needs 14 Amps whereas a 0.5mm wire needs 0.92 Amps to reach the activation temperature (given a 200mm wire length and a 90C activation temperature wire). Next to smaller diameter wires, shorter and low transformation temperature wires also positively influence the response time and current input as the temperature difference will be smaller (T-Tamb in (a) and ΔT in (b)) and the wire length will result in a higher resistivity (c).

In addition, ways to decrease the cooling time, apart from adjusting the wire geometry, are to use an external cooling agent, such as forced air, flowing liquids, and heat sinks.

To sum, small diameter, short and low transformation temperature wires can be considered to achieve a shorter cycle time and lower power consumption.

Fatigue

Two forms of fatigue are distinguished by Rao, Srinivasa and Reddy (2015): structural and functional fatigue. Structural fatigue refers to *'SMAs failing like other engineering materials due to repeated high cyclic mechanical loads'*. Functional fatigue refers to *'the process when repeated thermomechanical cycling causes the degradation of functional SMA properties'*. As such SMAs can have a reduction in shape recovery ('memory loss'), damping capacity affecting the hysteresis, lower transformation strains and transformation temperatures. The manufacturing process and a proper shape setting are essential to obtain high fatigue resistance. Factors that increase fatigue are overheating, overstressing/loading, and overstraining (Jani et al., 2014). Generally, for wires, it is assumed to apply one/third of the maximum load and restrict the strains to about 2-4%.

2.2.3 SMAs in a material system

Embedding SMAs in a material system requires shaping the SMA and integrating it into a substrate structure. The possibilities for SMA shapes and substrate structures are described.

SMA shape and geometry

SMAs come in different geometries such as wires, films and rods with wire being the most common. These wires, varying in diameters from 0.05mm to 4mm (Rao et al., 2015), can be shaped differently for various design applications (see table 2.10). However, with SMA wire strains limited to 2-4% yielding small displacements, a longer wire length is required to achieve larger displacements. Ways to cope with large amounts of wire in designs are to guide the wire with anchor points in a zigzag way, use a knitted structure or roll the wire in a PTFE/Teflon tube (Liu, Ghodrat & Jansen, 2022). The additional advantage of the tube-guided system is that it fixates the wire when heated which prevents it from going out of shape and provides thermal protection. Ways to enlarge the displacement and limit the wire length in pure tension strength is to amplify the stroke using a lever system, angled pull force or adjust the curvature (jani et al., 2017).

Furthermore, the wire itself can also be trained into a 2D and 3D shape such as springs, zigzags or other shapes to create a certain movement (and therefore displacement), relying on torsion and bending forces. As mentioned earlier, torsion and bending have a lower energy density (generate lower forces), however, the displacements can be significantly bigger in small areas compared to using the wire´s linear tensile strain. For example, the prototype springlets from Hamdan et al. (2019) can generate around 50% displacement (20 mm with a 45mm spring length and 0.62mm coil diameter). The mechanical response of springs are largely dependent on the spring index (spring diameter/wire diameter) which ranges between 5 and 12 (Kim et al., 2012; Rao et al., 2015). Especially for designs that do not require high amounts of forces, 2D or 3D shapes can enrich the way SMAs are used for haptic sensation as they enable a larger displacement in a small area.

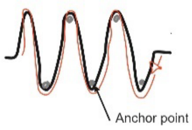
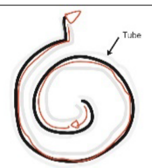
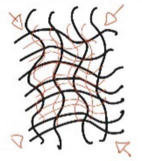
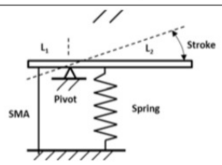
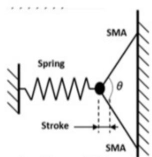
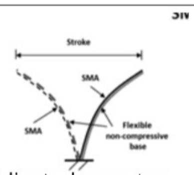
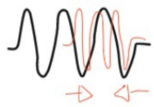
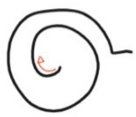
Type of force	Shape configuration	Options		
TENSION	Guiding wire in tension	 With anchor points	 Tube guided	 Knitted
	Amplifying stroke in wire tension	 Lever system	 angled pull force	 Adjusted curvature
TORSION OR BENDING	Using 3D structure	 Torsion bar	 helical spring	
	2D structure	 Bending bar	 zigzag spring	 rotational bar

Table 2.10 A compilation of different shape configurations found in literature; the illustrations of the amplified tension are from jani et al. (2017) .

Substrate structure

SMA wires can be integrated into different types of structures and materials to create a shape-changing mechanism that generates haptic feedback. The shape change created by the SMA can originate exclusively from the SMA itself and be coupled with an end effector to produce haptic feedback. Or the substrate structure can facilitate or accelerate the SMA movement and/or can serve as the counterforce. An overview of the parameters is illustrated in Figure 2.11.

As mentioned earlier, a one-way SMA will go back to its trained shape after being subjected to heat. A counterforce is needed to deform the SMA shape in the cooled state in the first place. This can be done by an external element outside the system such as the skin. Or an embedded element in the system which can be actively controlled such as an SMA antagonist, or passively like a bias spring, a substrate material or structure (Weirich & Kuhlenkötter, 2019). Using an integrated counterforce means that the counterforce needs to be smaller than the SMA force in the austenite state and bigger than the SMA force in the martensite state.

Qamar et al. (2018) distinguish three types of shape-changing structures next to SMMs: stretchable structures, deployable structures and variable stiffness materials. Stretchable structures rely on a material/structure that is compliant enough to allow for large-scale deformation categorized in elastomers and auxetics structures that. Auxetics structures rely on the spatial arrangement of their internal architecture and become wider when stretched and narrower when compressed (a so-called negative Poisson's ratio). Deployable structures enable an easy and precise expansion or downsizing of a shape-changing mechanism, categorized in rollable and foldable structures such as origami. Due to the high strength-to-weight ratio of foldable structures, it enables thin, lightweight, shape-shifting geometries for efficient 3D deployment and 2D flattening. Variable stiffness of the material often include different stiffness properties in different directions to create a shape change. This can be done using the anisotropy and multi-stability of the material property, which can for example be achieved with 3D printing.

$F_{SMA\_austenite} > F_{counterforce}$ & $F_{SMA\_martensite} < F_{counterforce}$

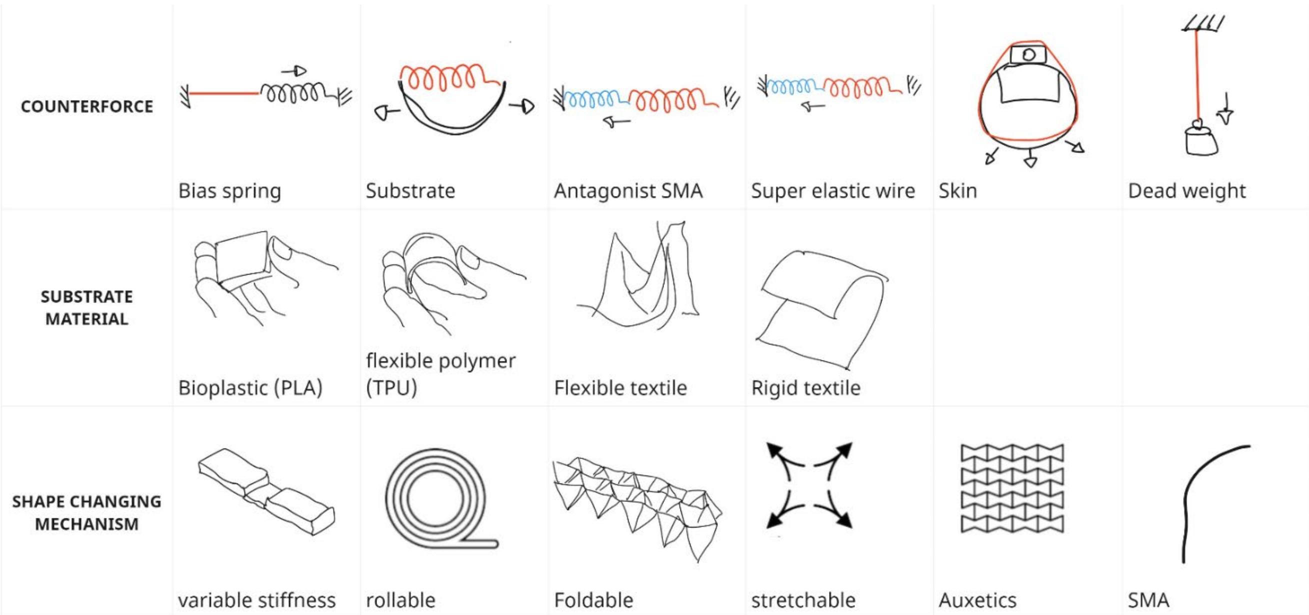


Figure 2.11 Overview of the different types of counterforces, substrate structures and shape changing mechnanisms found in literature.

Connection-joining

Nitinol wires are difficult to join and attach to other materials as they cannot be soldered (Rao, & Reddy, 2015). Joining nitinol to itself using TIG welding has been successful. However, joining nitinol to other materials such as stainless steel is challenging as it will affect the characteristic properties of SMAs. Laser welding provides good control over the heat input which limits the heat-affected zones. Another reliable option is mechanical techniques such as crimping, swaging or staking or bonding with high-grade epoxy or adhesives. Crimps are often used to connect electrical and SMA wires and limit the heat buildup in the connection place.

2.2.4 Main insights

As described there are many different shape memory materials categorized by their type of shape memory effect, external stimuli and material type. For this project, thermally activated SMAs wires were chosen due to their high load-bearing capacity, reliable shape recovery, and rapid response time.

SMAs change their shape due to the martensitic phase transformations in their crystal structures. This process is guided by specific temperatures (As, Af, Ms, Mf) that govern the transformations between austenite (heated) and martensite (cooled) phases. Key elements in the working principle of SMAs include alloy composition of which NiTi alloys are the most common, and manufacturing process. Characteristics to take into account are the limited strain of approximately 5%, a relatively low cycle times, low energy efficiency and fatigue which is influenced by overstraining, loading and heating. The cycle time and therefore the power consumption can be shortened by selecting small diameters (highest influence), short lengths and low activation temperature wires.

Embedding SMAs in a structure necessitates consideration of SMA shapes, substrate structures, and connection techniques. The most common used shape is a straight wire in tension, followed by 2D or 3D shapes, such as springs, applying bending and torsion forces. The advantage is the increased ultimate strain and design flexibility and the disadvantage is the substantial decrease in load capacity.

To enable a shape change back and forth a counterforce is needed to deform the system in the first place which can be an external element outside the system such as a manual action, or integrated in the system such as a bias spring, an SMA/SE antagonist or the substrate structure itself. To get an idea what is commonly used in SMA systems for haptics a benchmark is done for material systems based on SMA for haptic feedback.

2.4 BENCHMARK ON MATERIAL SYSTEMS BASED ON SMAS

A benchmark is made of material systems based on SMAs for haptics to understand the valuable and relevant areas to focus on in this project, described in a schematic overview and case studies. In addition, several SMA systems that react on an environmental stimuli are described to understand its working principle without the use of electricity.

2.3.1 Schematic overview

Figure 2.3.1 gives a schematic overview of the benchmark for material systems based on SMAs for haptics, involving around 40 papers (see Appendix A for detailed overview). It serves as a summary of all the possibilities for distinctive elements of SMA systems for haptics presented in the papers. The six columns represent the possible underlying mechanisms presented in the SMA systems for haptics (red coloured), the types of haptic feedback that are generated (yellow) and the locations to perceive the haptic feedback (blue).

A general observation is that most systems are wearables and work on electricity ranging from rigid skeleton structures to embedded flexible structures. The two main used and researched locations for haptic sensations are the finger and forearm, probably because the finger is the most sensitive body location and the forearm is an easy place to attach more extended prototypes.

Another general observation is that all used SMA wires have a rather small diameter, between 0.1-0.5mm. This has most likely to do with the response time: the smaller the diameter the faster the response time. The bigger diameter wires (0.3mm-0.5mm) are mainly used for (micro) springs and smaller diameters (0.05-0.2) are used for straight wires used in tension force.

Function	Location	Haptic type	Wire construction	Counter force	Haptic generator
VR experience	Finger	stretching	straight wire	bias spring	end effecter
Braille	Forearm	Pressing	Straight wire guided in zigzag	Stiffness of textile	wire
Navigation	wrist	Heating	(micro) spring	Structure	structure
Unspecified function	hand	pinching	Wire bending	skin	
	Back	squeezing		Counter SMA	
		Stroking/draging			
		Tactile difference			

Figure 2.3.1 Overview of used mechanisms in material systems based on SMAs.

2.3.2 Case studies

In these case studies main themes are described that involving wire construction, counterforce and activation temperature.

Wire in tension

Most SMA systems for haptics use straight wires and springs. *Touch me gentle* uses the wire strain to enable a shear squeeze sensation by contracting the guided zigzagged wire (Muthukumarana et al., 2020) (figure 2.3.2). They designed 3x3 cm adhesive plasters consisting of two insulating layers, to protect the user from the wire when heated. In between the insulating layers, a stretchable textile is placed where the wire is integrated in in a zigzag to enable a constant squeeze force over the area. The plasters can be placed in sequence to enable a wide variety of complex haptic sensations such as grabbing the arm, three taps down the arm or stroking down the arm.

Wire in spring shape

The project from *Springlets* (Hamdan, 2019) uses micro springs attached to adhesive plasters to enable haptic sensations for different body locations such as the neck, forearm and earlobe (figure 2.3.3). Hamdan et al. (2019) explored different types of sensations such as pinching, pressing, dragging and stroking by including an end-effector in the spring mechanism and different types of micro springs.

The advantage of using (micro) springs is the increased stroke of 50-200% of the total spring length (Tokio wire,2014) with a force range of around 0.2 N - 1.4 N (wire and coil diameter of 0.1 and 2.54mm) (Dynalloy, 2017; BMX catalog, n.d). The minimum force that can efficiently actuate the skin or move an object on the skin's surface is 30g (Hamdan et al., 2019). By combining several springs Hamdan et al. (2019) proposes several applications areas such as an intimate messenger on the ear or a navigator on the back where the stimuli of the stretchers are spaced 5–8 cm from each other to guarantee a clear two-point discrimination.

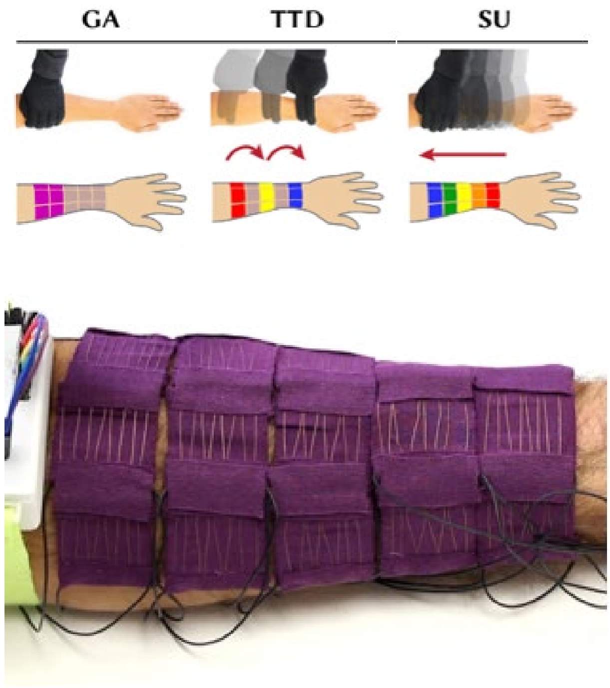


Figure 2.3.2 Touch me gentle with possible haptic feedback

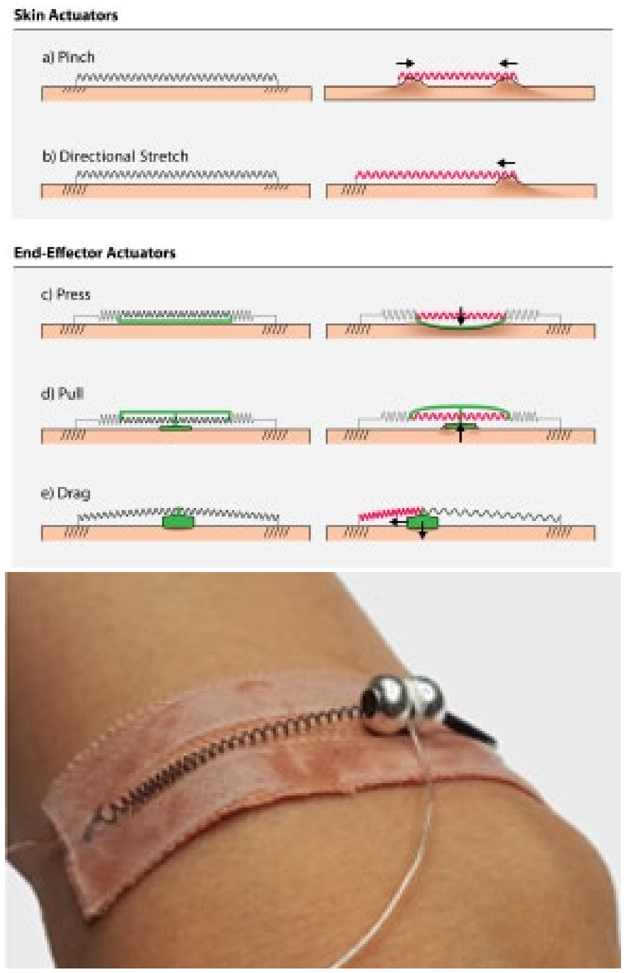


Figure 2.3.3 Springlets with possible configurations

In line with this paper, Sun et al. (2020) explored with *Weaving a second skin* ways to create interactive interfaces on the skin (figure 2.3.3). In one of their projects, they embedded a micro spring (0.15mm wire diameter with 0.62mm coil diameter) in a plain weave textile combined with adhesive plasters. When electrically activated (2.75V) the textile generated a subtle squeeze sensation.

Figure 2.3.4 Weaving a second skin

Similar to the previous examples, Simons et al. (2020) proposed with *In contact* a wearable design with micro springs and adhesives but managed to generate three types of pinching sensations (figure 2.3.5). They compared the design with vibrotactile sensations and demonstrated that an SMA-based mechanism is preferred over devices using vibrotactile sensations as is perceived as more natural and subtle. While this interface demonstrates a unique method of providing multiple haptic sensations on the skin, there remains a necessity to explore ways to create an integrate and therefore more subtle device.

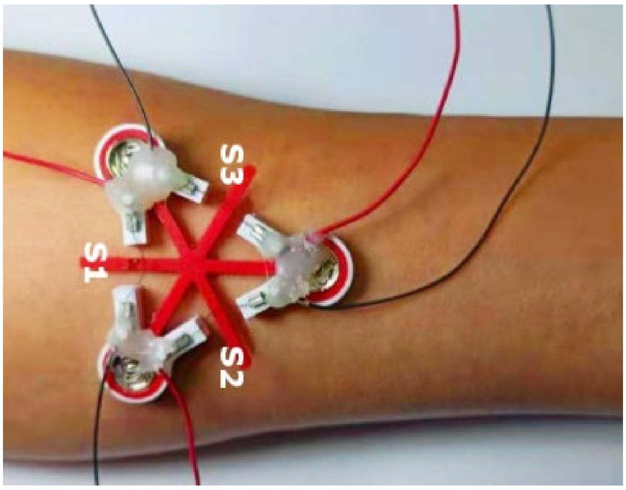


Figure 2.3.5 In contact

Wire in bending

Relatively new to this field is to use the SMA wire other than in wire tension of spring shape. Papadopoulou et al. (2019) explored the possibility of using a trained flat NiTi wire to generate pressure and heat sensations on the skin to reduce anxiety levels (figure 2.3.6). They used six cuffs of which in each 0.5mm NiTi wires were sewed that were trained to be straigth. In the cooled state, the wire was forced to curve due to the geometry of the sleeve with the advantage of not using adhesives. When the sleeve was activated the wire flattened creating a slight pressure increase and warmth on the forearm.

Figure 2.3.6. Sleeve with SMAs embedded to reduce anxiety

Bias spring as an integrated counterforce

The above mentioned examples use an external element, the human skin, to create the counterforce. To create an integrated counterforce, bias springs, SMA antagonists or the structure itself can be used. Bias springs are due to their 3D structure mainly used in rigid structures such as the *haptic cube* from Lim et al. (2019), providing tactile feedback to the finger (fig 2.3.7).

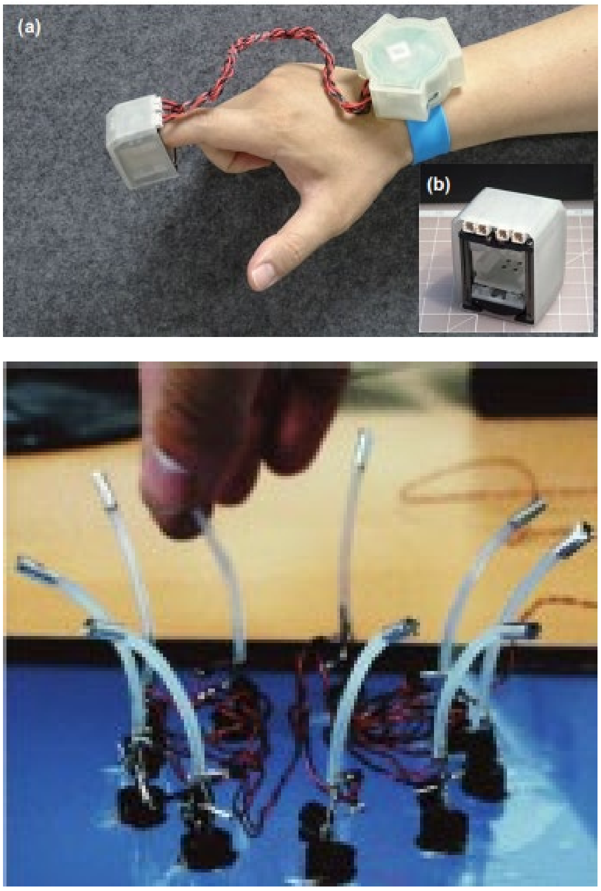


Figure 2.3.7. Haptic cube (upper) and tentacle (lower)

SMA antagonist as an integrated counterforce

To create a more integrated structure and SMA antagonist can be used. Nakayasu et al. (2014; 2016) explored with *Weaving tactiles* the usage of multiple counteracting SMA wires in one tentacle to create three bending directions in one structure (figure 2.3.7). In this way, the counterforce can be actively controlled which allows for precise haptic feedback control. Good to emphasive is that SMA wires need to be isolated from each other to prevent them from all activating at the same time.

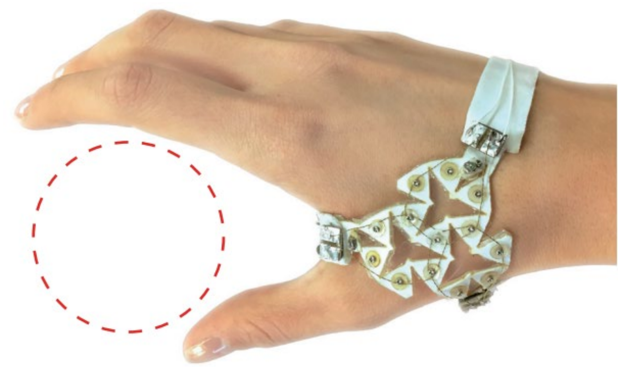


Figure 2.3.8 Skin+

Structure as an integrated counterforce

Another way to create a counterforce and guide the movement at the same time is the use of the substrate structure. Cao et al. (2018) combined an auxetic structure with 0.15mm SMA wires to enable a squeezing sensation on the hand with *Skin+* (figure 2.3.8). The SMA wire is twisted in a double-wire to increase the contraction force and the auxetic structure creates a counter contraction by showing a negative Poisson's ratio. Another example but then in a touchable is the *Bendi* from Park et al., (2015), a Shape-Changing Mobile Device for a Tactile-Visual Phone Conversation (figure 2.3.9). They also used the substrate structure as a counterforce embedded several SMA springs in the structure to create different haptic feedback movements.

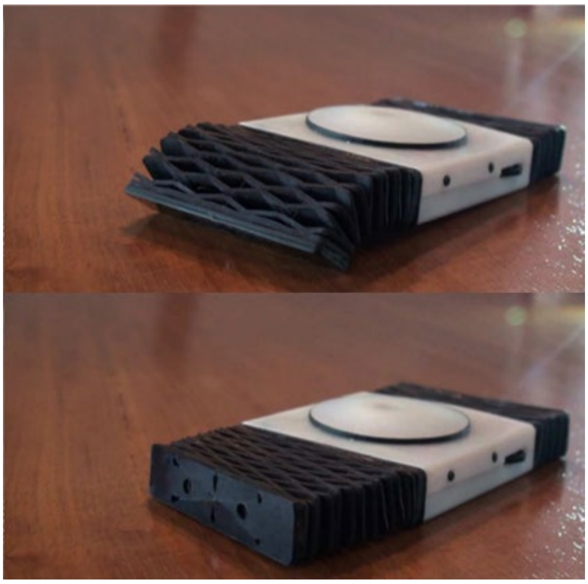


Figure 2.3.9 Bendi

2.3.3 SMA used as sensor and actuator

The case studies outline the possibilities of using the SMA as an actuator with the use of electricity. However, SMAs could also be used both as a sensor and actuator with the advantage of using no power and electrical connections.

Body temperature

An example were SMA systems react on natural environmental stimuli is the compression sock from the University of Minnesota (Granberry & Holschuh, 2017) (figure 2.3.10a). Embedding 0.381mm diameter SMA wires in a knitted structure with a temperature just above body temperature activates compression upon contact with the body. By doing this Holschuh addresses two main issues with SMAs: '*they take a lot of power, and they generate heat—too much heat*'. Their prototype was made with a 70C wire to illustrate the working principle and they considered using 37ºC wires with the advantage of using no electricity or 43ºC wires, if insulated properly to limit the battery volume. Important to take into account when the SMA will be activated solely with body temperature is that the actuators need to be attached to the body tightly to enable a precise actuation control.

Kim et al. (2021) tried the approach of using 45 temperature wires to enable a fast response time (less temperature difference needs to be bridged compared to 70C wires) and limit the power consumption (figure 2.3.10b). They used micro springs (0.5mm diameter) embedded in textile to generate a compressing sensation on various body locations (figure 3.2.11b). In this, the textile provided enough isolation to protect the skin.

An example where SMAs are truly reacting to an environmental stimuli is with *Thermo Insulation* from Yoo et al., (2008), an textile for automated insulation. This system makes use of a two-way coiled 1mm SMA wire reacting on outside temperatures (As-Af: -8-22C) and placed between two textile layers. When the temperature was reached below 0-5, the coils expanded causing an insulation layer with air (fig 2.3.10c). Above this temperature the coils contracted enabling less of an insulation layer.

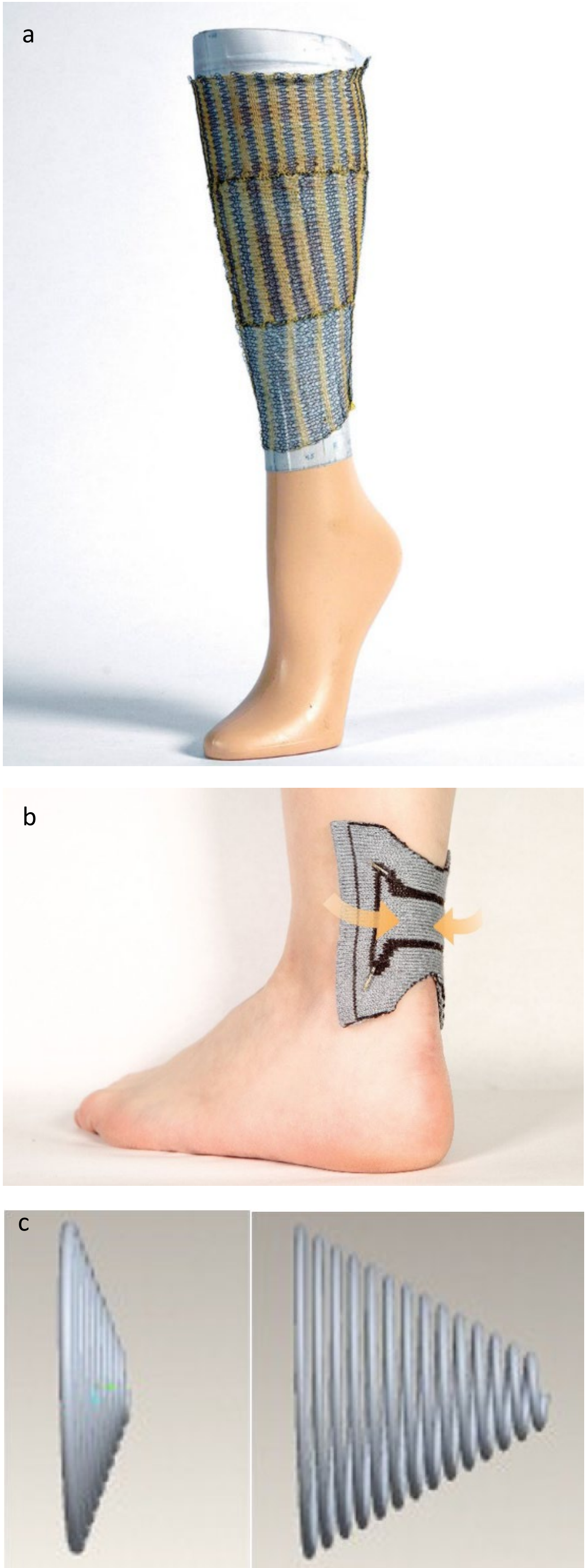


Figure 2.3.10 Compressive garmet (a); Knitdermis (b); Two way Coil shape from Thermo insulation (c)

External element as heat source

An example where indirect electricity/heat is used for haptics is Tactilia, a reconfigurable tactile pixel array display at braille resolution from Bhatnagar et al. (2021). They used a Nitinol sheet (27x27cmx0.3mm) with activation temperature of 40 degrees. The pixels rise 0.4mm vertically after activation with a pen that generated heat. After cooling the pixels can be mechanically reconfigured back to their flat state for repeatable actuation.

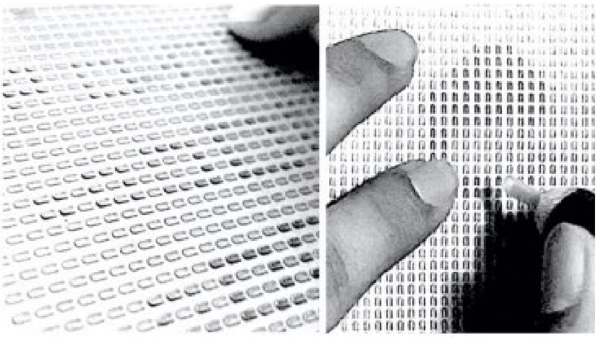


Figure 2.3.11 Tactila: braille with a SMA nitinol sheet

2.3.4 Main insight from benchmark

This benchmark has illustrated the diversity of SMA systems for haptics that are already explored, ranging from wearables and touchable systems.

Apparent is that the most used wire constructions are a straight wire in tension or a micro spring with an activation temperature of 70C and 0.2-0.5mm wire diameter. The disadvantage of using a straight wire is the need for a long wire to create a noticeable displacement. A (micro) spring can generate a much bigger displacement (10 times more) but these are difficult to integrate when a soft embedded structure is desired. Besides the isolation of a spring is a challenge to prevent the skin from burning. Creating an integrated structure with a larger displacement than in tension with the use of other trainable SMA shapes is worth investigating.

Another insight is that most wearable systems use the skin, an external element as the counterforce. Most touchable examples, use either a bias springs, an SMA antagonist or the structure itself as a counterforce. The disadvantage of using a bias spring is the difficulty to create an integrated structure. SMA antagonists have the advantage of designing precise movement but requires active control over the system increasing the power usage. The precise but passive control when a super elastic wire would be used is more promising, however no examples for haptics were found.

Finally, to account for safety issues and power consumption, there are examples of systems using low activation temperature wires. The advantage is the ability to react on body temperature or the need of little power to activate the system.

2.4 LITERATURE CONCLUSION

The literature demonstrates that there is potential to design a material system based on Shape Memory Alloys (SMAs) that generates haptic feedback for visually impaired people.

Outcomes paragraph 2.1 Haptic feedback is an emerging field for VIPs, and SMA systems can enrich this area by providing a unique form of haptic feedback due to their organic movement, distinct from conventional vibration motors. Moreover, SMAs have the potential to be noiseless, an advantage not shared by vibration motors while haptic feedback is particularly valuable when conveying subtle or private information.

Outcomes paragraph 2.2: To enhance the information transmitted through haptic feedback, various patterns, materials, and spatial properties can be employed. SMAs offer the potential to leverage both active (e.g., braille) and passive (e.g., vibration motors) feedback, as they can generate movement and change shape. This provides a new opportunity for generating tactile information, which could revolutionize haptics for VIPS/the cannot be achieved by vibration motors alone.

Outcomes paragraph 2.3. Next to the noiseless and organic characteristics, SMAs are characterized with a high load capacity, especially when the wire is used in tension. A contradictory uniqueness of SMAs is the ability to design the memory by training the wire in a certain shape. This diminish the high load capacity but enables the creation of flexible and complex shapes that could be fully embedded in a material system and create a larger ultimate displacement. Another important characteristic is that SMAs could act as both a sensor and actuator attributing to an autonomous, simple and lightweight mechanism as no electrical power and therefore electrical connections are needed.

Things to take into account when designing with SMAs for VIPs are that SMA have the characteristic to have a slow cycle time and low energy efficiency.

Outcomes paragraph 2.4 The benchmark reveals that most SMA systems for haptics are wearables that use the human skin as a counterforce. Typically, the tension force of a straight wire or 3D spring is employed to create a squeezing sensation on the skin. Given the unique SMA characteristic of designing a shape memory, it is worth investigating to which extent a designed shape memory can be utilized for haptics. In addition, this could increase the displacement (compared to tension) while keeping the ability to fully embed the shape into a material structure (which is difficult with springs). To create such an integrated SMA composite, the counterforce should also be integrated within the system, which could be best achieved by using the structure of an SE.

Finally, the literature shows that there are few SMA systems designed for haptics without electricity or with low activation wires. The use of low activation wires can reduce energy consumption, response time, and account for safety issues.

In sum

Based on the research and design gap, the focus for this project is on researching the possibilities of designing a shape memory in an autonomous material system to enhance the form freedom and ultimate displacement while accounting for energy and safety issues.

The next steps involves researching the target group to understand what role haptics play in their lives and identify needs where the described characteristics can be shown, and researching the basic principles of SMAs to understand their boundaries.

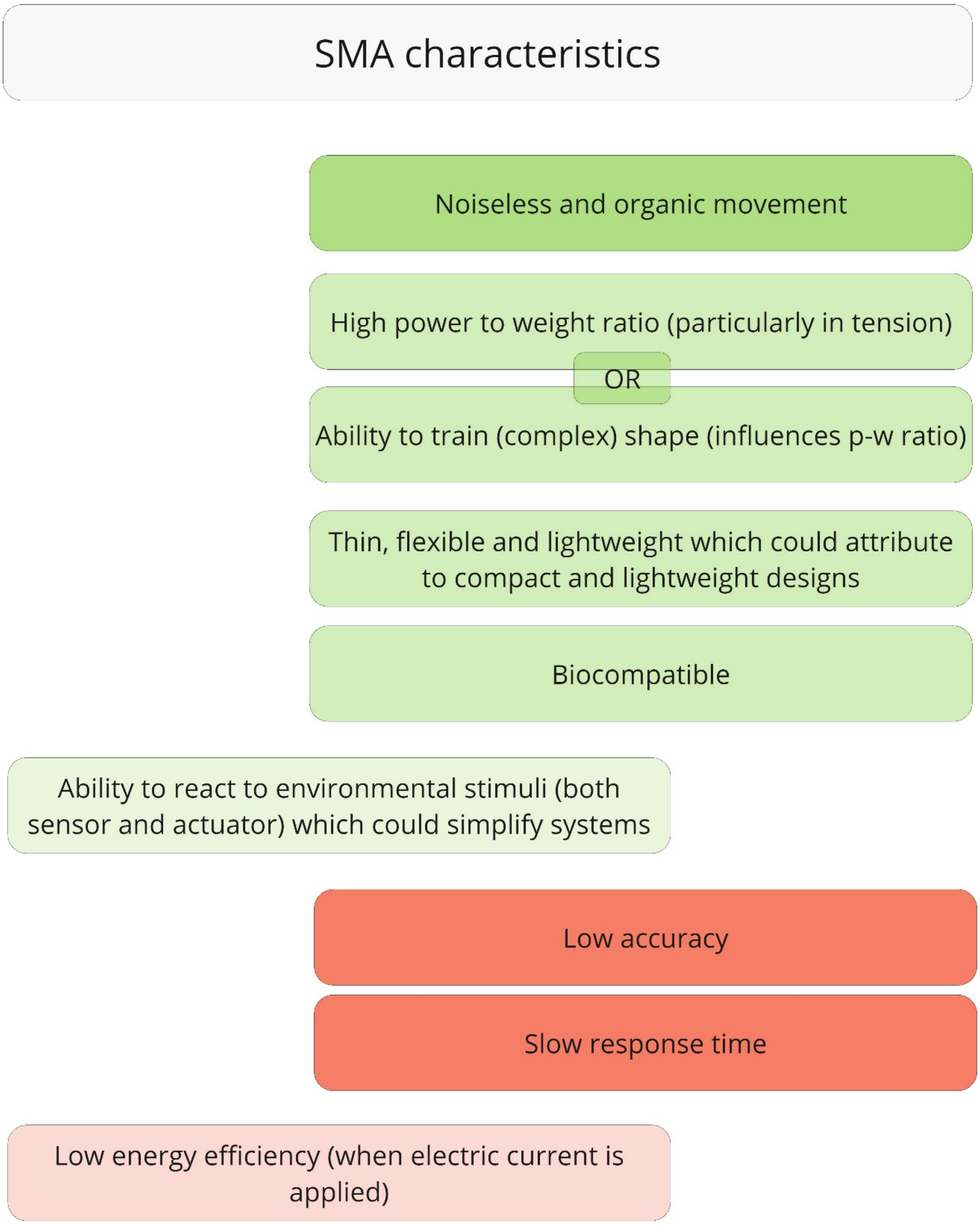


Figure 2.4.1 Overview of main characteristics of SMAs in systems with marked in green the advantages and in red the aspects to take into account when designing with SMAs (Jani et al., 2014).

3 TARGET GROUP RESEARCH

Figure 3.0 Picture of photographer Hannas Wallrafen who lost his sight in three months (NO CANDY, nd)

3.0 INTRODUCTION

To design for Visually impaired people, it is important to acquaint in-depth knowledge about the target group. Especially, as I have never been in contact with this target group before. The reason for conducting this research is to familiarize myself with the target group. The additional purpose of this research is to identify needs VIPs have where the possibilities of a material system based on SMAs can be shown. To do this, the following research questions were addressed:

- What obstacles do VIPs face in daily activities?
- How do VIPs use their touch sense in daily life?
- What are VIPs experiences with the usage of assistive device

By addressing these questions, an impression of the lives of VIPs can be compiled and needs where SMA systems could be valuable can be derived from the faced obstacles.

Based on a visit to Bartimeus, fields of interest for SMA systems concern subtle awareness of their environment (visit to Bartimeus). Bartiméus is a Dutch organization dedicated to improving the quality of life for people of all ages who are blind or visually impaired. In addition, Schölvinck, Pittens and Broerse (2017) identified ‘reduced mobility’ and ‘problems with social interaction’ as prominent problems with the main focus on improving self-sufficiency.

This research is conducted by doing semi-structured interviews with VIPs and the setup was approved by the ethics committee.

‘You know what bothers me is that I haven't seen my wife in 10 years’ –P4

3.1 METHOD

3.1.1 Participants

Six adults participated (2 women and 4 men) in the study, aged between 42 and 70 years (average is 55 years). Participants were recruited via a post on two Facebook groups for visually impaired people 'Blinden en slechtzienden' and 'Mobiliteitscafe blinden en slechtzienden' and one participant was recruited via a friend's neighbour. Inclusion criteria were the presence of moderate - severe visual impairment and blindness (30-0% sight) and the ability to hear.

3.1.2 Stimuli

The research method is a semi-structured interview (Eelderink, 2016) using a basic questionnaire to guide the conversation and further elaborate on each question. The questionnaire consisted of two parts, about daily routines and their experience using assistive devices (see Appendix E).

The interviews were conducted either via teams or at the participant's homes. Voice recording was done with a mobile recording app or teams recording, the recordings were reviewed and transcripts were made.

3.1.3 Procedure

The interview lasted around 90 minutes. First introductions were done, the project and reason behind the project were explained and the interview setup was described including the estimated interview time. Second, consent was asked by signing the informed consent form (see Appendix B). The consent letter was mailed beforehand to give the participants time to read it and if desired it was read out loud at the start of the interview. It was emphasized that there were no wrong answers and that the results would be anonymized. After the introductory talks (15 minutes), the interview was conducted consisting of personal questions, questions about their daily activities (Part 1) and questions about their assistive devices (part 2):

-Personal questions ranged from topics such as the cause and type of their visual impairment, type of work and their living situation.

-In part 1, the daily routines were questioned in frames of 2 to 4 hours, divided into the morning (08.00-12.00), the afternoon (12.00-16.00), the early evening (16.00-20.00), the late evening (20.00-23.00) and the night. Examples of questions were *'Can you describe your morning routine from the moment you wake up?'* and *'What elements do you find difficult when preparing dinner?'*

-In part 2, the use of assistive devices was questioned, emphasizing the aspect of haptic cues in the devices. Also, the reasons behind unused devices were asked.

After the interview questions, they were asked if they wanted to address another particular topic. It was further suggested that the outcomes of the project could be shared and it was asked if they would be open to participating in future research of my project.

A pilot session was done with one non-visually impaired participant to test the structure and length of the interview. Based on the pilot, more detailed questions were formulated, particularly those about their daytime activities and travelling to unfamiliar places.

3.1.4 Data analysis

In the semi-structured interviews, qualitative data was collected. The data was transcribed, filtered and clustered in themes using statement cards. This was done by finding common statements and/or words in the transcripts and grouping the similarities. Furthermore, profiles were made based on the personal question outcomes to describe the target group.

3.2 RESULTS

The interview results are shown coping mechanisms (figure 3.1), six profiles (figure 3.2) and obstacles (figure 3.3).

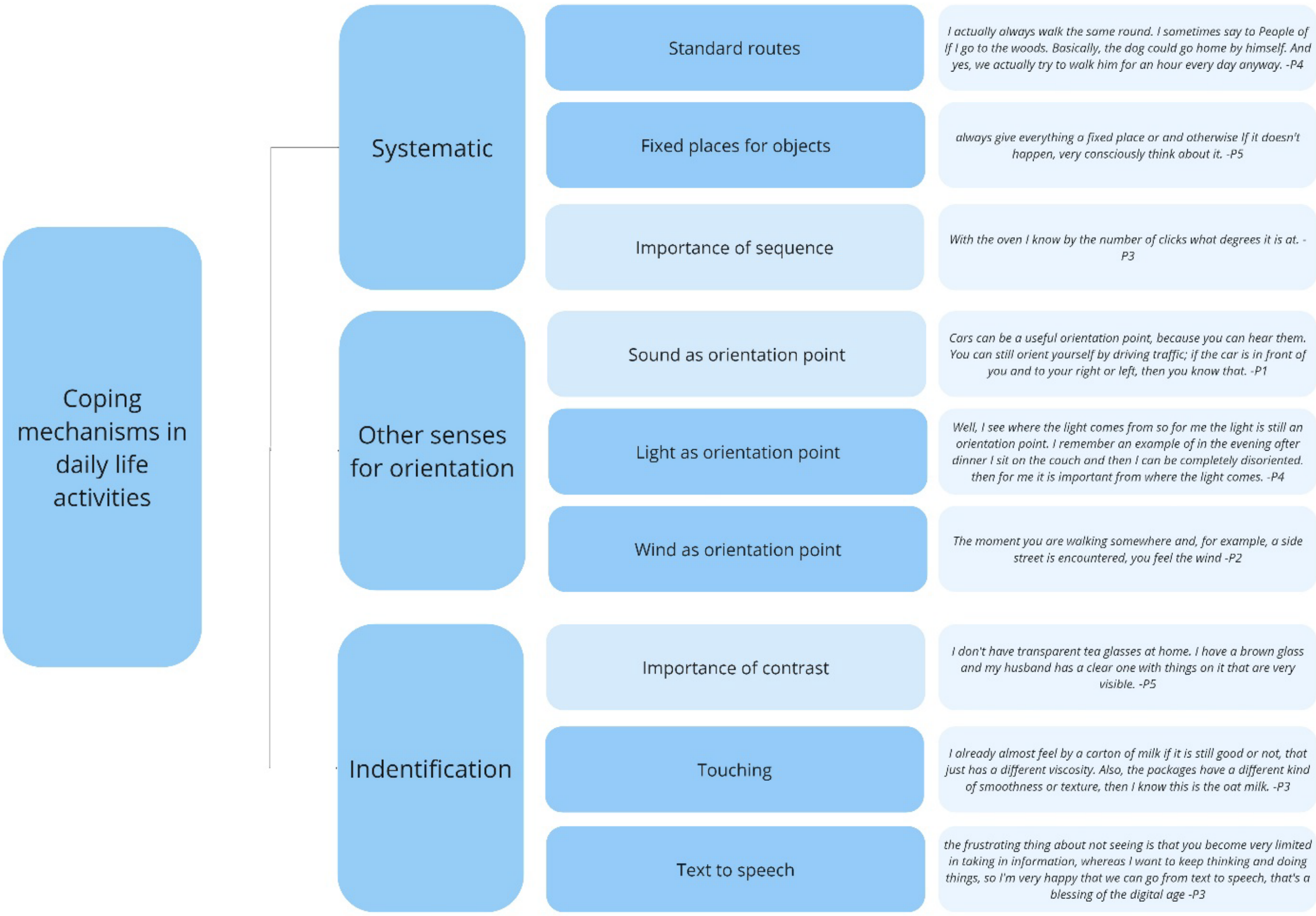


Figure 3.1 Coping mechanisms of VIPs categorized in themes and subthemes. The dark blue subthemes were mentioned more than 4 times by the participants and the light blue subthemes were mentioned 2-4 times.

3.2.1 Profiles

In the six profiles the degree of vision (window in the back), their work activities and their assistive devices are illustrated (see figure 3.2).

An important observation is that the group of mild-severe visual impaired people is diverse in terms of sight and their preferences of using haptic feedback. For example, a blind person can only see dark (figure 3.2 a) or distinguish light and dark (d and f). In the last case light is a crucial reference point for orientation. When there is some sight left, this can be in a tube vision needing a lot of light to still be able to see (figure 3.1 c) or a peripheral vision where every light is avoided as this blinds them causing them to walk with sunglasses (b).

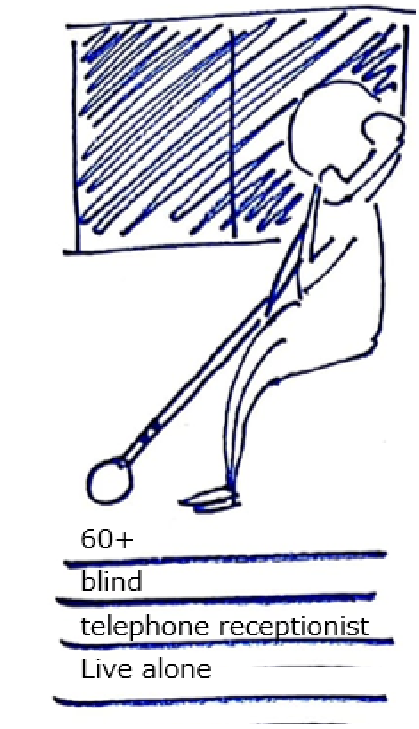
In addition, some participants were born blind or with severe visual impairment (a, d and f) whereas others became visual impaired at a later stage (b,c and e) which influence their way how to cope with their surroundings. Participants that were born blind incorporated haptic feedback at a young age with braille and a white cane as the most important assistive devices. Participants that had still some vision left did not used haptic devices but used their tactile sense mainly for exploration of their surroundings:

'*I already almost feel by a carton of milk if it is still good or not, that just has a different viscosity. Also, the packages have a different kind of smoothness or texture, then I know this is the oat milk.' -P3*.

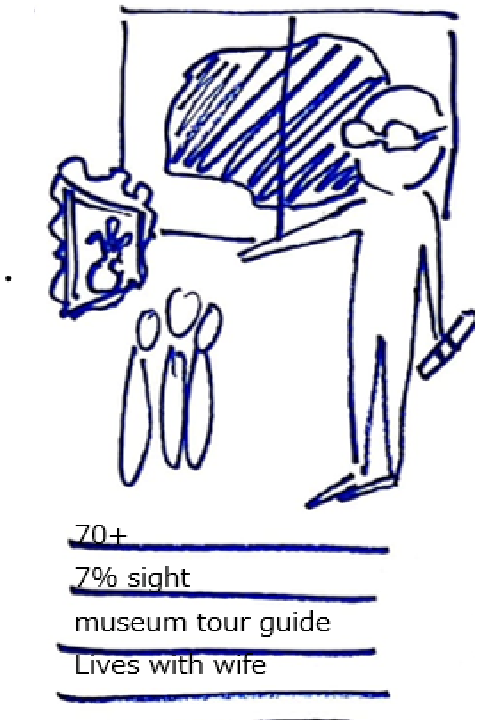
However, one participant mentioned the potential of haptic devices:

'*I think I would have to make quite a shift myself to make use of that haptic feedback. It's not in my system like that, and we all weren't actually raised that way. But maybe in doing so I am closing a whole section that could be quite useful.. '-P4*

Furthermore, notable is that all of them have had full-time or part-time paid employment most of their lives, mentioning the importance of being independent and contributing to society.



a



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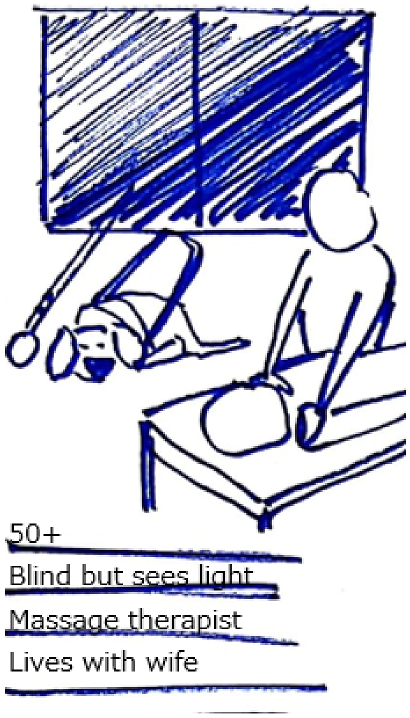
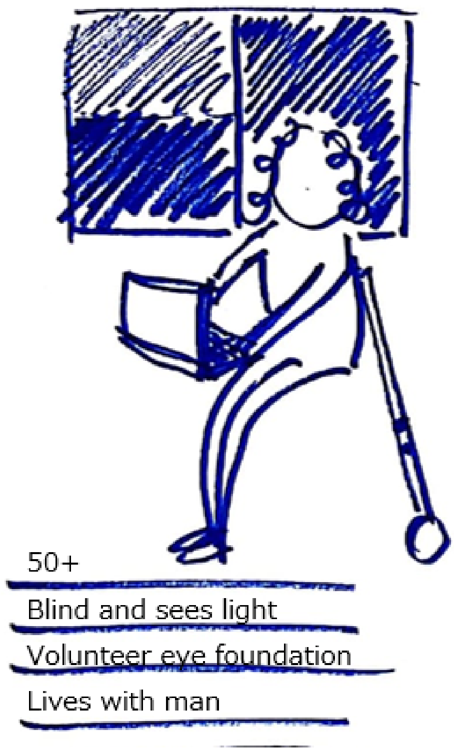


d

e



f

Figure 3.2 An illustration of the six profiles (a-f) where the degree of vision is presented in the window in the back, their work activities and their assistive devices are illustrated.

3.2.2 Needs where SMA systems for haptics could be of value

The identified obstacles are described in figure 3.3. The main apparent obstacles are in mobility and social interaction of which some are explained below.

Mobility- obstacle detection

An increasing and urgent problem in mobility is the lack of obstacle detection when having a rollator, mentioned by one of the participants:

'*People with a walker… can't see obstacles because they can't use a white cane, so it's difficult for them... and then they don't dare to go outside alone anymore. That is a real pity.'*

It was highlighted by an expert of Bartimeus as a relevant obstacle due to the increase of elderly VIPs and the lack of a suitable solution (Bartimeus Expert; Keunen et al., 2019). A way to encounter this need with SMA systems is to warn the users for nearing obstacles by providing tactile information in the walker's grip through a shape change. Different sizes of shape change could be used to explain the size and place of the object. Although this problem is very relevant and urgent the SMA characteristic of being less precise and slow compared to vibration motors does not resonate with the required exact and fast response of an obstacle detector.

Mobility- subtle awareness of surrounding

Other obstacles where haptics could be valuable are overcrowded places and the lack of environmental cues. As VIPs explain the importance of their hearing in these situations, one would prefer haptic feedback for additional information to understand their surrounding.

Social interaction

The lack of subtle environmental cues was perceived as an obstacle in social interaction such as recognizing faces and non verbal communication:

'I don't see how my daughter's lips move or understand her facial expression, which is important for a conversation.' -P4

'You've lost control huh, so you're kind of at the mercy of the People around you.' -P3

SMA systems could be valuable in this situation as the characteristic of conveying silent and natural tactile information is desired. Such a system could be combined with a face recognizer such as the envision glasses or Biped to translate facial expressions into tactile cues (see paragraph 2.1).

Cooking

A need were the unique SMA characteristic of using both the sensor and actuator capabilities could be shown is in knowing when your tea glass is filled. However, most participants had already an assistive device for this small obstacle or coped with it by touching the water decreasing the relevance of such a product.

3.3 DISCUSSION

In conclusion, the research targeting VIPs has provided valuable insights into their diverse preferences, use of tactile sense and daily obstacles. This knowledge highlights the importance of personalized approaches and inclusive environments to cater to VIPs needs.

As the interview results show, the most occurring needs were in mobility (navigation, obstacle detection and subtle environmental cues for orientation) and in social interaction (face recognition and non-verbal communication). Obstacle detection and navigating are very relevant needs, however, they require a fast and accurate response for safety issues which do not match the SMA characteristic of a relative slow cycle time and less precision compared to vibration motors. In addition, facial recognition of a specific person requires conveying detailed information that is difficult to provide with haptic feedback due to its limited information output. Thus, most opportunities for SMA systems lie in enriching the environment by creating a subtle awareness of one's environment in mobility or in social interaction. To investigate how SMA systems can fulfil these needs through haptic feedback, the material is first explored.

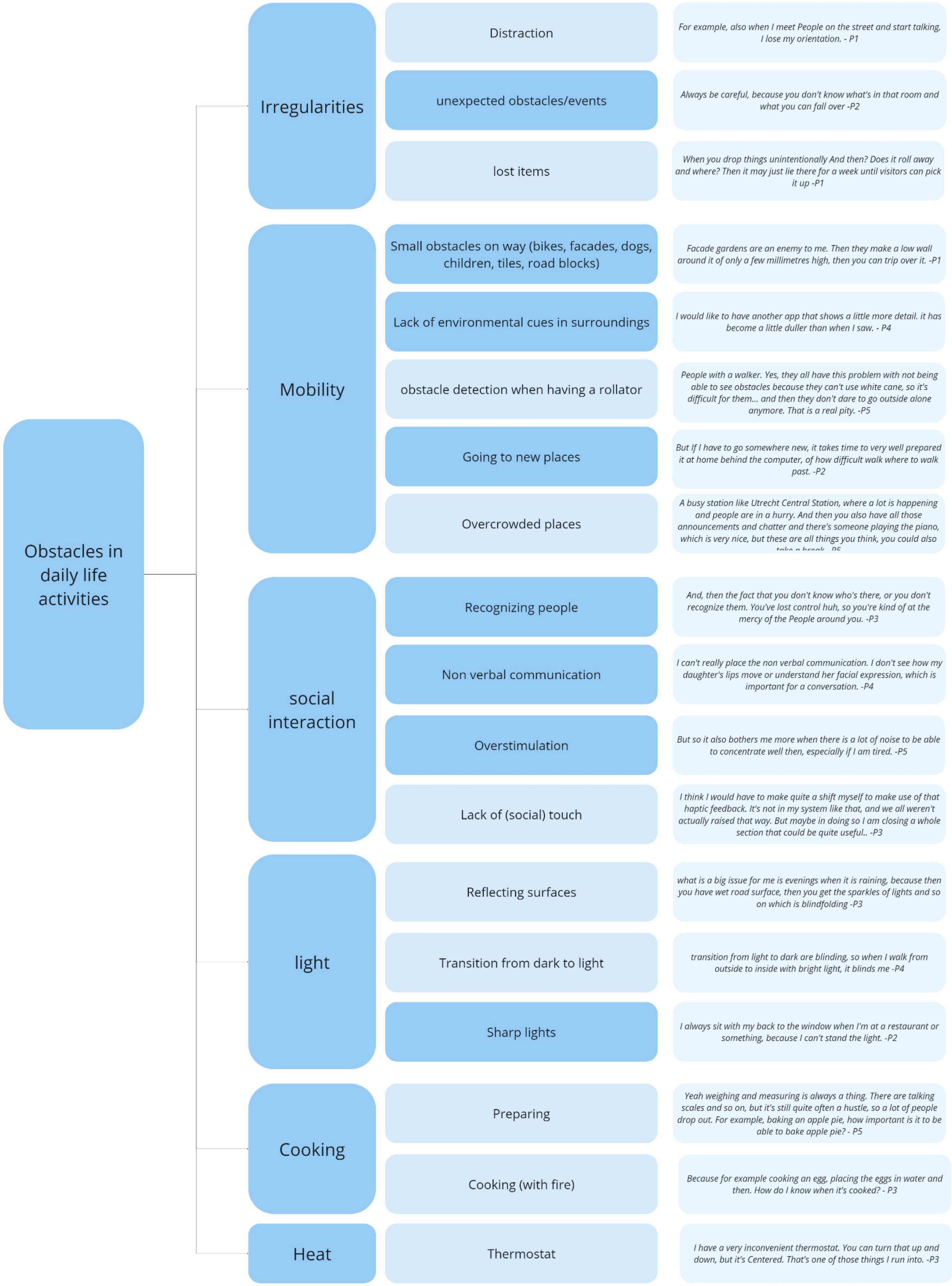


Figure 3.3 Identified obstacles of VIPs categorized in themes and subthemes. The dark blue subthemes were mentioned more than 4 times by the participants and the light blue subthemes were mentioned 2-4 times.

4 MATERIAL EXPLORATION

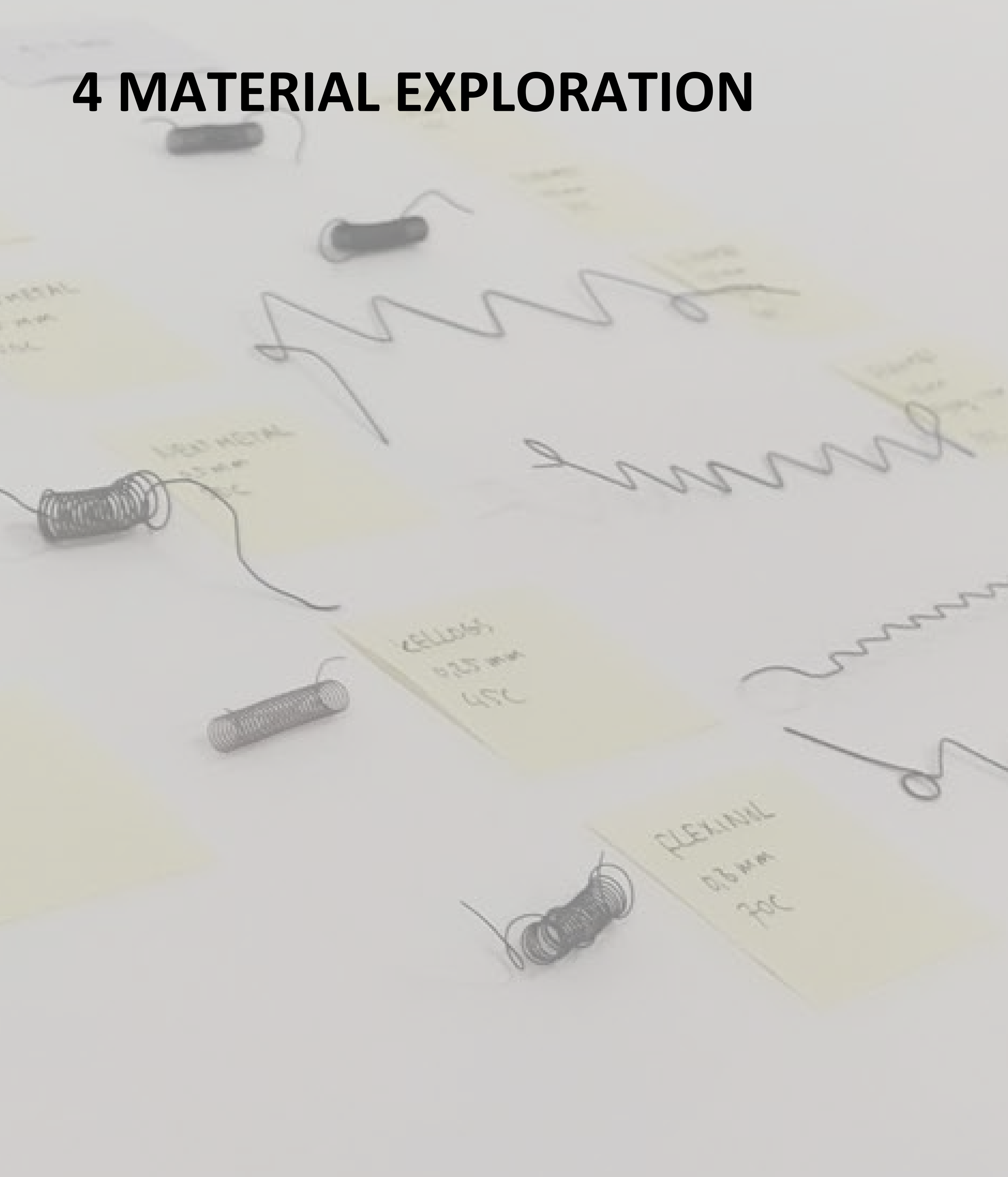


Figure 4.1. impression of first tinkering process

4.0 INTRODUCTION

This paragraph describes the first encounter with SMAs with the aim to understand their basic fundamentals, following the MDD method. As the literature concludes, the added value for research and design lies in training a SMA memory and using low-temperature wires to limit energy use and account for safety issues. Therefore, SMA wires from different manufacturers, the influence of geometries and shapes, and their training methods were explored.

For this, the first step of the MMD method is followed: *'tinkering with the material to get insights on what the material affords, its technical/mechanical properties, as well as how it can be shaped.'*

Figure 4.2 provides a material system taxonomy to get an overview of all the elements involved. As highlighted in dark yellow, in this paragraph the focus will be laid on tinkering with the making process, different manufacturers to understand the difference in transformation temperatures and with 2d and 3d shapes.

The insights gained will guide the order of new wires and serve as input for exploring material structures in chapter 7.

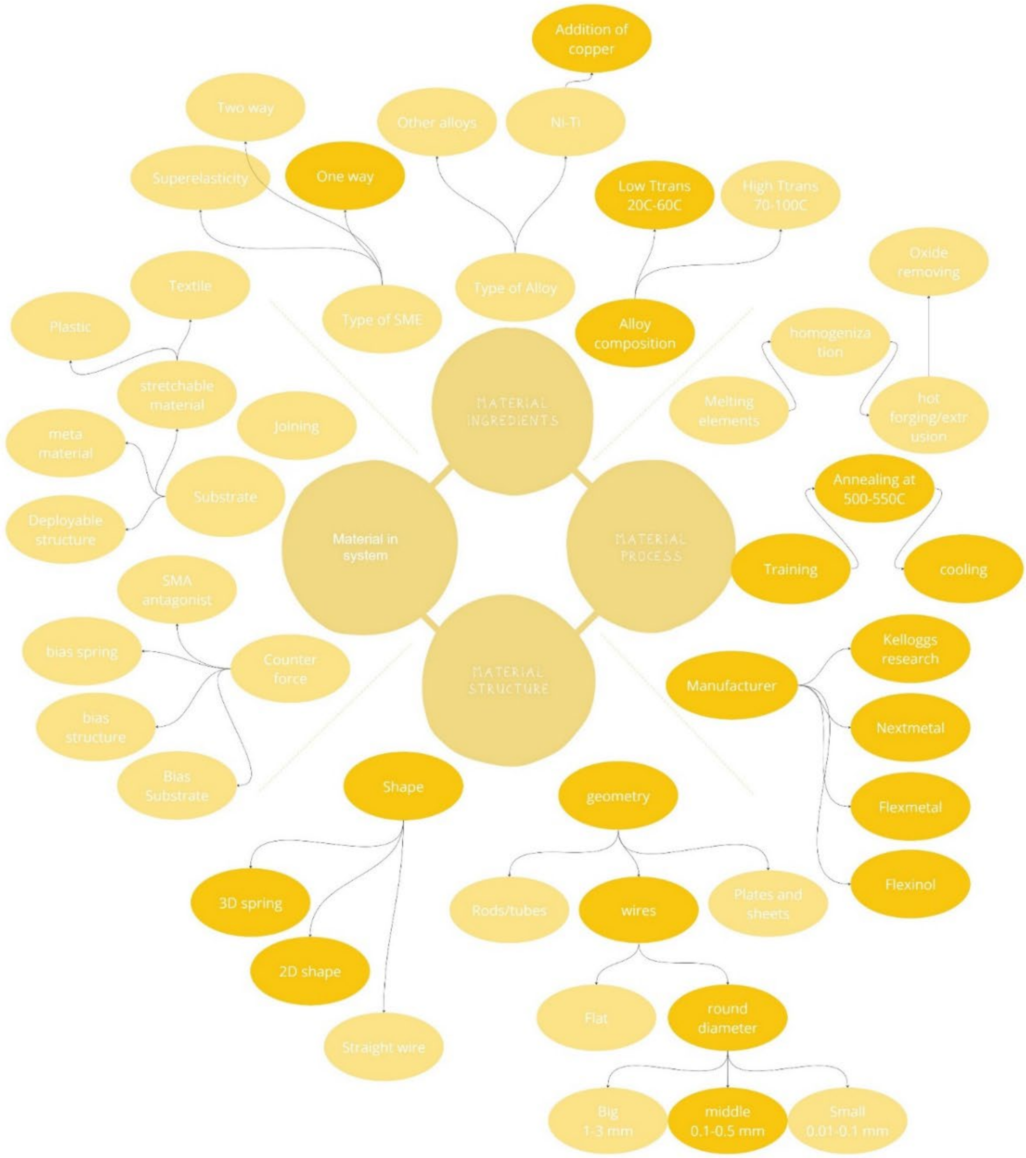


Figure 4.2 Material taxonomy of a material system based on SMAs with the focus areas for this tinkering part highlighted in dark yellow

4.1 TRAINING AND SHAPING SMA WIRES

To design a new shape memory effect, the SMA wires need to be trained, also called annealed, in the desired shape. To do this, SMA wires were fixed in a deformed shape and annealed in a ceramic oven at 500-550°C for 15-30 minutes. After heat treatment, the wires are quenched in a cold water bucket for cooling (Figure 4.3: c and d). Below the observational results when shaping 3D springs and unconventional shapes are described.

4.1.1 Shaping 3D springs

3D springs were made by winding up a wire on a bolt and fixating both ends with two nuts preventing the wire from going out of shape during the heat treatment (Figure 4.3.a). Initial explorations of shaping springs revealed that the way of releasing the spring wire from the bolt is crucial for maintaining its deformed shape when heated. It was found that using a rotating the wire over the bolt for releasing (figure 4.3.e) caused large deformations as is illustrated in Figure 4.3.g ii. When applying a screw movement (figure 4.3.f) the spring shape kept its trained shape after releasing the wire from the bolt. Additionally, wires with smaller diameters (<0.5mm) and those from the manufacturer Nextmetal demonstrated greater sensitivity to the release method employed.

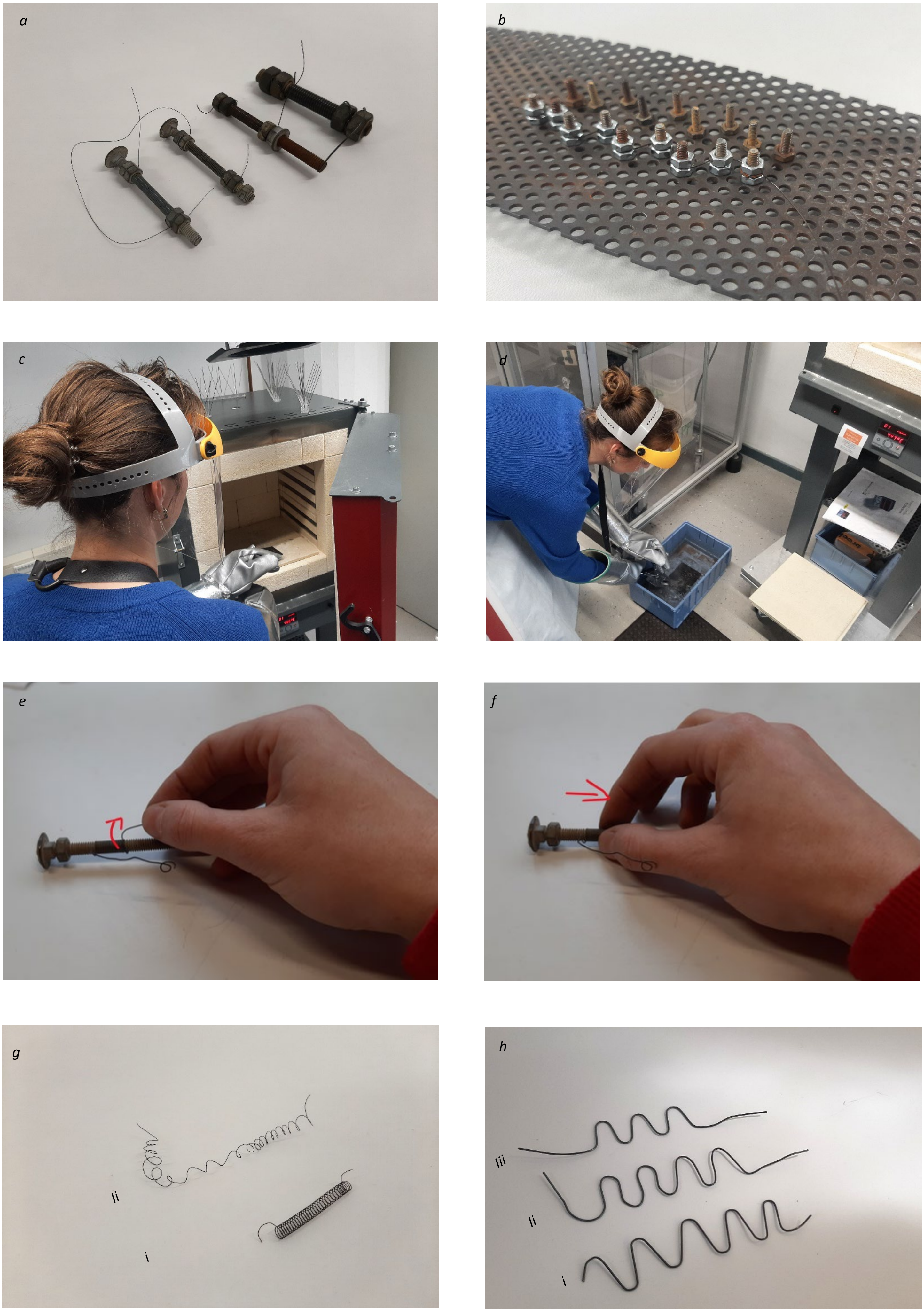
4.1.2 Shaping unconventional shapes

To create unconventional shapes a frame with nuts and bolts is used to fixate the desired shape (Figure 4.3.b). After creating many shapes it was found that next to releasing the shape securely, the shaping and fixating method greatly influence the smoothness of the shape. Initially, the wires were bent using a plier and fixated at the located points with the nuts and bolts to the frame. As this method is prone to human skills it resulted in inconsistent repetition of shapes which is not suitable for larger manufacturer implementations (Figure 4.3, h-i).

To limit human interference and create a better repetition of the desired shape, wires were guided using the bolts and fixated at every bolt. In this, frames with more small holes are desired due to the increased shape complexity that can be reached (more precise curves can be created). This method resulted in more aligned shape repetition as the bolts determined the distance between the curves. However, the smoothness of the radius curves was poor and inconsistent as the wire was clamped between a bolt and a nut (with frame) using human force. This resulted in an angular curve as is demonstrated in figure 4.3, h-ii).

To improve this, the wires were guided using the bolts, without fixating every point, and only fixated at the end of the shape (figure 4.3, h-iii). In this way, the influence of the tightness of every fixation point was limited resulting in more smooth and consistent curves while keeping a precise shape repetition. Using a frame with bolts and nuts provide a good starting point to explore different unconventional shapes. To provide precise control over the desired shape, a mould can be made with screw dread, which will be further explained in chapter 9.

Figure 4.3. Overview training and shaping SMA wires covering the fixation of a wire on a bolt (a), and on a frame (b), putting SMA wires in ceramic oven (c), water quenching after annealing (d), rotating method (e) and screwing method (f) when releasing from the bolt, the end results for the two releasing methods (g) and the end result →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4.2 SMA GEOMETRY AND SHAPE

3D springs and 2D zigzags were explored to understand their shape changing behaviour of which the main results are described below.

4.2.1 3D Springs

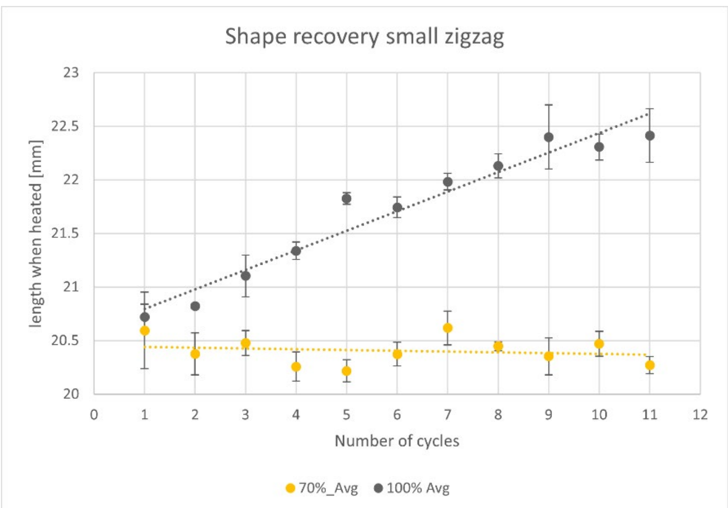
After tinkering with SMA springs with different spring and wire diameters and from different manufacturers (Nextmetal, Flexmet, and Flexinol), it was observed that springs made from small diameter wires (0.25 and 0.3mm) are fragile and prone to deformation. This suggests their value lies in creating micro springs (<1mm). Another observation was that both Nextmetal and Flexmet springs with 0.5mm wire diameter exhibited a spring-like effect after heating. As explained in Appendix C, when the spring was deformed by 50% or 100% of its initial length, it retained its shape upon heating but extended by 1 and 2 mm, respectively, when cooled.

4.2.2 2D zigzags

To get an idea what types of forces and displacements are involved for zigzags, three types of zigzag sizes (height-pitch: 5-10mm, 10-20cm, and 20-40cm) were evaluated using a dead end weight. As described in figure 4.5 (next page) the zigzags were first extended using a weight, subsequently the wire was heated and the zigzag length was measured using a ruler. A general observation was that all zigzags displayed less displacement in the first cycle (N0) which has probably to do with residual stresses hindering deformation. After 10 cycles, it was observed that smaller zigzag sizes (pitch-height) produced less displacement under the same applied force (see Appendix C for detailed evaluation): Applying 0.2N resulted in no displacement for the small zigzag, while the middle and large zigzags displaced 12% and 21%, respectively. At 0.5N, the small wire displaced only 1.7% which is still lower than middle and large zigzags at 0.1N (5.5% and 16.3%).

Extension rate

Two zigzags with a height-pitch ratio of 15-10mm (Big) and 10-10 mm (small) were evaluated on their shape recovery when deformed to a certain percentage of their initial length with a free-of-weight recovery (see figure 4.5 for test setup on the next page). The zigzags were extended using a ruler to 20, 50, 70 and 100% of their initial length. Subsequently, the zigzags were heated and their length in heated state were measured using a calliper (as figure 4.5 shows on the next page). The results for each zigzag when extended to a certain rate are shown in the graphs in Figure 4.4. As show, both zigzags did not fully recover after 10 cycles when deformed to 100% of their initial shapes as the lines in the graphs are increasing. A full recovery was achieved at 20% and 50% deformation for the big zigzag (a) and 70% for the small zigzag (b). This implies that the maximum extension percentage for zigzags with a 3mm curvature radius is around 50-70%.



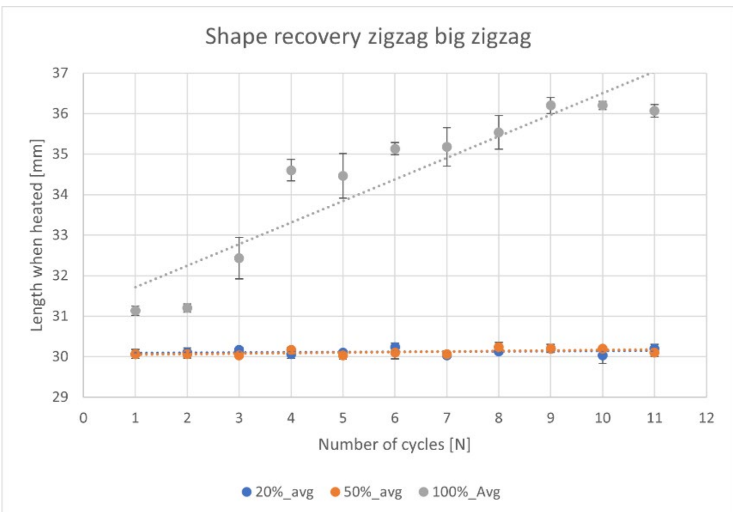


Figure 4.4 The measured zigzag length when the wire is heated for the big (height-pitch= 15-10mm) left and small zigzag (height-pitch= 10-10mm) right. The error bars are calculated with three measurements for every point with a ruler.

4.3 DETERMINING ALLOY COMPOSITION OF SMA WIRES

The solution space for this project revolves around SMA wires that react to low temperatures between 30-50C for safety and energy reasons, and the possibility to react on body temperature. To select suitable wires to proceed with, several available NiTi wire compositions from different manufacturers were explored on their As-Af range and reliable shape recovery.

4.3.1 Af-As range

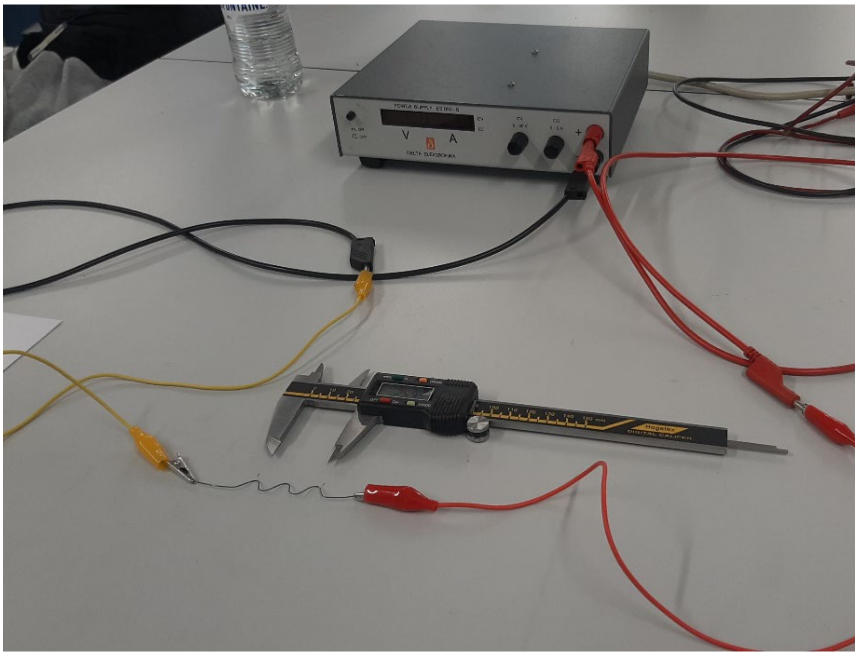
It was noticed that SMA wires displayed significant differences in austenite start (As) and finish temperatures (Af), with manufacturers typically reporting Af but not As (see Appendix C for tests on As-Af range). For instance, Flexinol and Flexmet wires had an As of 30-35°C and Af of 70 and 65°C, respectively. Only Kellogs and Nextmetal offer low-transition-temperature wires, with Nextmetal being more reliable. The available Kellogs' 0.25mm diameter, 35°C and 45C wire displayed superelastic behaviour at both room temperature (20°C) and in the fridge (4°C) after annealing. The wire demonstrated shape memory effect (SME) only at -20°C and regained its original form at 20°C. Nextmetal wires exhibited a consistent and relatively small As-Af range with a minimal difference between the 40C and 50C wires.

4.3.2 Shape recovery

The shape recovery was evaluated for the 40C and 50C Nextmetal wires with 0.5mm diameter in a 2D zigzag form using a dead weight of 0.2N (zigzag length = 10cm, height/pitch = 10/15mm), see figure 4.5 for test setup). Both zigzags showed a constant shape recovery over 20 cycles with 13% and 15% displacement. Notable is that in this setup a constant dead weight is used causing a sligth increase in deformation in cooled state. In the proposed material structure, a constrained force is preferred (such as a bias spring).

4.4 DISCUSSION

In this material exploration the fundementals of SMAs are explored. Important actions when shaping a complex 2D shape are in guiding and fixating the wire as well as in carefully releasing the wire. When tinkering with 2D shapes it seems that the bigger zigzags show more displacement when the same force is applied and the maximum extension rate with full shape recovery is 50-70% for zigzags. Finally the As-Af range could range between 3-30 C for different manuifacturers and Nextmetal wires show the most reliable shape recovery for low transformation wires. For the SMA system exploration



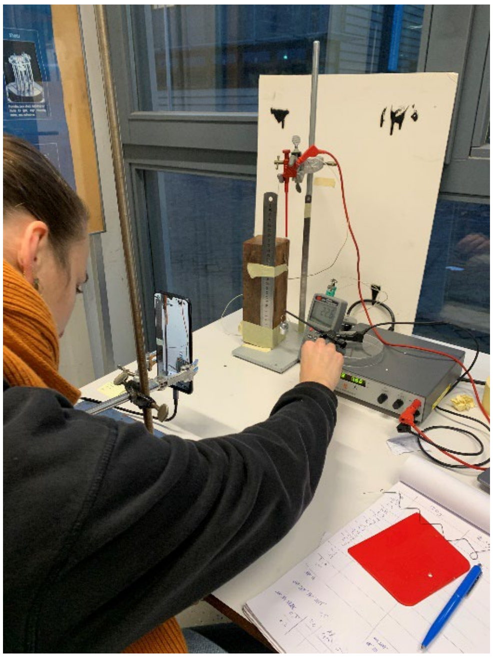


Figure 4.5 Test setup for evaluating the extension rate (left) and force/displacement balance (right)

5 DESIGN CRITERIA AND PARAMETERS

5.1 DESIGN REQUIREMENTS

The goal of this project is to explore the potential of a material system based on SMAs that generates haptic feedback for VIPs, showing the unique characteristics of SMAs to inspire designers. As the literature concludes, the focus will be laid on exploring the possibilities of 2D SMA shapes with low transformation wires and an integrated counterforce. This gives opportunities to design an integrated structure, account for safety issues and has the potential to react on natural environmental stimuli such as body temperature. Based on the target group, material and literature research outcomes, design criteria are formulated and design parameters are outlined from which a selection of parameters serve as the input for the next phase: form configuration.

5.2.1 Criteria

The material structure must···

1. Enable a noticeable haptic sensation for VIPs
2. Be activated in at least 10 seconds
3. Enable a shape change due to the SMA wire
4. Include a counterforce to deform the structure without manual actions
    a. The counterforce should be lower than the SMA heated force and higher than the SMA cooled force: $F\_sma\_h > F\_c$; $F\_sma\_c < F\_c$
5. Have a functional fatigue resistance for at least 10 cycles
    a. Not exceed 4% wire deformation in tension or 70% spring/zigzag deformation
6. Be an integrated structure
7. Be designed in a modular way to become both a wearable, touchable or graspable
8. Be used potentially with and without electricity
9. Be safe to use
    a. Not exceed 45C on places that are in contact with the user (Ungar & Stroud, 2010).
10. Be noiseless (make less noise than a vibration motor)
11. Show an organic movement

5.2.2 Wishes

The wishes are mostly based on showing the unique characteristics of SMAs in the system.

The material structure has to···

1. Convey clear tactile information
    - Rich way: Enable both passive and active sensation
    - Sensation as strong as possible
2. Convey a pleasant haptic sensation
3. Use as little energy as possible
    - Low transition temperature wires
    - Small diameter wires
    - Short wires
    - As few wires as possible
4. Have a short cycle time (response time and cooling time)
    - Small diameter
    - Short wire length
5. Enhance the SMA characteristic of having a natural movement
6. Explore new and inspiring ways how to use SMAs in a structure for haptics
    - To inspire designers on how to work with SMA systems
7. Enable a simple operating interaction
8. Be easy to (dis)assemble
    - As few parts as possible
    - Easy to connect elements

5.2 DESIGN PARAMETERS

Eight design parameters relevant for a material system based on SMAs for haptics are outlined in a morphological chart on the next page (Figure 5.2). A morfological chart aims to help generate principle solutions in an analytical and systematic way based on the deconstruction of the overall functions of a product into sub-functions (Roozenburg and Eekels, 1995). Based on the research outcomes, three combinations of sub-functions are proposed in the morphological chart as possible mechanisms to proceed with, highlighted in the dots and presented below in figure 5.1. Option 2 is considered as most promising as this material system shows the most innovative qualities for the field of haptics and SMAs and has the potential to generate tactile information in a rich way, as described in the Harris profile ranked on the following requirements:

1. **Convey clear and rich tactile information**
   Option 1 and 2 could generate both passive and active feedback through pressure movement and texture difference whereas option C is limited to a squeezing sensation.
2. **Explore new and inspiring ways how to use SMAs in a system for haptics**
   Combining a trained SMA with textile and origami is new to the field of SMAs for haptics as well as combining this with an integrated SE as a counterforce.
3. **Be designed in a modular way to become both a wearable, touchable or graspable**
   Option 3 can only be used as a wearable whereas option A and B can be used in various haptic device configurations.
4. **Be easy to (dis)assemble**
   The integration of SMA wires in textile is easy as they can be sewn. The integration of SMA wires in flexible polymers is difficult as some sort of adhesive is required which limits the disassembly.

The next chapter will explore how to create a material system based on these parameters

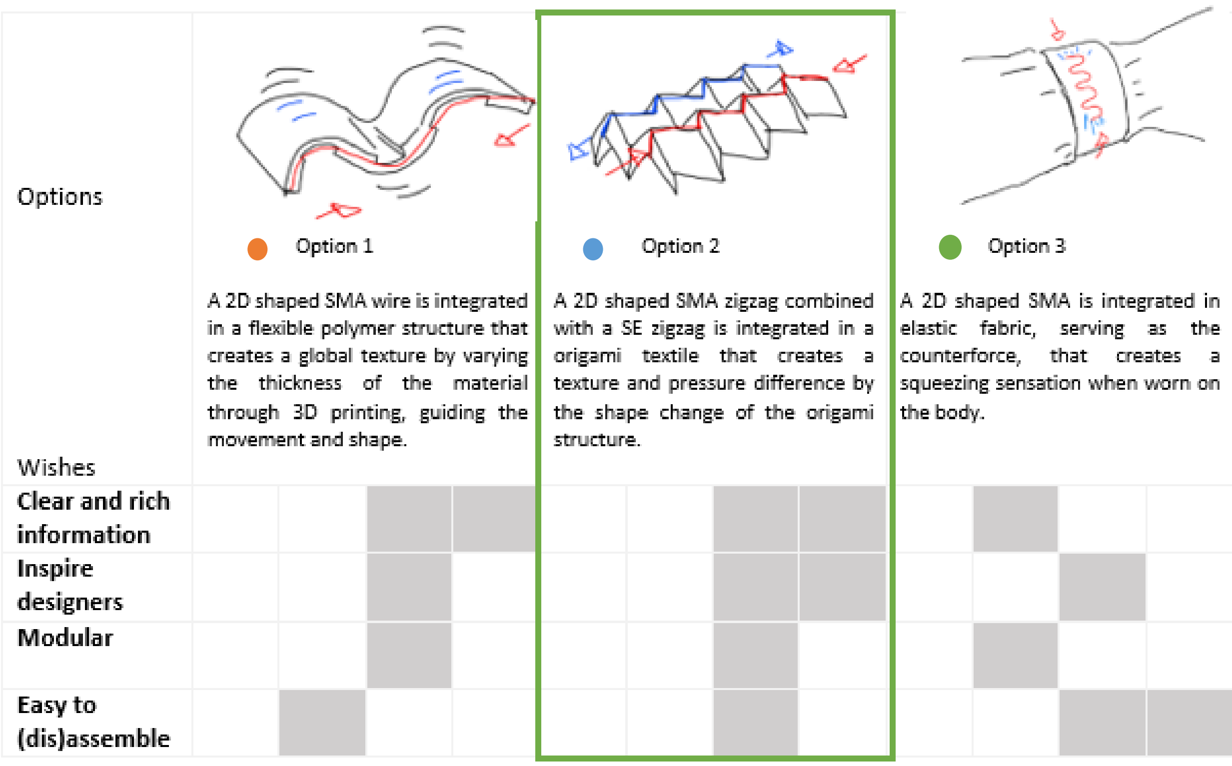
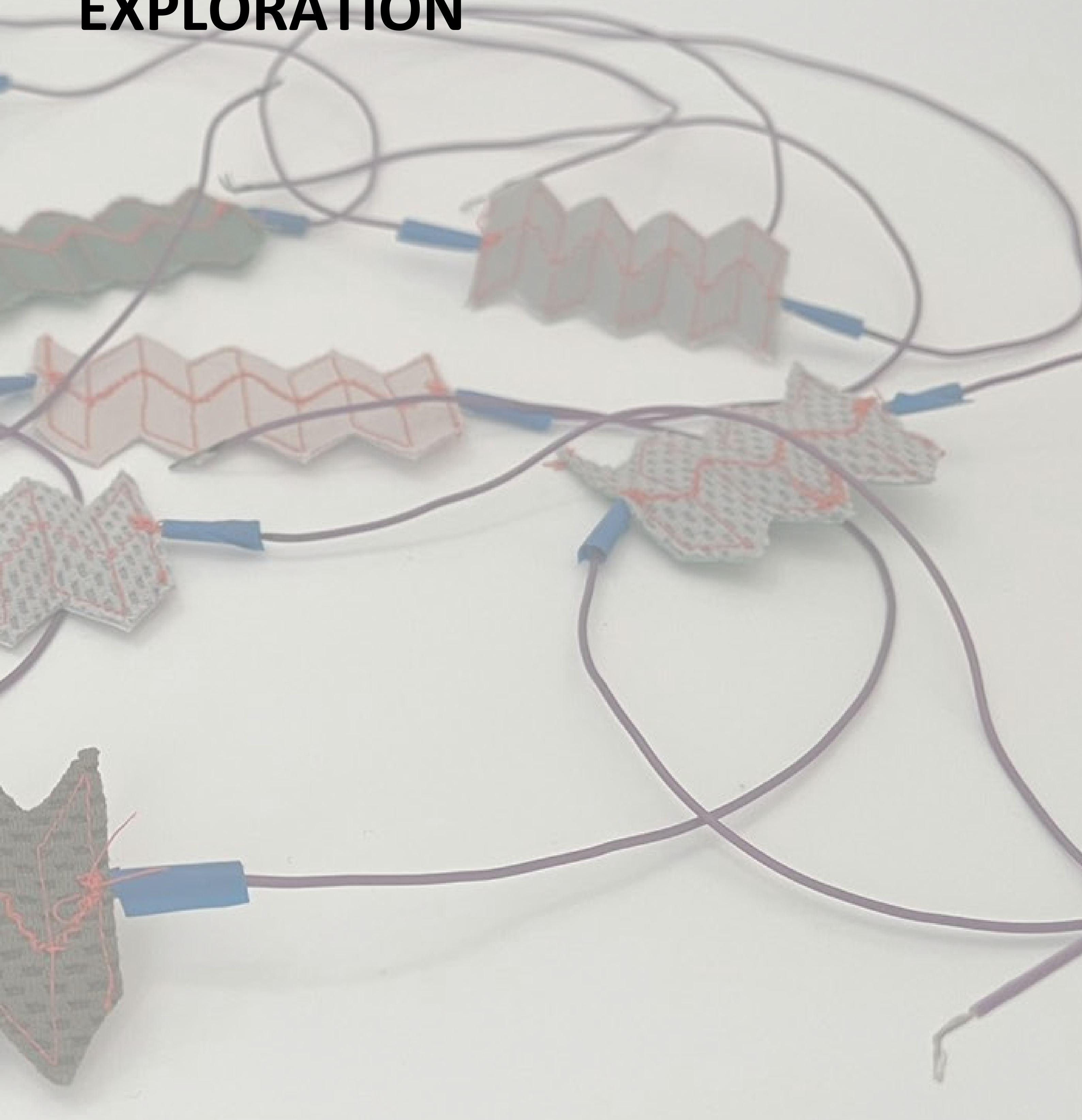


Figure 5.1 Harris profile of most promising mechanisms based on the morphological chart

FUNCTION	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6
SMA ACTIVATION	Ambient medium	Body contact	External source	Electric current		
HAPTIC SYSTEM DEVICE	Graspable (G)	Wearable (W)	Touchable (T)			
TYPE OF FEEDBACK ACTION	active	passive				
GENERATED HAPTIC SENSATION	Stroke (T, W, G)	Press(T, W, G)	Textured (T, G)	Heat (T, W, G)	Squeeze (W, T)	Pinch (W,T)
SMA SHAPE	wire guided in tube	Wire guided with anchor points	2D shape	3D spring	Flat spring	wire amplified with lever system
COUNTERFORCE	Bias spring	Substrate	Antagonist SMA	Super elastic wire	Skin	Dead weight
SUBSTRATE MATERIAL	Bioplastic (PLA)	flexible polymer (TPU)	Flexible textile	Rigid textile		
SHAPE CHANGING MECHANISM	variable stiffness	rollable	Foldable	stretchable	Auxetics	SMA

Figure 5.1 Morphological chart of all functions derived from the literature. The green, blue and red dots present the combination of the chosen parameter from where option 1, 2 and 3 are derived.

6 MATERIAL SYSTEM EXPLORATION



6.0 INTRODUCTION

This chapter describes the tinkering process of the material system based on SMAs using the MDD approach.

MDD encourages tangible interaction with the material in hand, from the first encounter through to exploring and understanding the material in detail with its unique qualities and limitations. -(Karana et al., 2015)

In Chapter 4 about material exploration, the fundamentals of SMA wires were explored: how to train, shape, and determine the transformation temperature of SMA wires. Since the aim it to make a composition of a SMA wire embedded in a structure, it is important to tinker as well with all the parameters involved in the overall composite structure to understand the inherent qualities of the total material system as the MDD method propose. Using this method small variations will be explored and evaluated to understand what the material affords and how it can be shaped.

The aim is to define a suitable material structure based on the selected design parameters that works without manual actions and enable haptic feedback. To do this, the different parameters selected in chapter 5 are researched (material benchmarking) and tinkered with to generate insights on how to incorporate these elements into a structure. First, origami structures and the integration of SMA wires in origami structures are addressed (H6.1), followed by exploring the possibilities of finding a SE-SMA balance (H6.2) and explore the influence of different paper-textiles combinations, respectively illustrated in figure 6.2. a, b and c). Finally, a compilation based on all the explorations is proposed as a material system and further tinkering with the material system is described.

6.1 ORIGAMI PATTERN

6.1.3 Introduction to Origami

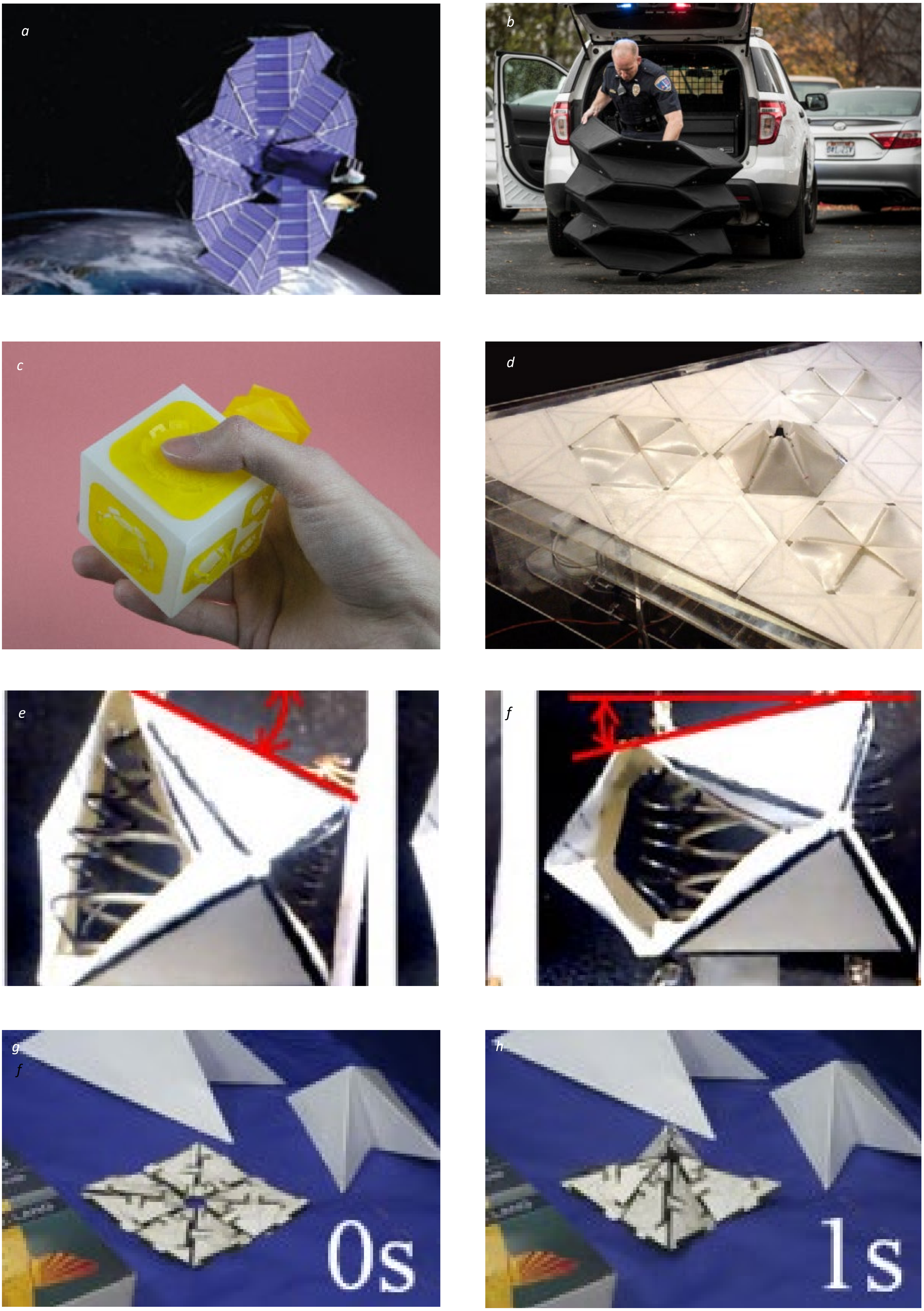
Origami and Kirigami is an ancient Japanese art of paper folding that has a general underlying principle of transforming a two-dimensional surface into a three-dimensional one by simple folds in a flat sheet. It is commonly used to enable easy and reproducible shape change for compact storage deployment capabilities and the reduction of manufacturing complexity (Qatar et al., 2018; Dureisseix, 2012). Common examples are the deployable solar array for spacecraft applications (Baek, Lee & Cho, 2016) and the bulletproof origami shield (Briggs, 2017), figures 6.2a and b.

Due to the gradual surface change from 2D to 3D, it can be used to generate tactile information as the paper by Chang et al. (2020) describes. One of their proposed designs is a multisensory toy that aims to help the development of the sense of touch for young children (figure 6.2c). By providing diverse types of origami structures on the six faces of the cube different force properties and form factors are created that could be touched.

Another example is the integration of a force feedback mechanism based on an origami structure in a driver seat, the Poking Seat (Ghanizadehgrayli, 2020) (figure 6.2d). The origami structure is activated by pneumatic actuation.

In essence, the created shape change, speed and maximum displacement of origami structures are dependent on an external structure that actuates the system (Qatar et al., 2018). In this case, SMAs actuate the system and the origami pattern guides the movement from a 2D to a 3D structure. Several examples show this integration of SMA wires in origami structures for different application areas. Salerno et al. (2014) and Lee et al. (2013) integrated SMA springs in an origami structure to enable respectively minimally invasive surgery and a deformable wheeled robot. They reported a proof of concept by showing the actuation range of a paper prototypes with SMA springs attached to it (figure 6.2.e). Another proof of concept has been made by Koh et al. (2014) embedding torsion shape-memory alloy wires in origami structures (figure 6.2f). The wires are aligned with the fold lines which enables a direct twist of the faces. As described by Koh et al. (2014), this method has the advantage of using an easily available wire SMA and the advantage of a flat form factor similar to that of sheet SMA. They trained the SMA wire in the illustrated shape and integrated an antagonist torsion wire to enable the folding and unfolding of the structure.

Figure 6.2 deployable solar array (a) (Baek et al., 2016), bulletproof origami shield (b) (Briggs, 2017), multisensory toy (c) (Chang et al.,2020), Poking Seat (d) (Ghanizadehgrayli, 2020), minimally invasive surgery (e) (Salerno,2014), torsion shape-memory alloy wires in origami structures (f) (Koh, 2014) →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6.1.3 Origami folds

The creation of the 3D origami shape structure is obtained by fold lines (also called crease) and faces, the regions bounded by the folds (Hernandez, Hartl & Lagoudas, 2019). In most engineering structures that do not include paper but larger thickness materials, the crease is obtained by bending localized regions. In this, the type of material determines the bending radius.

The fold lines are either mountain or valley fold lines (respectively dotted and straight lines in figure 6.3). Gardiner (2018) has illustrated the five most known origami natural folding patterns in Figure 6.3. It shows the geometric relationship between forces and the resulting patterns. As illustrated, Yoshimura and Kresling patterns have a cylindrical compressible shape which is interesting for creating 3D structures integrating an SMA spring in the middle to actuate the shape change. The Miura and Resch patterns have a planar compressible shape which is interesting for creating texture differences on surfaces allowing the SMA wire to be fully integrated. These different patterns will be explored in the next paragraph.

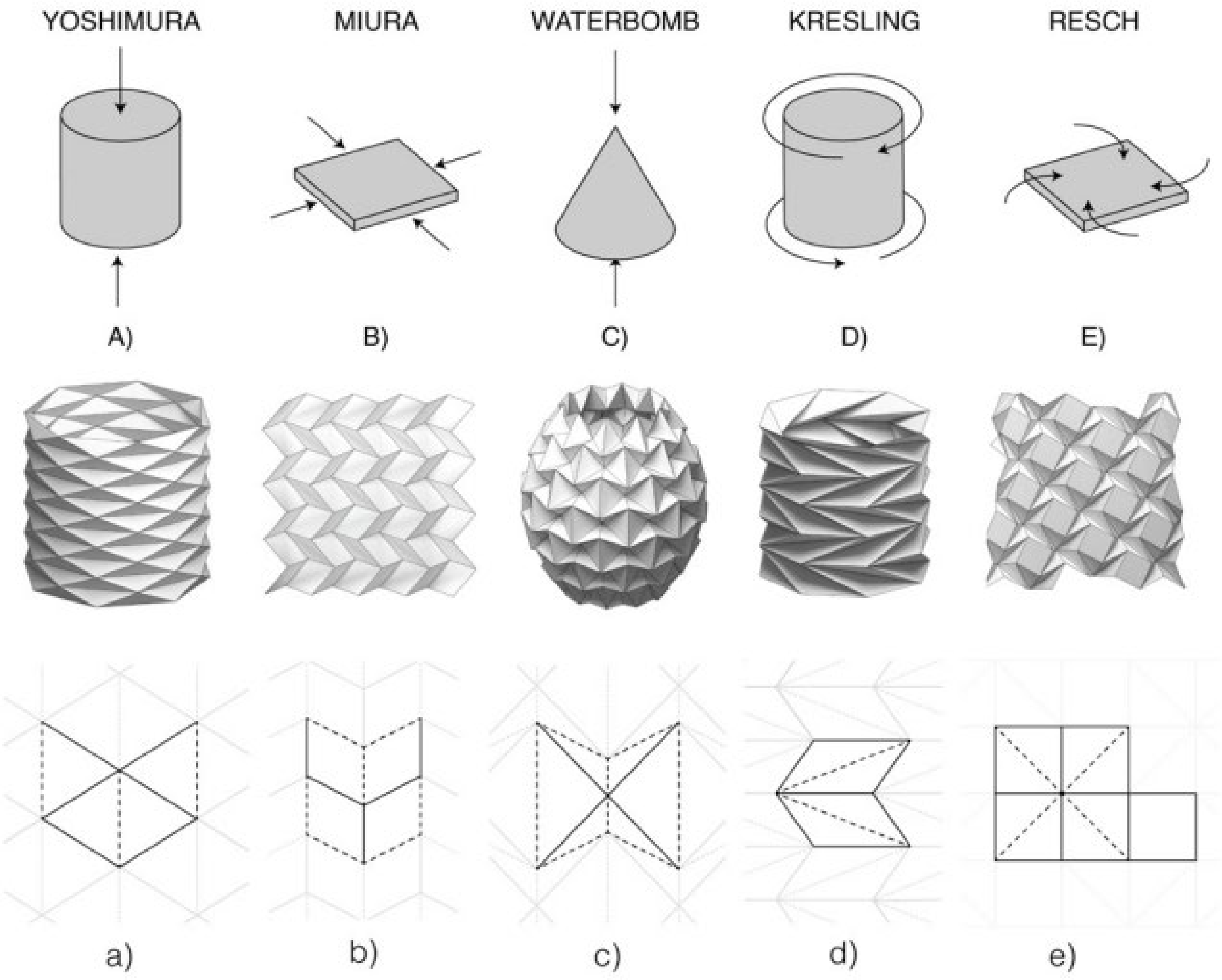


Figure 6.3, from Gardiner (2018). Natural Folding Patterns: Illustration of Force + Matter: the geometric relationship between forces and fold patterns. From left: a) Yoshimura cylindrical compression b) Miura transverse planar compression c) Waterbomb conical compression d) Kresling rotational-twist-compression of cylinder e) Resch torsional compression of the plane

6.2.2 Integrating of SMAs

The five primary origami patterns were explored on their integration of SMA wires. The most promising combinations are described below. The wires are machine-sewed into the paper to ensure precise control over the wires as using duct tape resulted in the movement of the wires in previous samples. As illustrated in Figure 6.4, three combinations of origami patterns with SMA wires were made. The left one is a Kresling fold with an SMA spring in the middle which is compressed when heated due to the contraction of the SMA spring. The downsides of this structure is that the shape change was limited and integrating the SMA spring was difficult as it was hard to connect the spring to the system. The second one is a mushi fold with three straightened SMA wires integrated enabling a movement from 3D to 2D. Testing showed a noticeable shape change although the wires seem to show some memory loss. Moreover, a movement from 2D to 3D is preferred compared to 3D to 2D as the folded state can translate more meaningful haptic information than a flat sheet. The third one is also a mushi pattern but then with three trained zigzag wires which are compressed when heated due to the contraction of the SMA zigzag. Testing showed a noticeable and consistent shape change. This pattern was also tested with 0.3mm wire diameter wires which resulted in limited shape change. Based on these results, the mushi fold with 0.5mm diameter SMA wires seems to be the most promising to proceed with this project.

Figure 6.4: Left: Kresling fold with SMA spring in the middle; Middle: Mushi fold with three wires trained to be straight; Right: Mushi fold with three wires to be trained in a zigzag.

6.3 COUNTER FORCE BALANCE

6.3.1 Introduction to SEs

The selected actuation mechanism combines two properties of SMAs, the one-way shape memory effect and the super elasticity which acts as the counterforce. As mentioned in paragraph 2.3, super-elastic wires are shape memory alloys with a low transformation temperature of around -20C. In this way, the wire is always in an austenite state and creates a spring-like effect based on a force at room temperature. Interesting about using SEs rather than a bias spring as a counterforce is that one can design the shape of the SE which allows for complex structures as the book of Andani et al. (2015) explains. To enable back-and-forth movement it is important that the memorized shape set force of the SE is bigger than the SMA martensite force in cooled state and smaller than the SMA austenite in heated state:

$F_{SMA\_austenite} > F_{SE\_austenite}$ & $F_{SMA\_martensite} < F_{SE\_austenite}$.

The actuation stroke and shape depends on the geometry, material properties and shape set forms (Andani et al., 2015). Figure 6.5 left and right describes two examples of SE-SM configurations.

In the book by Andani et al. (2015) a system is proposed where the SMA wire is a flat wire that is wrapped around a SE ring (figure 6.5 left). The SMA wire tends to close the system when heated and the SE ring tends to open the system again when cooled. A similar configuration but then with a SE flat wire wrapping around an SMA ring has been used to design a cardiac tissue clamp which has the advantage of being lighter, and smaller and still generates a large actuation stroke compared to conventional devices (Andani et al., 2015).

Another SM-SE configuration is proposed by Caltagirone et al. (2021) combining an SMA spring with an SE leaf spring (figure 6.5 right). The SMA NiTi barrel spring was fabricated with 1mm wire diameter, 12 coils and an outer spring diameter of 12.7mm. The SE NiTiCo leaf spring had an Af of -15 and 2.5mm thickness and the open shape was trained with heat treatment to achieve the geometry. In this way, the system could successfully expand and collapses effectively and quickly.

These examples show a success of training a SE in a desired shape and combine it with an SMA wire as a counterforce.

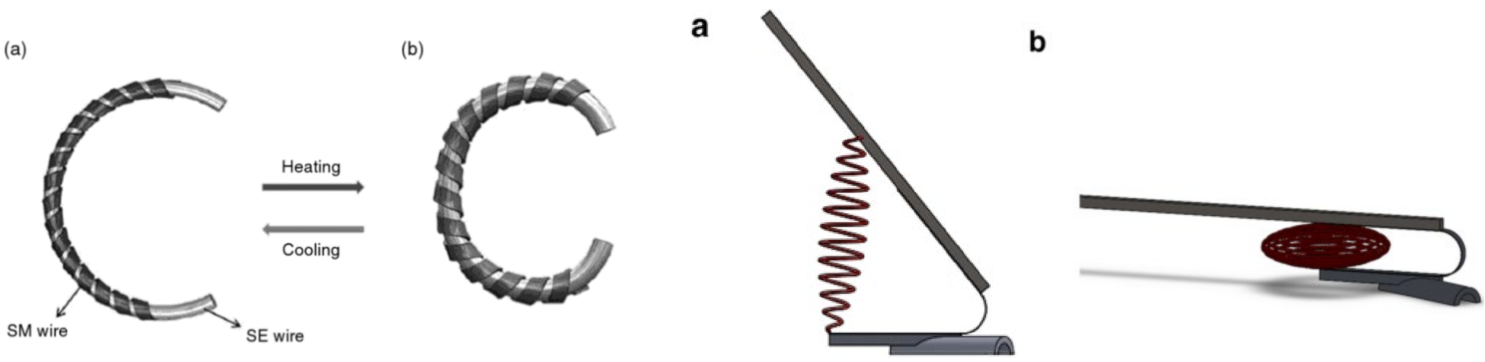


Figure 6.5 SM-SE configurations. Left: SMA wire wrapped aroung SE wire (Andani et al., 2015). Right: SMA barrel spring connected to SE leaf spring (Caltagirone et al., 2021

6.2.2 Integration of SE and SMA

To create a composition that could change its shape back and forth, several compositions of SE wires and the SMA-origami structure were explored. In the first exploration, the SMA wire diameter of 0.5mm embedded in a Mushi fold was fixed and the SE wire shape and available diameters (0.6mm and 0.75mm) was varied, of which an overview is shown in Figure 6.6. The aim was to create a fold-unfold movement and evaluate if it was possible to train a SE wire (see Appendix D for the evaluation of SE wires).

Based on the exploration, the most promising configurations are demonstrated in Figure 6.6 1b and potentially 3c, when the right SE wire is used (marked in green). Configuration 1b demonstrates the best fold-unfold movement, indicating a successful SE-SM proof of concept. The configurations of 4 (of Figure 6.6) are potentially most promising as in this way, the SE wire is fully integrated into the origami structure which is desired. However, the available SE wires in this phase couldn't be trained in a zigzag shape (as the 0.6mm wire behaved like an SMA wire after training) or achieve the desired motion (the 0.75mm SE wire was too stiff for bending(Figure 6.6 2 and 3)). The reason for choosing configuration 4b over 4a is due to the direct connections of the SE and SMA in 4b which ensures a consistent movement.

So overall, this shows that a SE as counterforce can enable a two-way actuation (demonstrated by 1b). The next step involves integrating smaller SE diameter wires trained in a zigzag shape and examining the SE-SMA balance (based on the potential of 4).

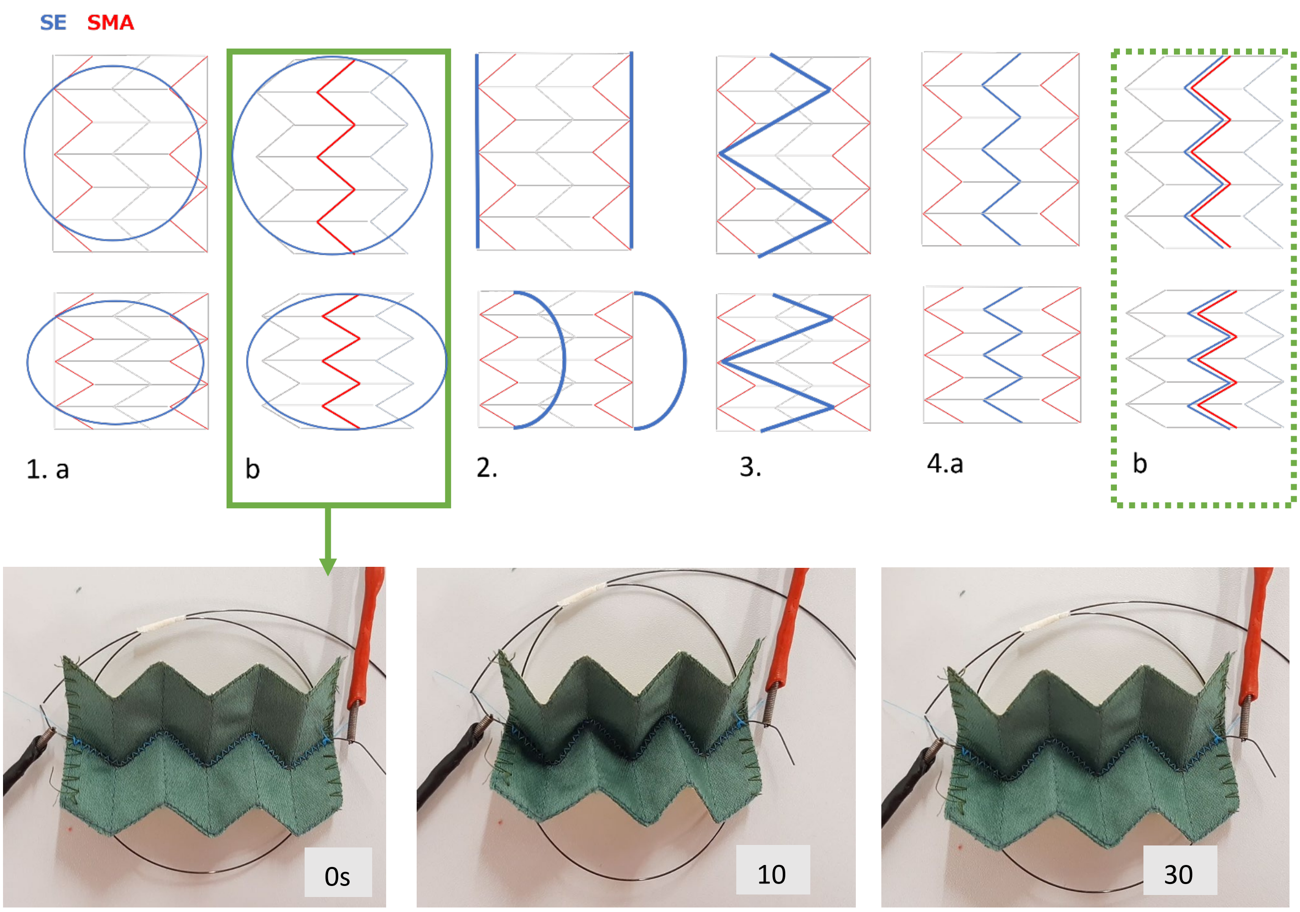


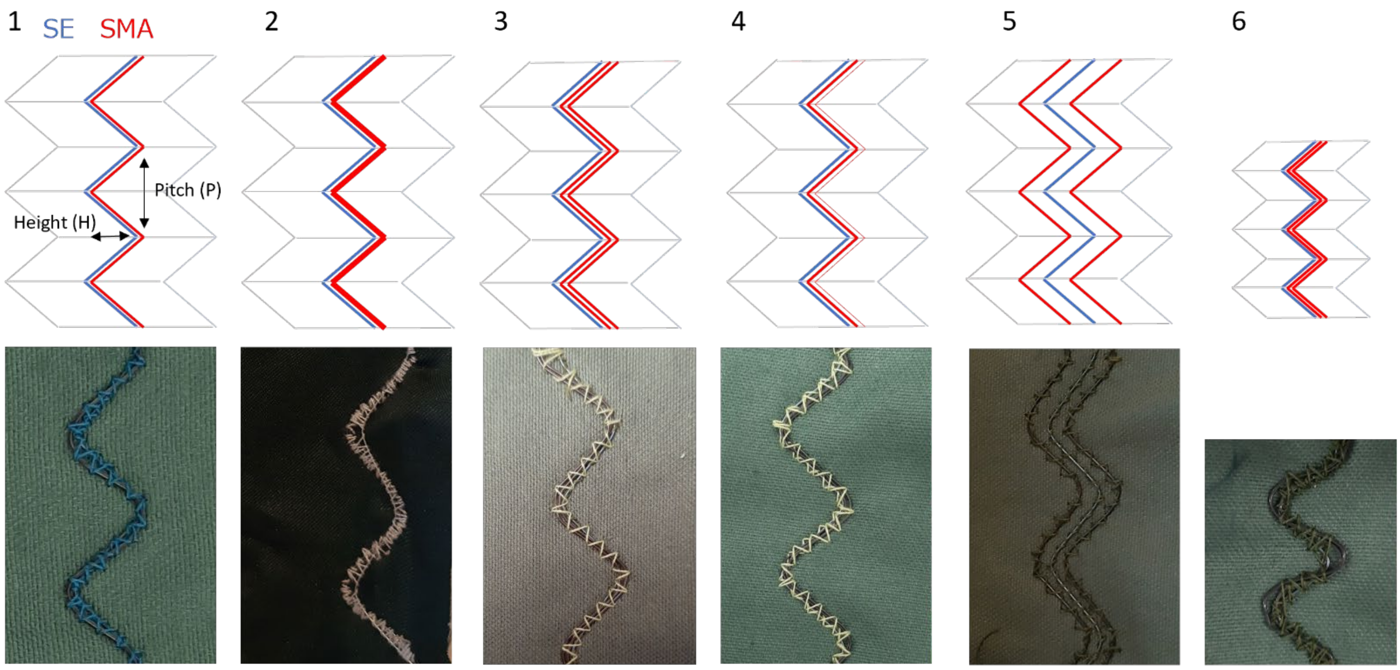
Figure 6.6. Overview of explored SE shapes with 0.6mm (thin blue line) and 0.75 mm (thick blue line) wire diameters integrated into the SMA-origami structure. The dotted line represents the most promosing configuration in potential and the straight line represents the proof of concept with pictures attached. Below the tested proof of concept

6.2.3 Search for SE-SMA balance

To find out the right SE-SMA balance for the proposed SE and SMA-origami configuration (4a in figure 6.6) different SMA geometries and compositions were explored of which an overview is shown in 10 configurations (figure 6.7), see Appendix D for more details and configurations. The aim was to find a balance where the SMA part was able to contract to its set shape when heated (SMA recovery) and the SE part was able to expand to its set shape when cooled (SE recovery). The SE-SMA configurations varied in the following parameters using the available frame mould in the lab with 3mm bolts and nuts:

- SE wire diameters: 0.5mm, 0.35mm, 0.3mm and 0.25mm
- SMA wire diameters: 0.3mm, 0.5mm
- Amount of wires: one or two
- Zigzag size: small (height-pitch of 10-10mm and wire length = 33mm) or 'big' (height-pitch of 15-10mm and length = 24mm)
- Heigth-pitch ratio: and Height-pitch ratio using the available mould in the materials lab.

All configurations consisted of 3 peaks and were sewn into a polyester/cotton satin weave fabric using the sewing machine and tested on their SMA and SE shape recovery. The described displacement is measured using video recording: The initial displacement means the first measured displacement without taking into account the SE recovery ((L_Cold_init-L_heated)/L_Cold_init). the ultimate displacement means the displacement base on the deformation generated by the SE in cold state (L_cold_SE-L_heated/L_cold_SE). Poor recovery is noted as the displacement was below 5%.



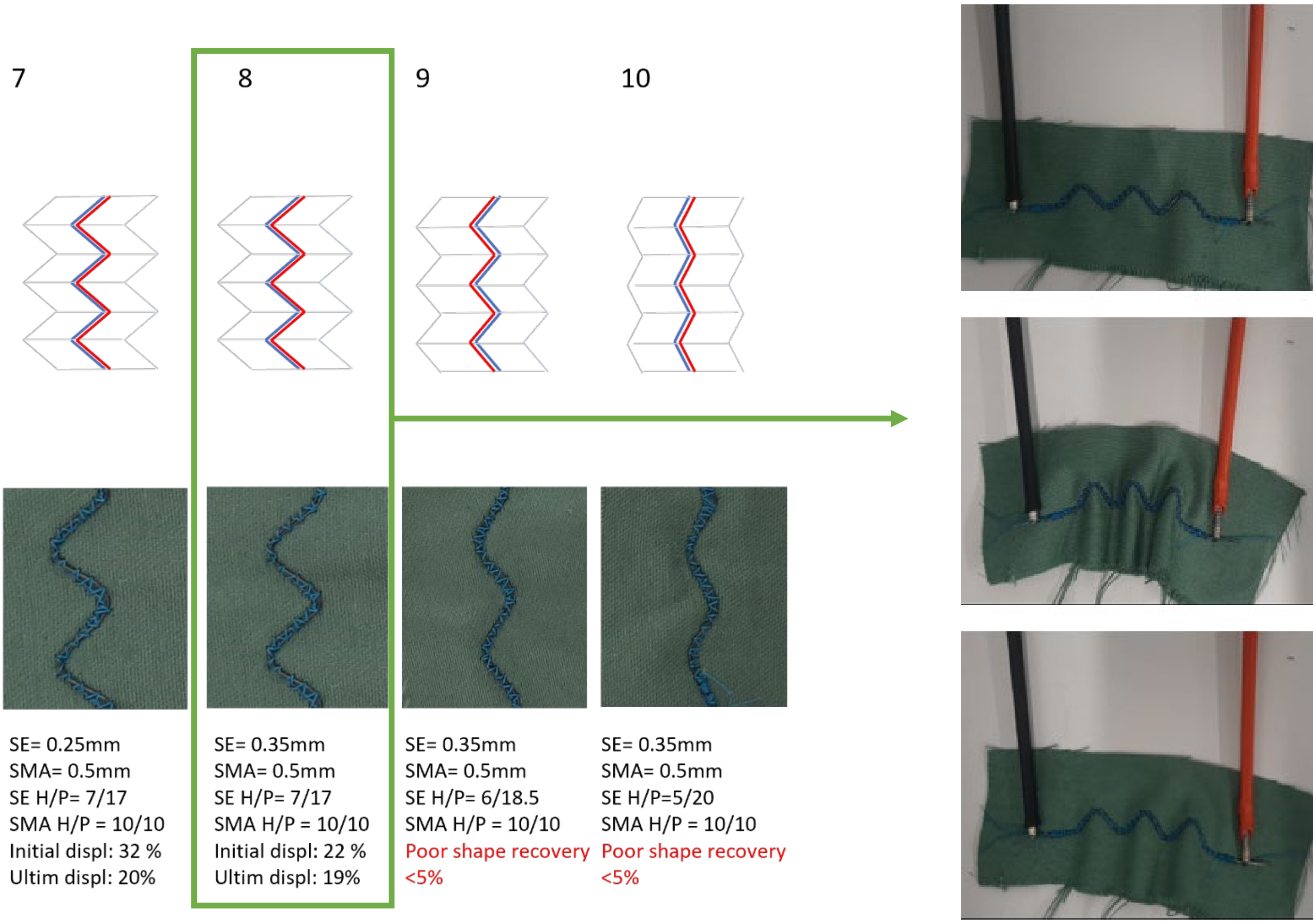
1	2	3	4	5	6
SE d= 0.5 mm SMA d= 0.5 mm SE H/P= 8/20 mm SMA H/P= 12/13 Poor shape recovery <1%	SE d= 0.5mm SMA d = 1 mm SE H/P= 8/20 mm SMA H/P= 12/13 *SMA wire diameter too thick for curves	SE d= 0.5 mm SMA d= 2x 0.5mm SE H/P= 8/20 mm SMA H/P= 12/13 Initial displ: 10% Ultim displ: 5%	SE= 0.5mm SMA= 0.5mm + 0.3 mm SE H/P= 8/20 mm SMA H/P= 12/13 Poor shape recovery <5%	SE= 0.5mm SMA= 2x 0.5mm SE H/P= 8/20 mm SMA H/P= 12/13 Initial/Ultim displ: 11% *Displ varies SMA and SE	SE= 0.5mm SMA= 2x 0.5mm SE H/P= 7/17 SMA H/P= 10/10 Initial displ: 16% Ultim displ: 10%

Figure 6.7 Overview of 10 configuration to find out a suitable SMA-SE balance.

Initial tinkering of the first 6 configurations (figure 6.7 1-6) revealed that the total of SMA diameters in the system needs to be bigger compared to the SE diameter (1 vs 3) and the SMA and SE need to be connected to each other (3 vs 5). In addition, a smaller zigzag generates a larger initial displacement when 0.5 mm SMA and SE wires are used (3 vs 6), probably due to the bigger arm length of the bigger zigzag size (1-5).

When smaller zigzags with smaller SE wire diameters were evaluated, it seemed that the SMA diameter needs to be around 1/3 bigger compared to the SE wire diameter to overcome the austenite SE force and for the SE wire to overcome the martensite SMA force. When the SE diameter was too small (0.25 mm in configuration 7) the system contracted perfectly to 30% but did not recover its deformed shape when cooled, causing a curved fabric. Furthermore, when exploring different Heigth/Pitch (H/P) ratios between the SMA and SE, the SMA 10/10 and SE 7/17 performed best referring to 70% of extension of its initial length.

Based on all the configurations, configuration 8 is most promising due to an acceptable initial displacement of 22% and ultimate displacement of 19% using a 0.5mm SMA and a 0.35mm SE. In the next paragraph the integration of different papers and fabrics are described.



6.3 TEXTILES

6.3.1 Introduction to origami textile

Knitting and weaving represent the primary methods of textile production. Knitting comprises looping yarns together to form a flexible, stretchable fabric (Xu et al., 2022). Weaving entails interlacing two distinct sets of yarns—warp and weft—at orthogonal angles, resulting in a stable, rigid fabric (Knittel et al., 2015). With both methods, origami structures can be made by manipulating the weave of knit stitch architecture (Amanatides et al., 2022). Archi Folds of Studio Samira Boon and the University of Tokyo, is a good example of creating digitally woven origami structures that can be folded and unfolded into different shapes (see figure 6.8) (Digitally woven..., 2018). Due to the scope of this project, the origami patterns are not digitally woven or knitted but are made of paper and combined with pre-woven/knitted textiles.

Integrating SMA wires into origami textiles can be done with machine sewing. According to Nabil et al., 2019 the type of fabric, thread and stitch are of importance to determine the desired actuation. More stiffness, rigidity and weight in a fabric can cause less malleability and loose threads and stitches minimizes the shape recovery. Overall flammable fabric and threads should be avoided.

An example were SMA wires are integrated in origami textiles is the Enfold from Lin, Zhou and Koo (2015) which is a self-folding jacket that uses lightweight synthetic fabric to create woven origami patterns. By inserting Nitinol wires (0.75mm) in thin tunnels that were created by the stitch lines following the fold edges they manage to fold and unfold the jacket in a controlled way. Another example is the dynamic light filter from Cabral et al., (2015) that incorporates 30C shape memory alloy wires (0.3mm and 0.5mm) with different trained shapes. In this way, they create a square twist and waterbomb origami fold for adjustable light transmittance.

Figure 6.8 Origami-textile installation -Samira Boon (a), Self folding jacket from Lin, Zhou and Koo (2015) (b) Dynamic light filter from Cabral et al., (2015) (c)

6.3.1 Integration of paper and textile

Different paper and textiles were explored to sew the SMA and SE zigzag wires in of which an overview is given in Figure 6.9. When comparing paper thicknesses (1-4), sample 1 and 2 were most promising for this structure as it gives moderate stiffness in the faces and is still flexible in the fold lines. Besides, it was noticed that too flexible fold lines (sample 4) cause a random origami fold meaning that the structure does not follow the mountain and valley folds.

The textile also contributes to the stiffness of the overall structure as a more rigid textile (sample 7 and 8) cause an additional counterforce whereas a flexible textile (sample 5, 6 and 9) has less shape solidity. Considering the textiles, sample 5, 6 and 9 are most promising to further explore as these show interesting distinguishable characteristics in terms of roughness: the green one being smooth due to the satin weave and the grey one being soft and textured and the rose one in the middle. In addition, due to the elasticity of sample 6 the stitches and the SMA wire are less perceivable resulting in a more unified surface whereas sample 5 has a very prominent stitch line and sample 9 a prominent but soft line.

Furthermore, during the process is was explored that a perfect shape fit of the SE and SMA wires and a tight zigzag stitch (1.5 stitch width and 1.5 stitch length) is required to enable a precise deformation of the structure. Otherwise, the SMA wire deforms between the stitches without causing the desired deformation percentage.

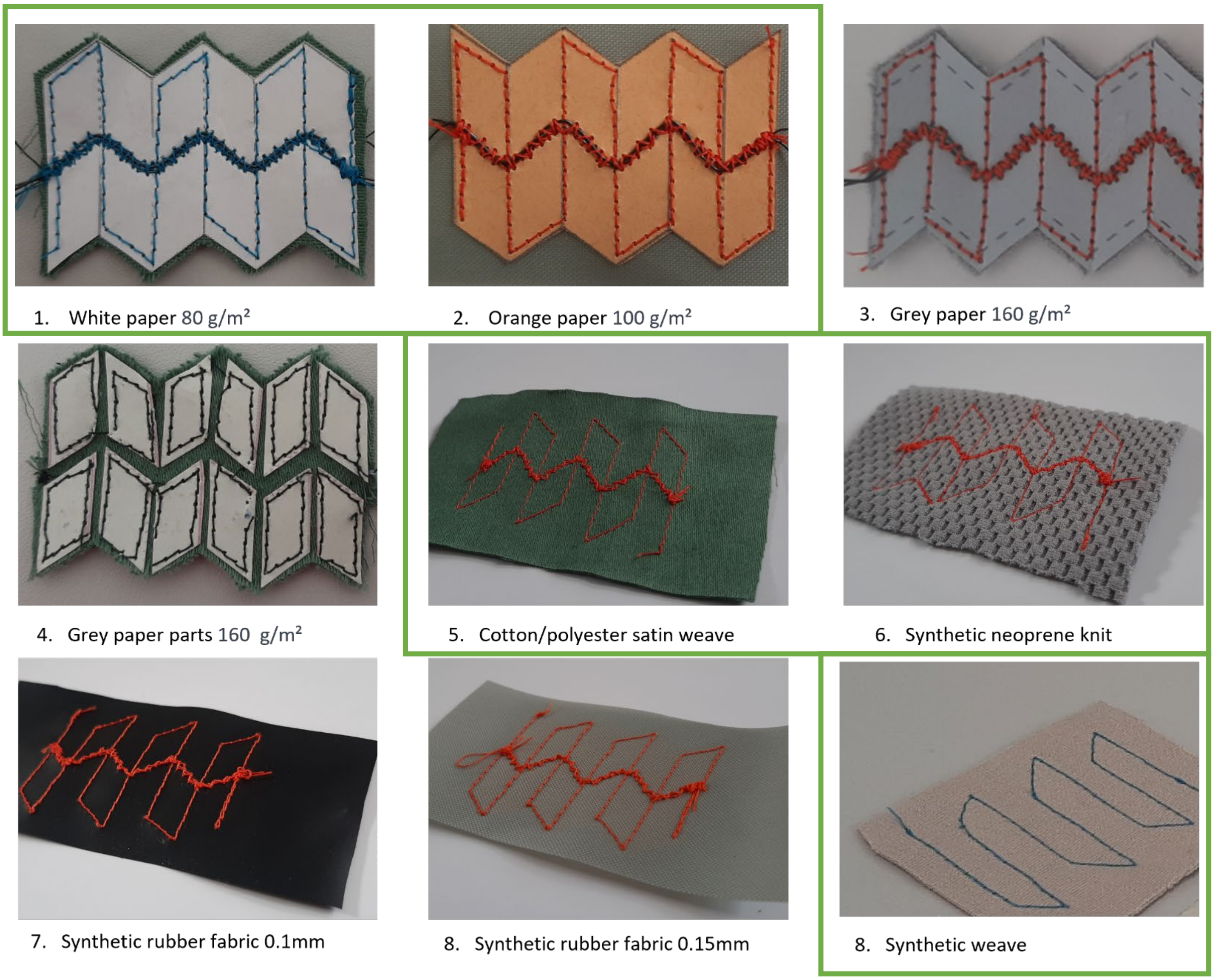


Figure 6.9 Overview of explored papers thickness and fabrics

6.4 COMPILATION OF ELEMENTS

Based on the material system explorations it was found that a Mushi fold in combination with a flat SMA spring that moved from flat (cold state) to a three-dimensional shape (hot state) was most promising to use for haptic feedback. Furthermore, combining one SMA wire of 0.5mm together with an SE wire of 0.35mm resulted in the most promising displacement back and forth. Integrating this into a paper-textile resulted in the following material system (see figure 6.10). The initial displacement resulted in 17% and the ultimate displacement 15%. This is +- 2% lower compared to the displacement produced without the use of paper.

In this material system exploration, the alloy composition of the SMA wire was kept constant, namely a NiTi wire with an activation temperature of 40 degrees. The next paragraph will focus on a technical characterization of several SMA wires with different alloy compositions, shaped in flat springs, to determine the influence of the alloy on its transformation temperature, force/displacement and cycle time.

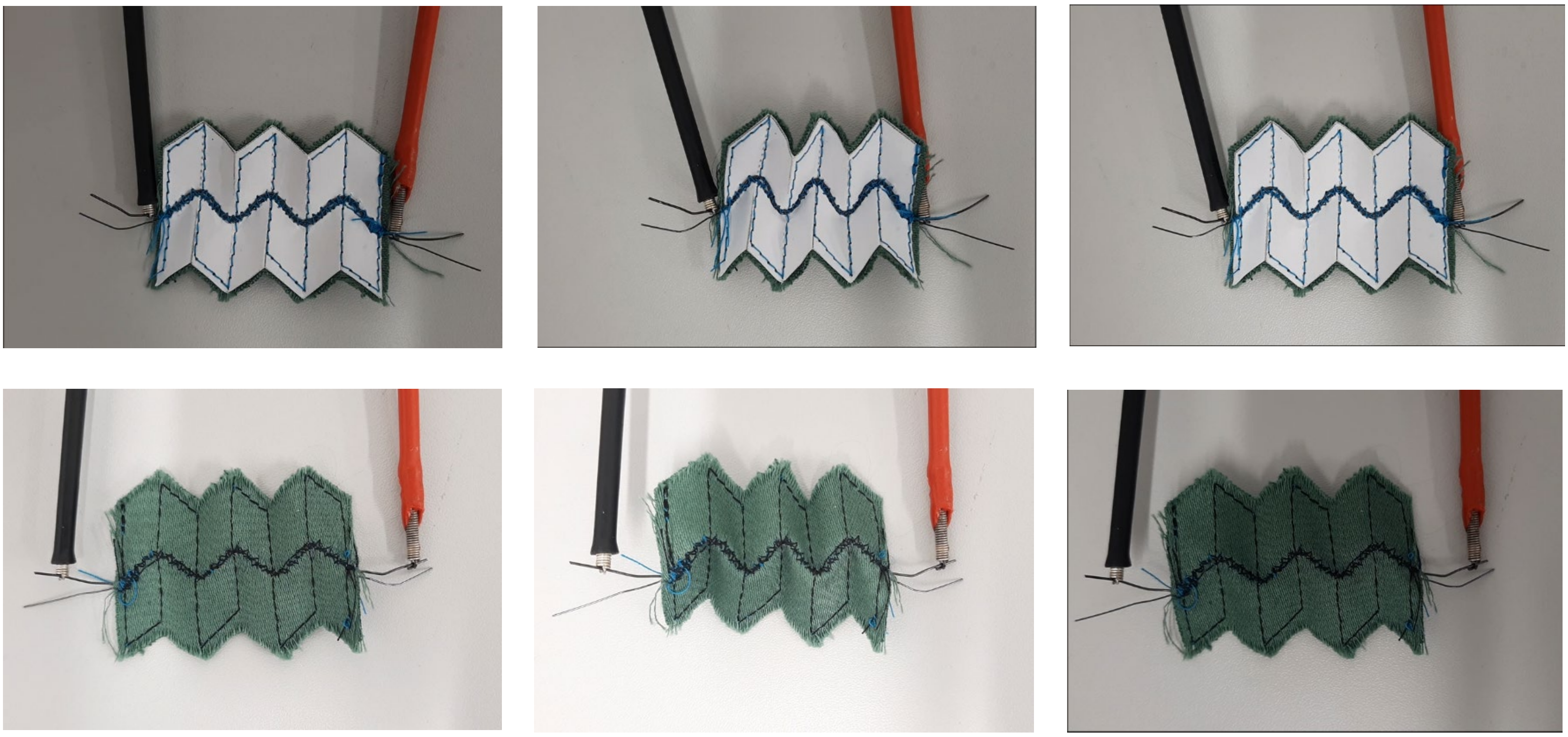
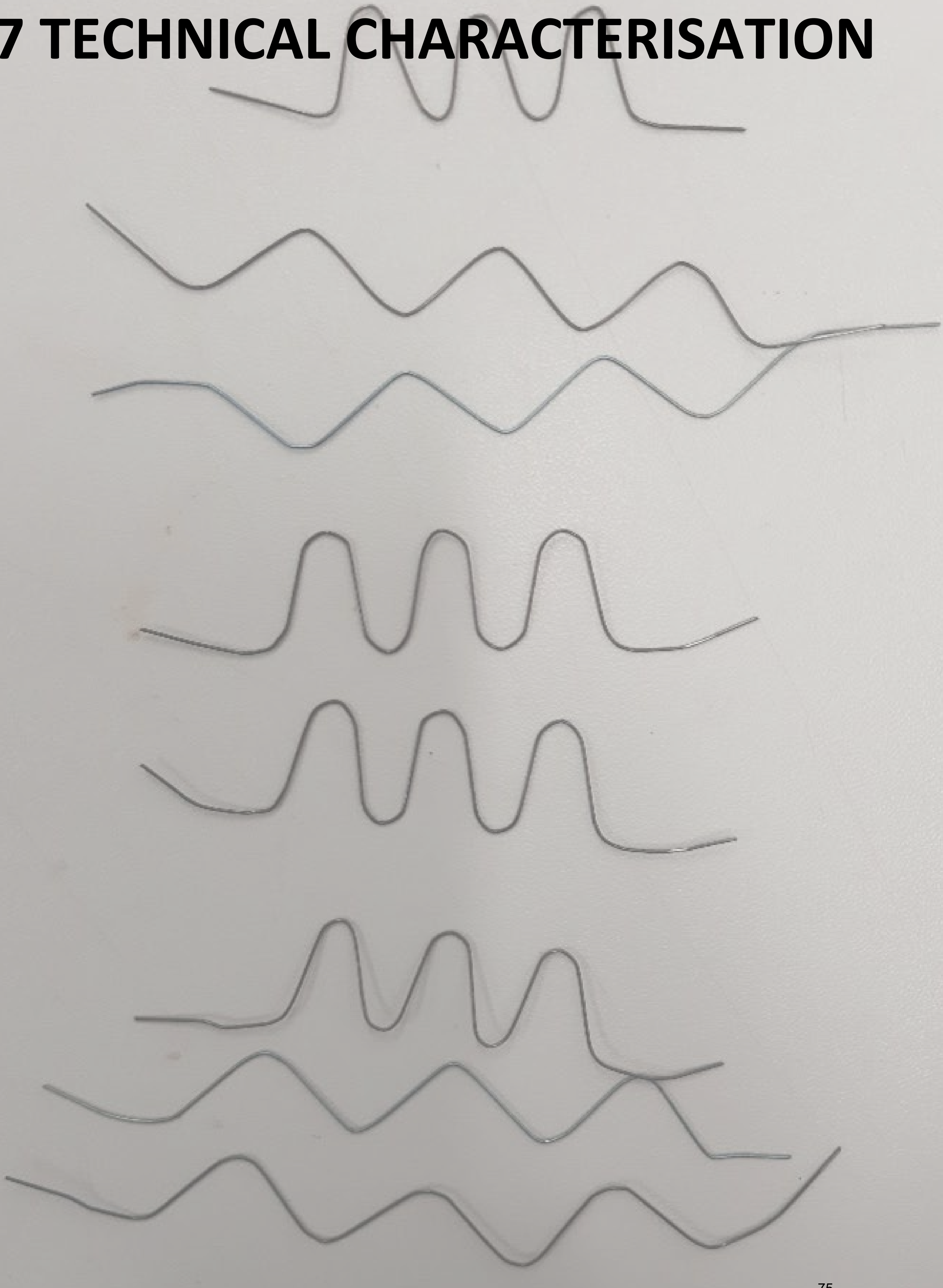


Figure 6.10 Material system with 0.5mm NiTi40 SMA wire (H/P= 10/10), 0.35mm SE wire (H/P= 7/17), 80g paper and cotton polyesther satin weave fabric. Total wire length is ~72mm and amount of flat spring peaks are 3.

Figure 6.2 Overview of stages of this chapter presenting the exploration of origami structures (a), SMA/SE balance (b) and papers (c)

7 TECHNICAL CHARACTERISATION



7.0 INTRODUCTION

This chapter describes the technical characterization of the proposed material system with the main focus on the zigzag SMA wire. As the MDD method prescribe, the aim is to get a clear understanding of the unique technical properties of the material and how these change when compositions or preparation methods vary (Karana et al., 2015). As the proposed material system is a composition of a SMA zigzag, SE zigzag and a textile-origami structure, every parameter is evaluated separately to understand its influence on the material system and iterate upon it. In this, the main focus is on evaluating different SMA zigzags as the movement of the material system and its most important technical properties (e.g. transformation temperature, force/displacement and cycle time) come from the SMA wire.

Therefore, the main question revolves around determining the key technical properties of a 0.5mm zigzag SMA wire (height/pitch 10/10mmm; 4 peaks; wire length 240mm) for different alloy compositions and when a SMA wire is re-trained:

- **NiTi30:** Nitinol wire with an As-Af of 30C
- **NiTiCu30**: Nitinol wire with the addition of copper (amount not specified) with an As-Af of 30C
- **NiTi40**: Nitinol wire with an As-Af of 40C
- **NiTi40_retrained:** NiTi40 that is annealed for a second time after usage

The key technical properties include the transformation temperature (As-Af) (7.1), the force/displacement in martensite and austenite (7.2) and the cycle time including response and cooling time (7.3).

In addition, an impression on the force/displacement is also given for SE wires, varying in diameter, and the origami-textile structure in paragraph 7.2.

7.1 TRANSFORMATION TEMPERATURE

The exact transformation temperatures of the ordered wires (As and Af) and how these are influenced after standard heat treatment were evaluated for the described samples.

7.1.1 Test procedure

To determine the As and Af for the wires, the ASTM-F2082 standard test method, proposed by Kellogs researchslab (Kelloggs, n.d) is used. With this method, water is gradually warmed and the temperature is tracked using a digital thermometer to see at which temperatures the wires start (As) and stop (Af) to move after bended in a free of weight shape recovery (figure 7.1).

First, the samples were deformed in a curved shape and placed in temperature-controlled water to see if the wires recovered their straight shape for different temperatures, without undergoing any heat treatment. The degree of shape recovery (either full, semi or not) was noted together with the tracked temperature. Second, the specimens underwent the standard heat treatment (annealing) for 30 minutes at 550 C in a ceramic oven to train the wires straight. After annealing, the specimens were water quenched and the test was repeated in the same way.

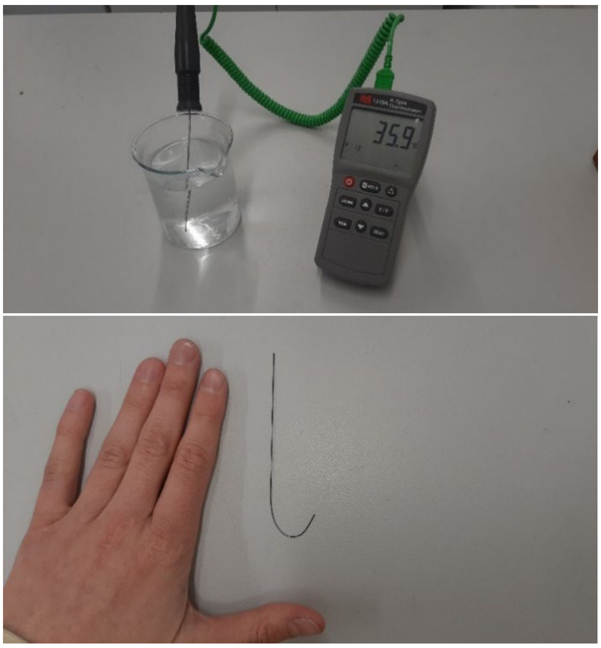


Figure 7.1 Setup of the experiment

7.1.2 Results

Figure 7.2 shows the results of shape recovery at certain temperatures for the different wires before and after training (see appendix E for a more elaborate graph). The austenite starting temperature (AS) represents the temperature where the wire showed a full recovery and the austenite finishing temperature (Af) represents the temperature where the wire showed a movement.

As shown in Figure 7.2, the transformation temperature range correlates with the transformation temperature defined by Nextmetal, which was around 34 and 33 C for 30C wires and 45 and 44.1C for 40C wires. Interesting is that As-Af range is rather small (less than 4C) which means that the activation can be controlled precisely. However, the transition temperatures seem to change after annealing for 30 minutes at 550 degrees as the transformation temperatures of the untrained and trained wires differ significantly. The 30C wires were tested after training to have an As-Af range of 42-44.6 (0.3mm) and 38.2-42 (0.5mm) which is an increase of around 10C and the 40C wires were tested to have an increase of almost 20 degrees: 64-68C for both 0.3mm and 0.5mm. The wires were trained for a second time to see if transformation temperatures kept increasing after each training. This was not the case: the wires kept the same transformation temperatures after the first training applying the same annealing conditions. This result seems to imply that the microstructure of the alloy changes due to the heat treatment which is verified by literature.

Adjusted annealing conditions

Yoon and Yeo (2004) tested the thermomechanical behaviours of 1 mm nitinol shape memory alloys on varying annealing temperatures and times using DSC and XRD (see figure 7.3 for main result).

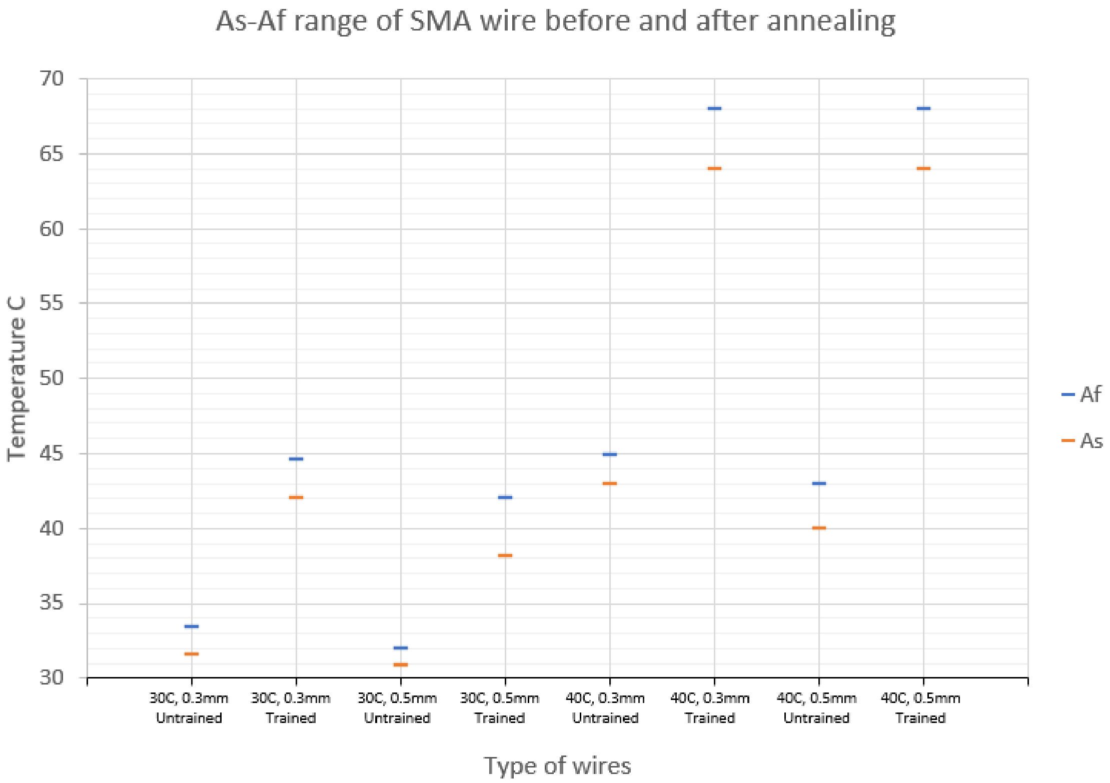


Figure 7.2. Evaluated As-Af range before (untrained) and after annealing (trained)

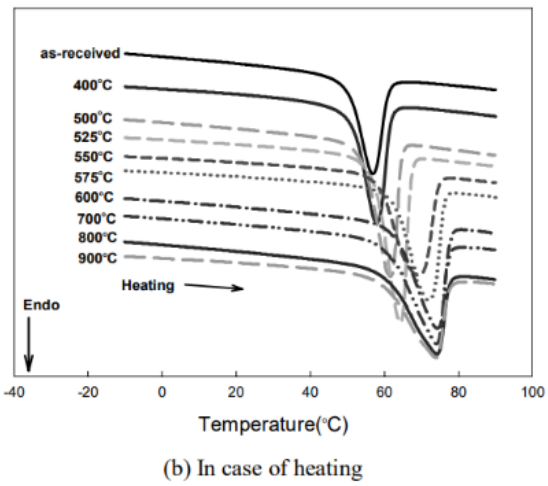


Figure 7.3 Activation temperature for different annealing temperatures

The main findings explain that the thermomechanical properties are stable after 15 minutes of treatment and are strongly influenced by annealing temperatures increasing linearly between 400-600°C, which is also in line with Kus and Breczko's experiments (2010). Based on the results from Yoon and Yeo (2004), Kus and Breczko (2010) and email contact with Flextmet, a new 30C wire (0.5mm diameter) was evaluated with adjusted annealing conditions of 500C for 15-20 min, following the same test procedure. Results showed only a small increase in transformation temperature before 33C and after training 34C, as expected.

To account for the recovery with trained shapes a zigzag with 2 peaks was evaluated with the adjusted annealing conditions. After deforming the zigzag to 20% and 50% of its initial length for 5 times, the shape was successfully recovered in water of +- 34 degrees. This means that the adjusted annealing conditions are suitable to train the proposed zigzag shapes. Good to emphasize is that the activation temperature for a noticeable shape change is most likely higher when the wire is integrated in the structure due to the influence of load.

SE training with 500C for 10 minutes

According to Flexmet, the annealing conditions for training a SE wire should be around 500C for 10 minutes, with thicker diameters taking longer. When the annealing conditions are increased too much, the activation temperature of the SE wire, which is often around -20, could rise too much and showing a shape memory effect.

7.2 FORCE/DISPLACEMENT FOR SMA WIRES

Mechanical test were conducted to understand the behaviour of the described trained zigzags in martensite and austenite (NiTi30, NitiCu30, Niti40, Niti40-retrained). The insights of force distribution in martensite and austenite state are relevant to determine which wire is best suited; can generate the most force when heated and is most malleable when cooled in order for the SE counterforce to overcome the SMA martensite force. Based on the literature (see paragraph 2.2.2) and email contact with Flexmet (see appendix E), the hypothesis is that the NiTiCu30 shows less force in martensite and more force in austenite. Furthermore, it is assumed that the retrained zigzag will show less force at lower temperatures temperature due to the increased activation temperatures.

7.2.1 Test procedure

The mechanical tests were conducted using the Zwick machine at TuDelft faculty. The force/displacement distribution in martensite state was measured using the following machine settings: test speed = 10 mm/min, preload = 0.1N, L_0 = 51.15 mm, maximum extension = 25,57mm (50%). In this way, a clear overview is given of what forces are elicited at certain extensions.

To understand the zigzag behaviour in the austenite state, the temperature and force were measured for two extensions of 20% and 50%. To do this a more elaborate setting was created including a power supply, thermometer and video recording to record the displayed force and temperature in the two pre-stretch states of 20% and 50% (see figure 7.4). The reason for choosing this setup is that it is relevant to know what type of forces are generated at certain extensions in relation to the desired temperature.

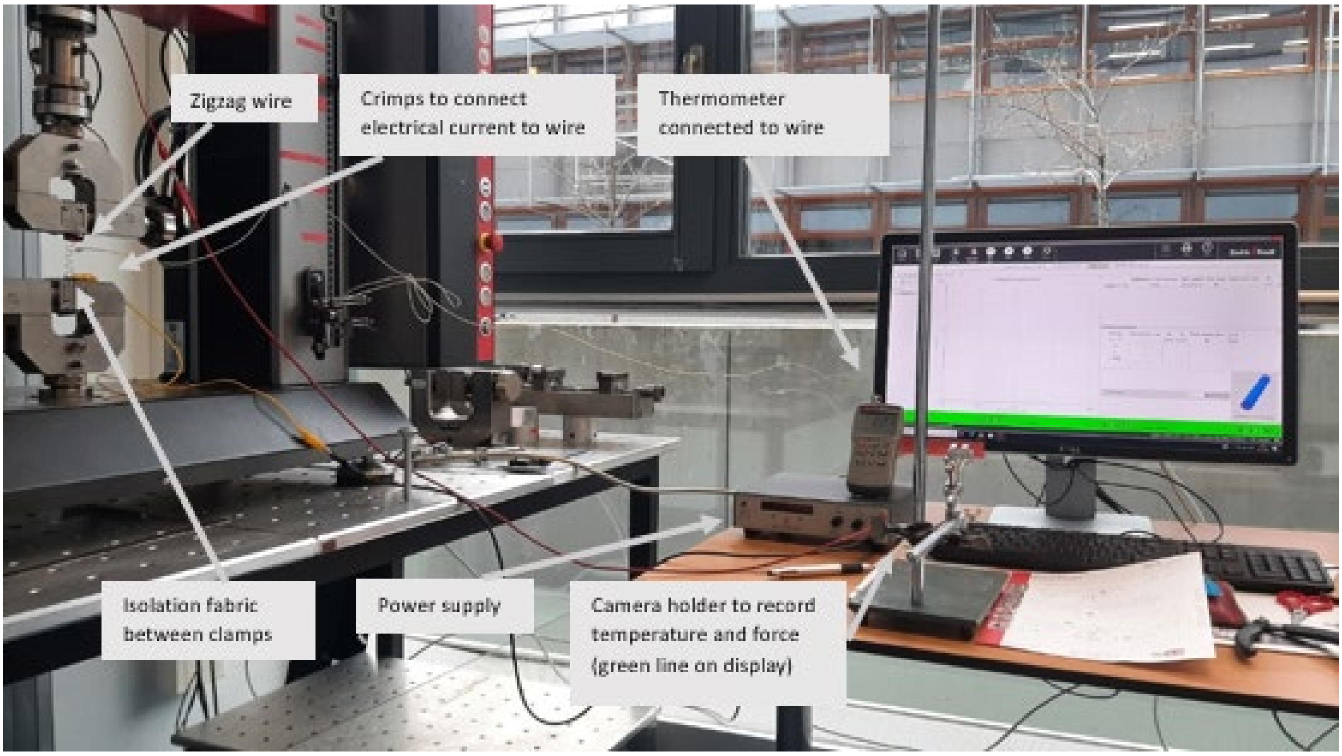


Figure 7.4 Test setup for evaluating the force/displacement in austenite state.

7.2.2 Results SMA wires

Figure 7.5 and 7.6 show an overview of the generated forces at displacement percentages for the examined zigzags respectively at ambient temperature and at 40 degrees.

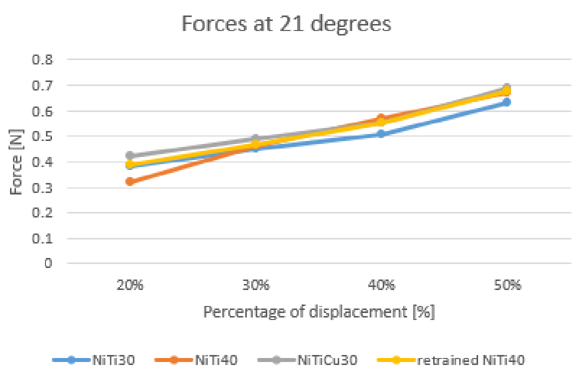


Figure 7.5 Force/displacement at martensite

When evaluating the martensite behaviour, all zigzags show more or less the same linear behaviour of generating more force when stretched with around 0.4N at 20%, 0.55N at 40% and 0.68N at 50% from its initial length (see figure 7.5). There is a little variation of 0.1N at different extension percentages which can be caused by the relatively large tolerance of the Zwick machine (0.1% on 500N) or impurities while making the samples. NiTiCu30 shows no clear distinction of generating less force in martensite state, which is not in line with the hypothesis and information from Flexmet.

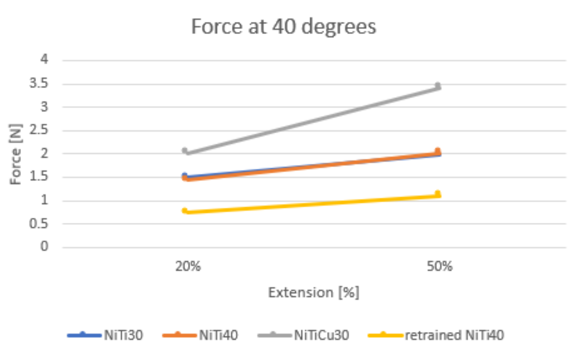


Figure 7.5 Force/displacement at austenite

When evaluating the austenite behaviour, it seems that the acquired force when heated to 40C are slightly bigger when stretched to 50% than 20% extension (see figure 7.6). Notable is that the retrained NiTi40 exhibit much lower forces compared to the NiTi40. A reason for this can be that after annealing a second time the transformation temperature and stress division can be influenced.

Another finding is that NiTiCu30 exhibit around 2N at 20% and 3.5N at 50% extension which is respectively 0.5N and 1.5N higher than NiTi30. This suggests that the addition of copper for Nextmetal wires cause higher generated force when heated to 40C at 20% and 50% extensions which is in line with the information got from Flexmet (Appendix E). However, the overall produced forces of the flat springs are slightly lower than the information got from Kellogg's manufacturer, stating that an 0.5mm NiTi flat spring with an spring height (also called amplitude) of 10mm produces 3-5N. An explanation for this can be the training method of the wires which was in this stage of the project not yet optimal: the shape was fixated at every bolt resulting in less smooth curves (see material exploration, paragraph 4.1)

Shape recovery in constrained loading condition

To get an idea of the shape recovery in loading condition, one NiTiCu30 zigzag of three peaks was evaluated for 50% extension of its initial length with 1.3N and 2.3N constrained force (see figure 7.7). Results showed after one cycle a shape recovery of 90% when 1.3N was applied and a 100% shape recovery in unloaded condition. When 2.3N was applied the shape recovery was 70% and the shape was not fully recovered in unloading condition. Although this was tested for only one cycle, it gives an indication of the force/displacement balance in loading condition.

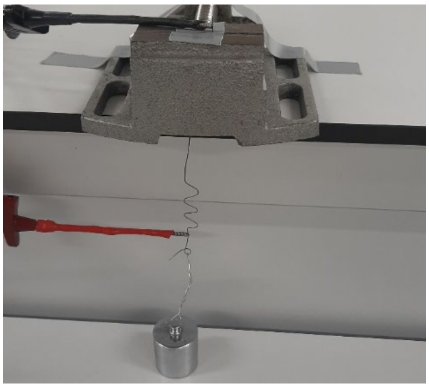


Figure 7.7 Test setup

7.2.3 Impression of force/displacement SE wires and structure

To get an impression of the force/displacement balance involved in the structure several SE wires and the origami-textile structure are evaluated with a Newton meter.

SE force/displacement

The force/displacement is measured for three types of SE wire diameters (0.25,0.3 and 0.35mm), each differing in their pitch length while keeping the same wire length (figure 7.8). The force was measured for four fixed lengths to where the SE spring was compressed: 17mm, 15mm, 13mm and 10mm, of which the latter is correlated to the SMA trained length. This means, the wire with a 20mm pitch length was compressed 50% at 10mm whereas the wire with a 17mm pitch length was compressed to 39%. The forces where measured for one and two peaks to get an impression of the relation of accumulating peaks. Measuring more peaks was not possible with the available equipment due to warping of the spring (see figure 7.8 below).

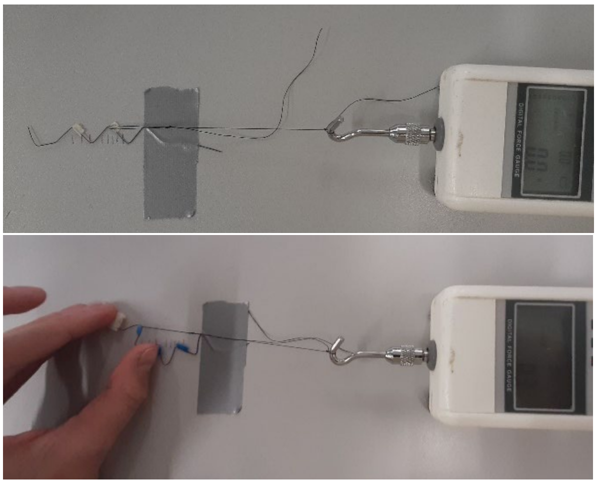


Figure 7.8 Test setup

As shown in the graph, the force becomes bigger when compressed more and the larger the pitch length the higher the generated forces for the same displacement. Furthermore, the 0.35mm diameter generated more force compared to the smaller diameters. When considering the 0.35 mm SE wire with 17 mm pitch length, which was used in the structure, a compression force of 0.5N was measured at 10mm, which is 38% of displacement. This was 0.2N for the 0.3mm wire.

The influence of two peaks on the force/displacement seems to be minimal: 0.1N bigger for the 0.35mm wire pitch 17mm and the same for the smaller diameter wires 17 mm pitch.

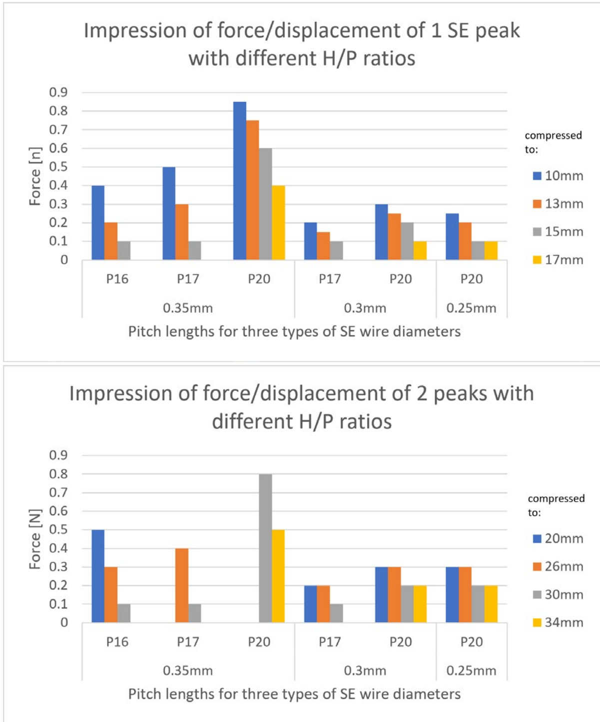


Figure 7.9 Force/displacement for 1 (up) and 2 (down) peaks

Origami-textile force/displacement

Considering the origami-textile structure with satin weave fabric and 100g/m paper), the force was measured to be around 0.0-0.1N when compressed to 30mm. However, the forces within the structure could still influence the total SMA/SE performance.

Figure 7.10 Measured force for the structure

7.3 CYCLE TIME OF SMA WIRES

The response time was measured for the different wires with the calculated and tested Voltage and Amperage, using the formula in paragraph 2.3. The wires had 4 peaks and the wire length was 130mm. The measured response time refers to the time when the shape was fully recovered and the As in the As-Af range is an estimate of when the shape recovery started which was done by observing. The zigzags were extended to 20% deformation to observe a clear shape change (see figure 7.11 for setup).

Figure 7.11 Test Setup to measure the response time of the SMA wires

As shown in table 7.1, the calculated and measured response time were the response time of the NiTi40 C wire was 12 sec which is much higher compared to the 30 degrees wires responding in 4 sec. Also the cooling time is longer for the NiTi40 wire. The retrained wire of 40 degrees showed a similar behavior as the Niti40 wire. To reach a similar the response time of 4 sec for the NiTi40 wire the power was increased to 1.8A. Good to emphasize is that the response time and cooling time when the wires are integrated in the structure will be longer due to respectively the applied counterforce and the isolation of the structure. Also, this test does not give an insight in when and at what temperature the material system will deform to its martensite phase which is hard to observe.

7.4 DISCUSSION

Based on technical characterisation it seems that when a specific transformation temperature is desired, the annealing conditions for training SMA wires should be set on 500C for 15-20 minutes and for SE wire 10 minutes. When increasing the annealing temperature, the transformation temperature will as well be increased. Something for future studies is to examine the influence of the stress/strain for different annealing conditions and wire diameters.

Furthermore, it was observed that the addition of copper results in higher generated forces at 40 degrees compared to the wires without copper. When designing for low activation temperatures the addition of copper could be valuable due to the fast response time and high generated force.

	Power unloaded, displacement of 20 % of length, 4 peaks						
	Temp [C]	V_ther	A_the	V_test	A_test	time_resp	time_cool
NiTi40	50	1	1,34	1	1,35	13	60
				1,4	1,8	5	
NitTi30	40	1,1	1,26	1	1,25	4	30
NiTiCu30	40	1	1,3	1	1,3	4	25
Retrained	50	1	1,34	1,1	1,35	19	60

Table 7.1. The results of the measurements for the theoretical (V_the and A_the) and tested (V_test and A_test) voltages and Amps with the corresponding response time (time_res) and cooling time (time_cool) and the observed As-Af.

8 EMBODIMENT OF UNIT

8.0 INTRODUCTION

This chapter describes the embodiment of the proposed material system based on the insights gathered from the material system exploration and the technical characterization. The material system based on a SMA is defined as a ‘Shape memory origami’ unit which generates haptic feedback by transforming its shape from a two dimensional surface to a three-dimensional one. The aim of making this material system is to demonstrate the potential of generating haptic feedback with SMAs, therefore called a demonstrator.

In this chapter the embodiment of the proposed material system will be described. First, several design iterations will be described that were prior to the final material system unit design. Second, the final material system will be explained based on its dimensions and assembly. Additionally, its technical properties will be evaluated. Finally, a design guideline is outlined that was made based on all research and explorations insights.

8.1 DESIGN ITERATIONS

Two main directions were explored to iterate further on the material system unit. The first one was the integration of multiple wires in one material system unit and the second one was integrating SE wires in tension and creating smaller samples.

8.1.1 Integration of multiple wires

The integration of multiple wires in one material system unit was considered to see if the displacement could be enlarged, as shown in figure 9.1. For sample 1, two SMA-SE wires were integrated on the sides of the material system. This resulted in an displacement only at the sides were the wires were positioned, leaving the middle fold flat. For sample 2, three SMA-SE wires were integrated in one material system, one in the middle and two halfway. Sample 2 showed a consistent displacement over the material system but the shape recovery when cooled was for some reason limited. Besides, due to the higher amount of SMA wires, there were more difficulties connecting all the wires to the electrical supply and a considerable amount of power was needed (+- 2.3A vs 1.3A for sample 3). Lastly, for sample 3, one SMA-SE wire was integrated in the middle of the material system. This resulted in a consistent displacement over the material system and an easy assembly of the wires to the electrical supply.

Considering the requirements of limiting the power use (less wire length in one material system unit) and enable an easy assembly, Sample 3 was considered as most promising to focus on.

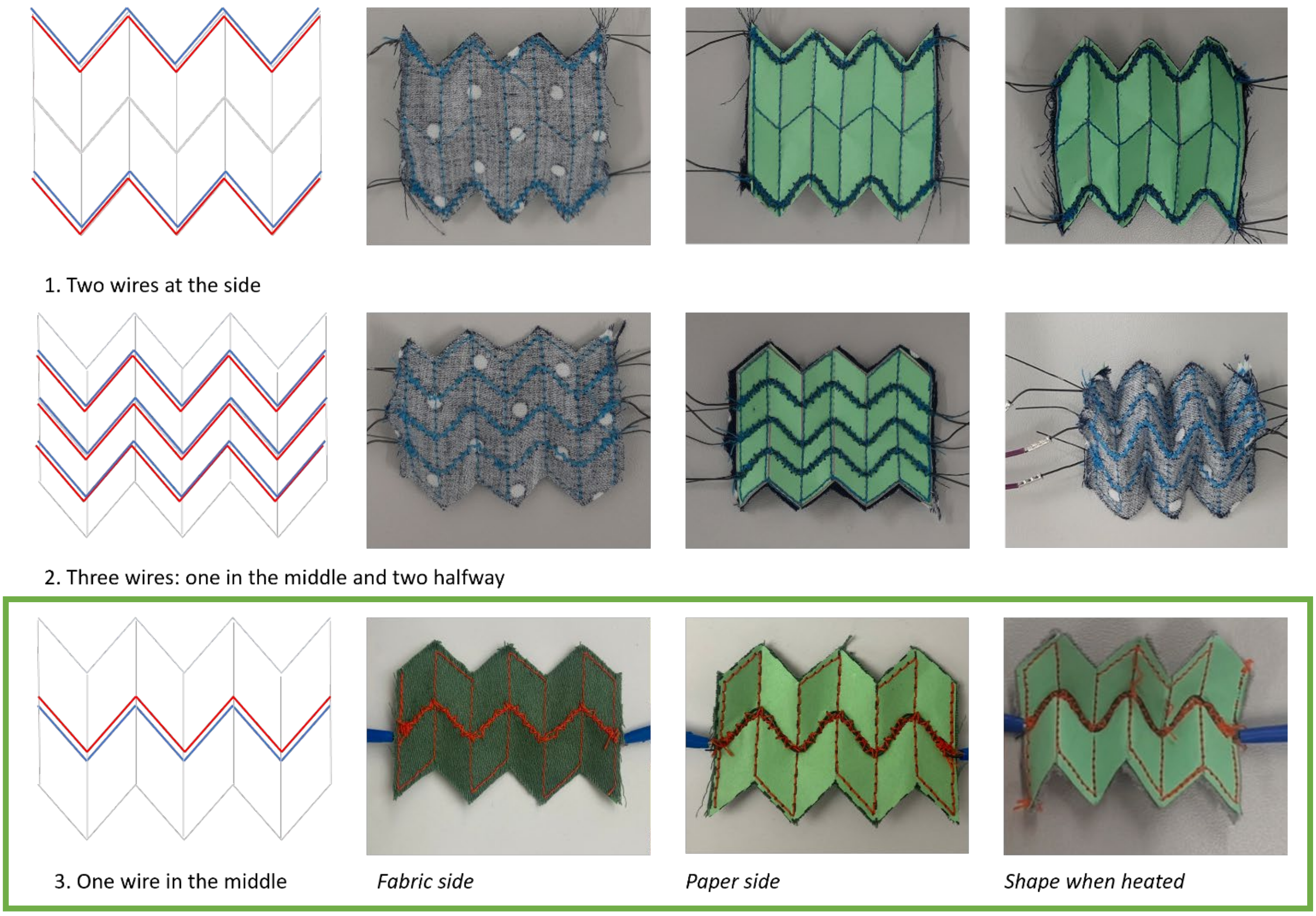


Figure 9.1 Three design options for the material system unit with multiple SMA-SE wires integrated. In the green box, the sample to proceed with is marked.

8.1.2 Reconsidering SE-SMA balance

Several SE-SMA wire integrations are considered to optimize the displacement of the material system unit based on the outcomes of the technical characterization, where the addition of copper was evaluated as stronger in Austenite and several SE's pitch lengths were evaluated. The 0.5mm NiTiCu30 and NiTi40 SMA wires were combined with SE wires of 0.35 and 0.3mm of which the latter is integrated in compression. The reason for integrating the wire in compression is to examine if the material system could go back to its flat shape entirely. To do this, the SE wire was trained with a bigger pitch than needed for the structure and sewn in compressed, see Figure 9.2. Initial explorations revealed that integrating a 0.35mm SE flat spring in compression (pre-compressing a SE wire with 20mm pitch to 17mm, corresponding to 15% pre-compression) was difficult due to the large produced forces (see paragraph 7.2, Technical characterization). Also, these material systems displayed a smaller displacement compared to the systems that did not include a 0.35mm SE wire in pre-compression and were therefore eliminated as a viable iteration.

The displacements of all material systems were recorded with a camera and the averages were calculated over three cycles, measuring every point three times with a digital caliper. As marked in green in Figure 9.2, NiTiCu SMA 0.5mm with SE 0.35mm (1) is selected as most promising as this material system shows the biggest displacement compared to NiTi40 and flattens reasonably compared to the ones that use a smaller SE diameter in compression (0.3mm). Good to emphasize is that both material systems that consists of a 0.3mm SE wire with 15% pre-compression displayed a significantly higher initial displacement and ultimate displacement. However, the gap between the initial and ultimate displacement is larger, meaning that the structure contracts more but flattens less.

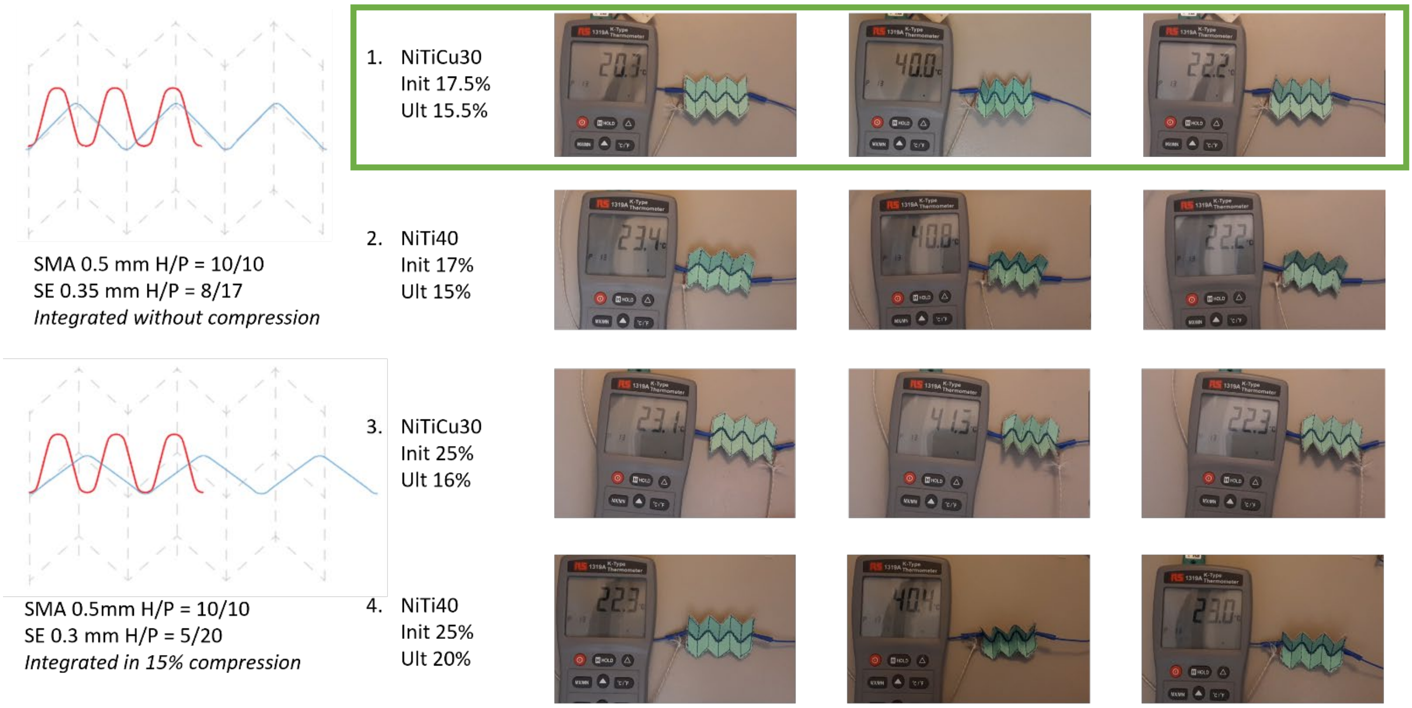


*Figure 9.2 Displacement of 4 SMA-SE wire integration. *All systems showed a reliable repetition of displacement over three cycles with a SD below 0.5%.*

8.2 FINAL MATERIAL SYSTEM UNIT

The material system based on SMAs is defined as a 'Shape memory origami' unit which generates haptic feedback by transforming its shape from a two dimensional surface to a three-dimensional one (see figure 9.3). Through the use of a flat SMA spring, a two-dimensional shape change is generated and through the use of origami, this two-dimensional shape change is translated into a three-dimensional one with the following characteristics and tactile sensorial qualities:

Contraction and upward movement

The material system contracts in horizontal (y) direction (16% of its deformed length/ cold state length, which is 8mm for three peaks). In addition, it contracts in vertical (x) direction and expands in the upward (z) direction. The contraction movement aims to generate a stroking sensation and the upward movement a pressure sensation. This can be passively perceived by the kinesthetic and cutaneous system.

Texture difference through size and curvature (spatial property)

The material system creates a shape change from a larger 2D surface (51x37mm) to a smaller textured 3D surface. This can be actively explored by the cutaneous system by stroking the fingers around the created curves and size.

Coldness-warmth (material property):

The SMA wire heats up the textured surface to a maximum of 40 degrees which can be perceived passively by the cutaneous system.

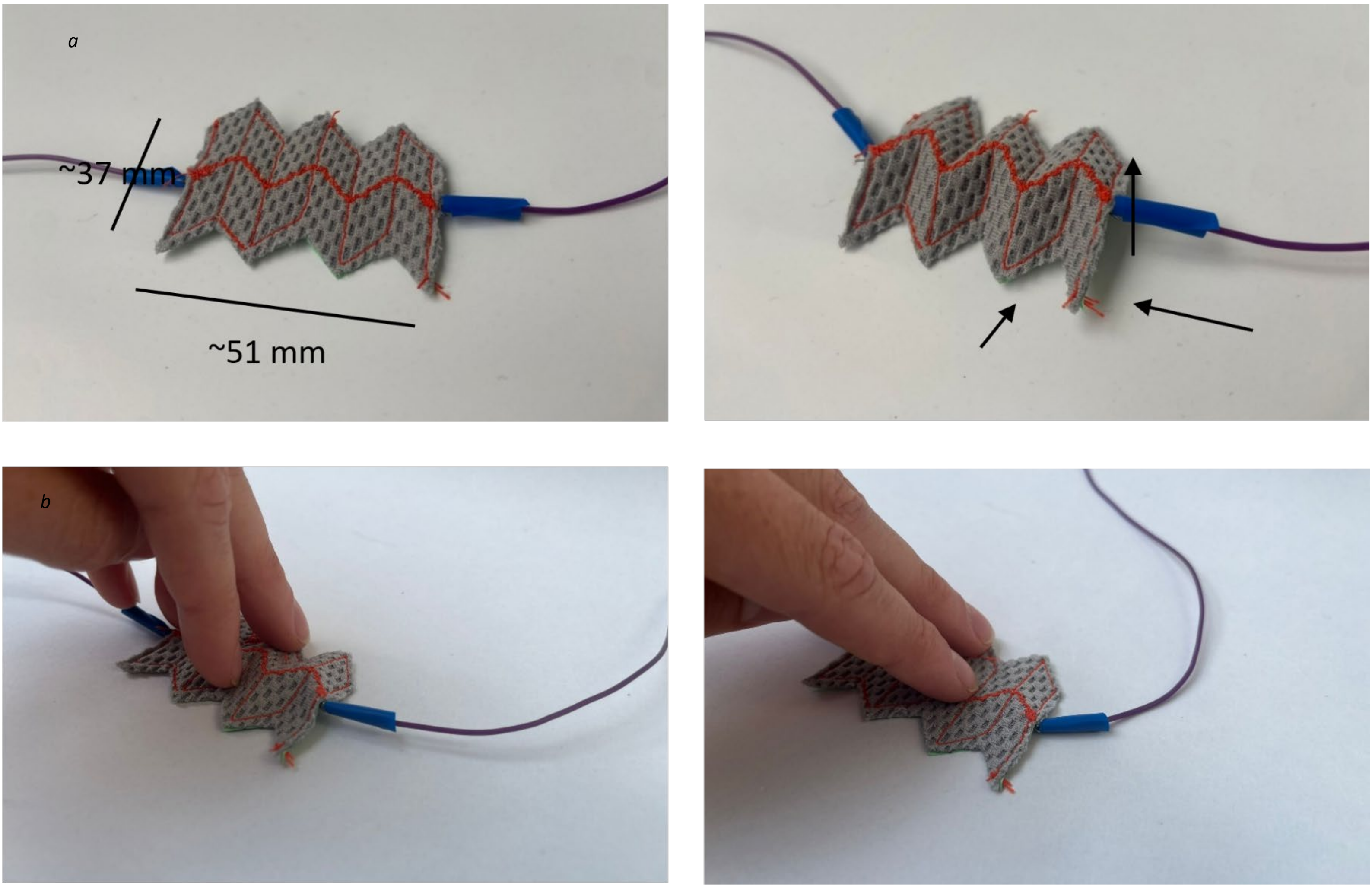


Figure 9.3 the material system based on SMAs in deformed (cold) state (left, a) and activated (heated) state (right, b). The general dimensions (a) and movement directions (b) are illustrated as well as the user interaction (lower pictures)

8.2.1 Dimensions

Figure 9.4 describes the exploded view to outline all the different elements of the material system. As shown in the figure, it consists of a fabric combined (in this case a synthetic neoprene knit) with 100g folded paper, a 0.35 NiTi SE flat spring wire (Height/Pitch= 8/17mm, L_total ~72mm) and a 0.5mm NiTiCu SMA flat spring wire (H/P= 10/10mm, L_total = ~72mm) with an activation temperature of 33C. The material system can be activated by connecting the SMA flat spring wire to electrical current (1.3V and 1.3A) to change its shape in a three dimensional way.

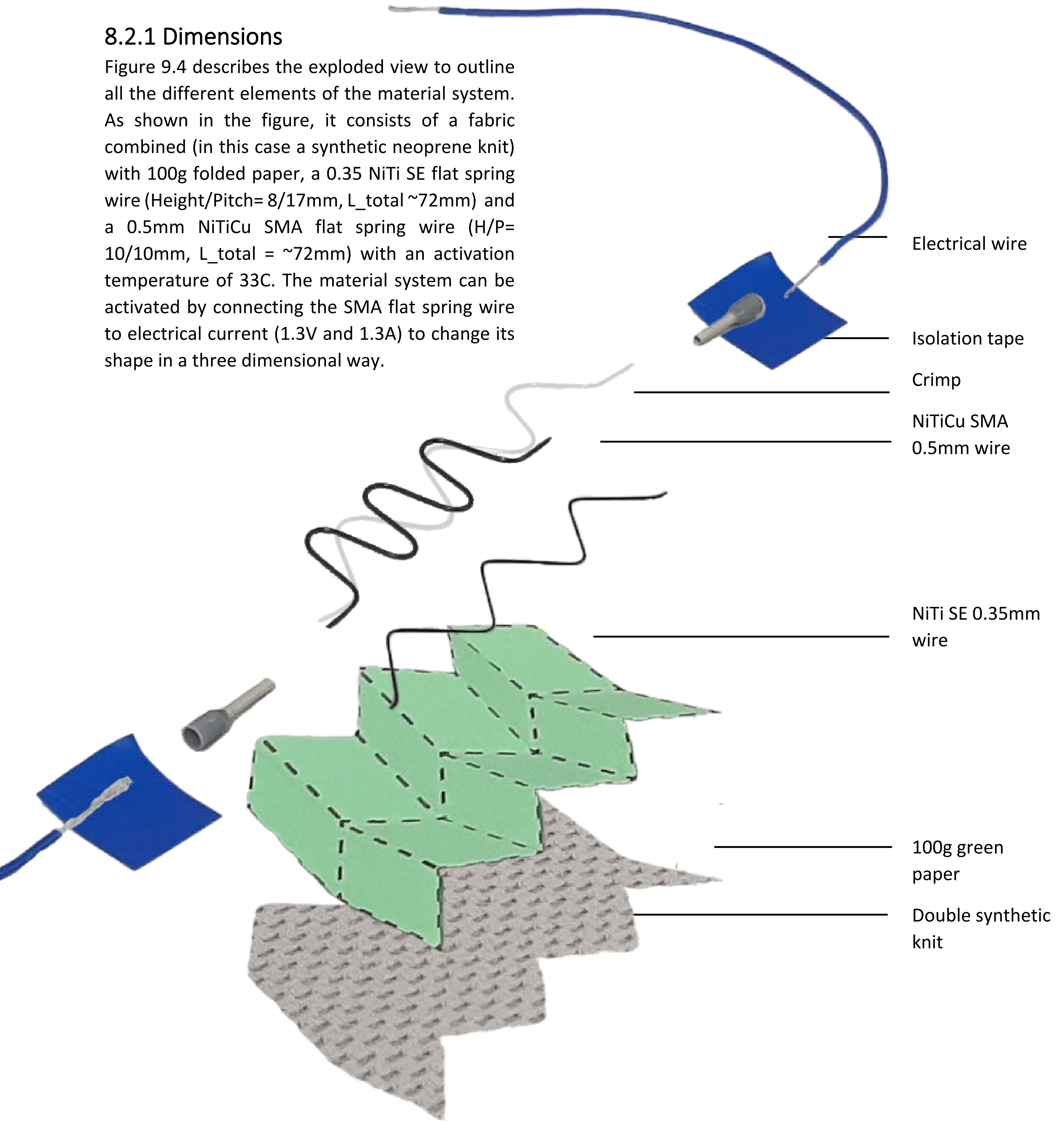


Figure 9.4 Exploded view of material system unit

8.2.2 Mould

A mould is made for the final design to enable more precise control over the wire designs. The material of the mould is steel and has a 3 mm thickness to prevent warping when it comes into contact with high temperatures. The mould was made using a milling machine to drill 2.5 mm holes first and create screw dread second. The wires are spanned between the M3 bolts and fixated at the ends with a 2.5M bolt and nut. Incorporating screw-dread into the mould eliminates the need for nuts, offering two advantages. First, it allows for the creation of smaller and more precise shapes as the spacing between the holes in the previously used frame restricted the possibilities for forms. Second, it simplifies the fixation process of the wires as the bolts are screwed directly in the mould without nuts rather than fixated at every single bolt and nut first and add an additional nut at every point to keep the wire in place (see paragraph 4.1). The downside of using a handmade mould is that for every shape, a new mould is needed which is time-consuming. However, a small variation in spring height (or amplitude) can be managed by using smaller bolts at every point, 2M.

8.2.3 Assembly

To make the material system, the SE and SMA wires were first grounded using the mould and annealed in a ceramic oven for 15-20 minutes at 500 degrees. The paper was folded in a Mushi fold and together with the flat SE spring sewn into the fabric using a sewing machine with zigzag stich size 1.5L-1W. Subsequently, the SMA flat spring was extended 70% of its initial length and sewn in the system using a larger stich size of 1.5L-1.5W. To keep the wires in place while sewing, duct tape was used. To activate the system with electricity, the SMA wire was connected to electrical wires with crimps and isolated with isolation tape. An overview of the assembly process is demonstrated in Figure 9.5

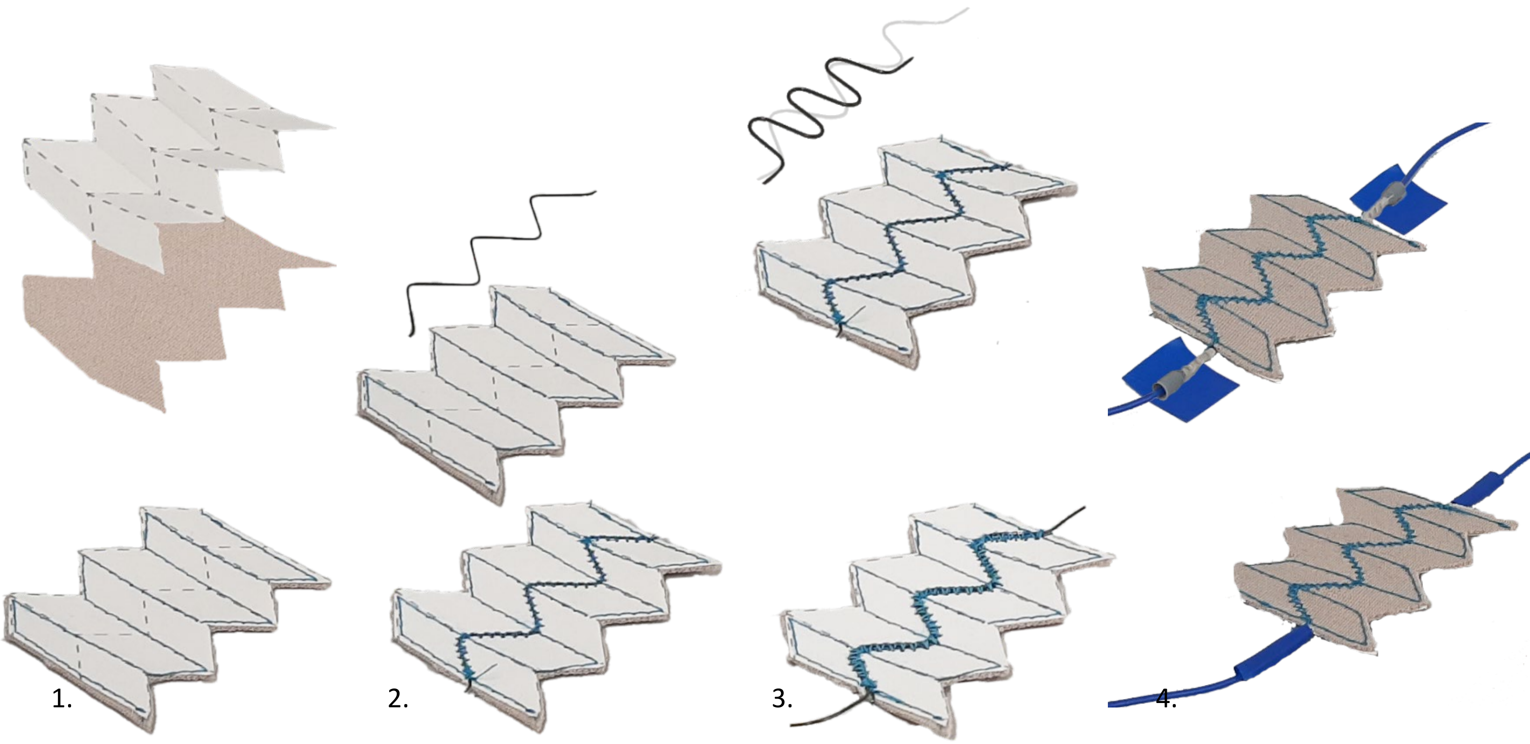


Figure 9.5 Assembly process of the proposed material system. First, (1) the fabric and paper were attached together. Second, (2) the SE was sawm in the material system after which the (3) SMA was sewn in the system. Lastly, (4) the crimps and isolation tape were connected with the SMA wire.

8.2.3 Technical properties

The following technical properties of the material system will be explained: the displacement, produced force and cycle time.

Displacement

As mentioned in the design iterations, the initial displacement was +- 17.5% and the ultimate displacement +- 15.6%, calculated for three cycles with the following formula:

$$Displacement = \frac{L_{deformed} - L_{heated}}{L_{deformed}} * 100\%$$

This displacement percentage was constant over the three cycles (N1 = 15.4%, N2= 15.7% and N3 = 15.7%). Translating the displacement to the absolute displacement resulted in 8mm displacement for the material system. The shape recovery for the SMA wire was calculated to be 81% and for the SE wire around 98-99%.

Produced force

The produced force was evaluated for the material system using the same method during the technically characterization of the SMA flat springs in Chapter 7.2 with the aim to understand the behaviour of the material system. The material system consisted of an 0.5mm NiTiCu flat SMA spring and a 0.35mm SE flat spring. It was placed in the ZWICK machine (test speed = 10 mm/min, preload = 0.1N, L_0 = 46.01 mm) and connected to a thermometer and power supply (see figure 9.7a). The material system was evaluated on its produced force for different temperatures when not stretched and stretched to 1% of its initial length. Figure 9.7b outlines the results of the produced forces over a temperature range of 23-50 degrees for 0 and 1% extension.

As the figure shows, the ultimate produced force at 40 degrees when not stretched is 2.9N and when extended 1% of its initial length it is 4.2N. The increase in force when 1% stretched is most likely due to the SE wire that also produces force.

Cycle time

The cycle time is measured using a video camera while activating the wire with 1.3A and ~1.2V (this slightly varied for all samples). The average response time from ambient temperature ~23C to the time when the system stopped moving (which was around 35-40C) was calculated over three cycles. The response time (from ambient temperature to 40C) of the material system, with three peaks when 1.3A was used, for a NiTiCu wire was ~6 seconds which is 1s slower when not embedded in a material system (see Paragraph 7.3). When increasing the Amps to 1.5A, the response time was 5 seconds and was reached at 35 degrees. Good to emphasize is that the temperature meter is most likely delayed due to the wire length of the temperature meter. The cooling time from 40C to 23C was 60 seconds which is 30 seconds slower when not embedded in the system. An explanation for this increase is the isolating factor of the origami-textile structure.

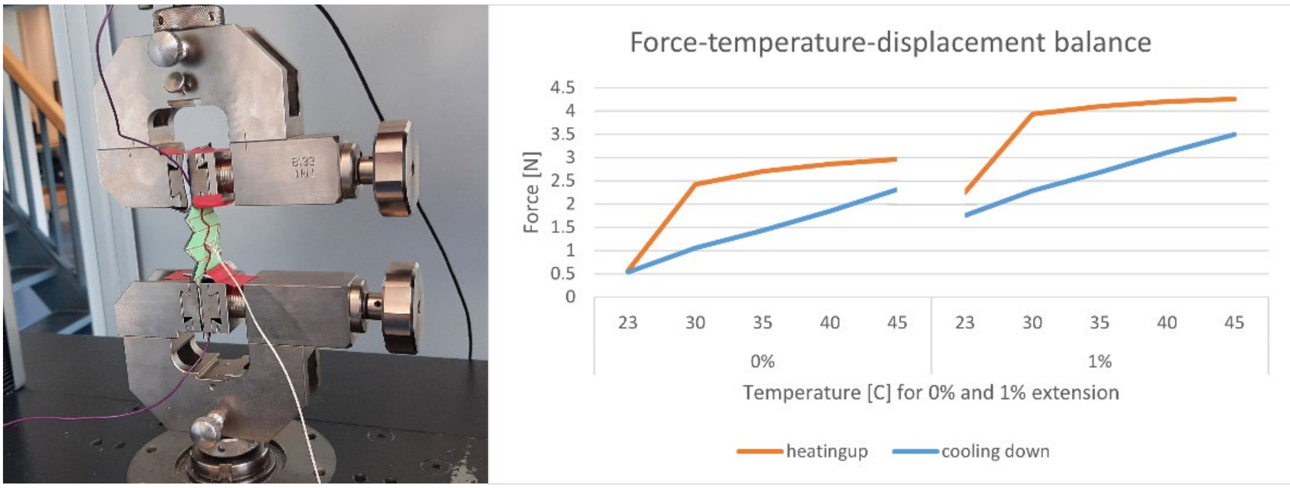


Figure 9.7 Setup fo force test (left) and the graph of force-temperature- displacement balance. In the graphs, the red line illustrates the force when the wire is activated and the blue line illustrates the force when the wire is cooled after activation.

8.3 SMA DESIGN GUIDELINE

Based on all the literature research and experiments that have been done in this project, a guideline is made. The aim of the guideline is to create an overview of all the parameters involved when designing a material system based on one-way SMA wires for designers. First, a schematic tree-overview is given of the classification of the proposed material system in relation to alternatives. Second, 5 steps (marked in the schematic overview) are described to consider when designing a material system based on SMAs: (i) material selection, (ii) load/displacement configuration, (iii) counterforce mechanism, (iv) shape training and (v) integration in structure. Each step describes the options that need to be considered, outlined with straight arrow lines, and/or sub-steps that are relevant to understand, marked with 'i' and 'ii'. The marked black box in each step represents the choice that is made for this project.

8.3.1 Explanation parameters

The options and sub-steps are explained including their influence on relevant parameters such as response time and deformability. The influence of these parameters is presented using icons. The icons describe the effect of increasing the design parameter, meaning that when 'transformation temperature' as a design parameter increases it creates a slower response time.

Response time

The response time is the time it takes for the system to start and finish its shape change after deformation of the martensite. The response time is dependent on the wire dimensions, transformation temperatures and loading conditions and is related to the power supply when electricity is used. As such, the response time can be reduced by applying more current and therefore requiring more power. The left picture in red indicates a slow response time and the right icon in green indicates a fast response time.

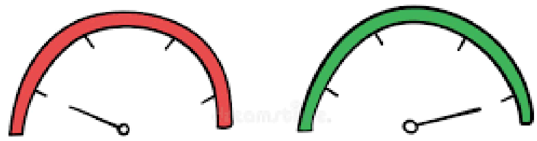


Figure 8.3.1 Slow response time (left) and fast response time (right).

Deformability in martensite

The deformability in martensite reflects how easy it is to deform the SMA wire in martensite condition. A high deformability influences the shape complexity, could give an indication about the amount of displacement that can be applied and the required actuation force. The left picture reflects a high deformability and the right picture reflects a low deformability.

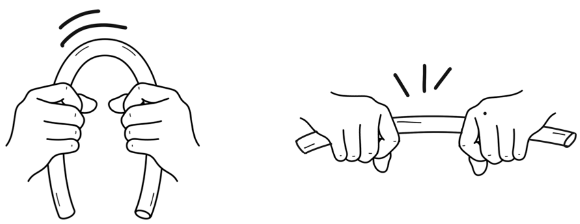


Figure 8.3.2 Highly flexible (left) and stiff (right).

8.3.1 Explanation guidance tree

Figure 8.3.3 presents the overview of the classification of the proposed material system (dark-colored boxes) in relation to alternatives (light-colored boxes) to obtain an understanding of the choices to be made when designing a material system based on SMAs. In this overview, 5 segments are distinguished that can be used as guidance when designing a material system based on SMA's, each associated with a color: the SMA material selection (yellow), load/displacement configuration (blue), counterforce mechanism (purple), shape training (red) and integration in the structure (green). The dotted lines present segments to consider in parallel with the straight lines.

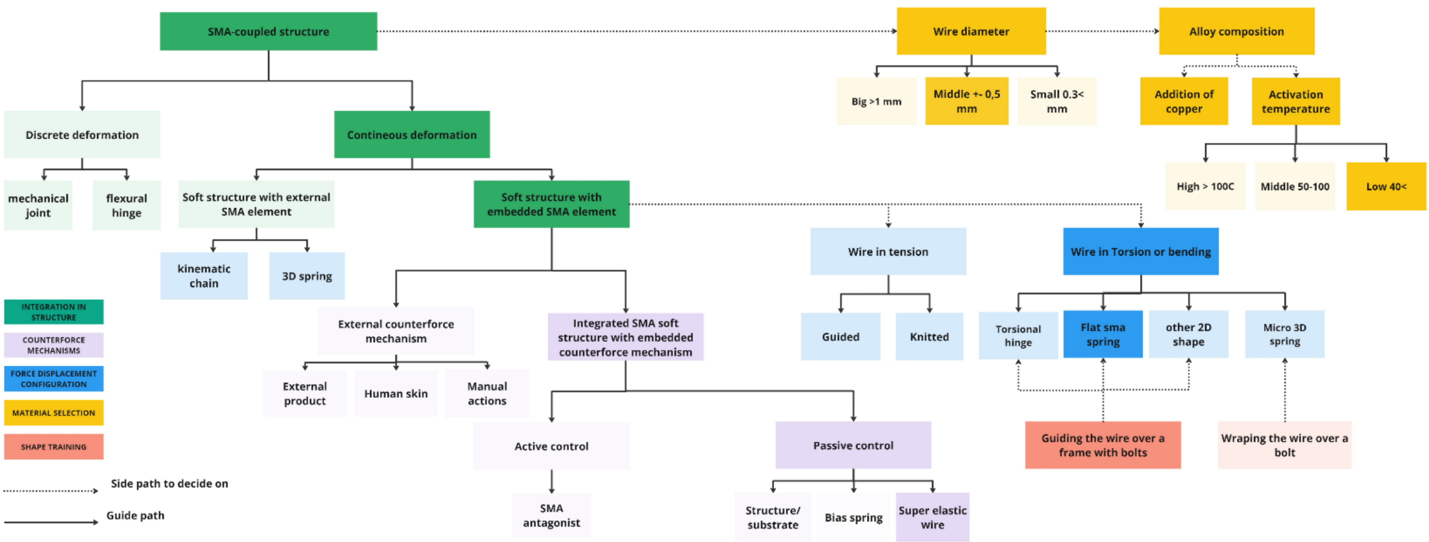


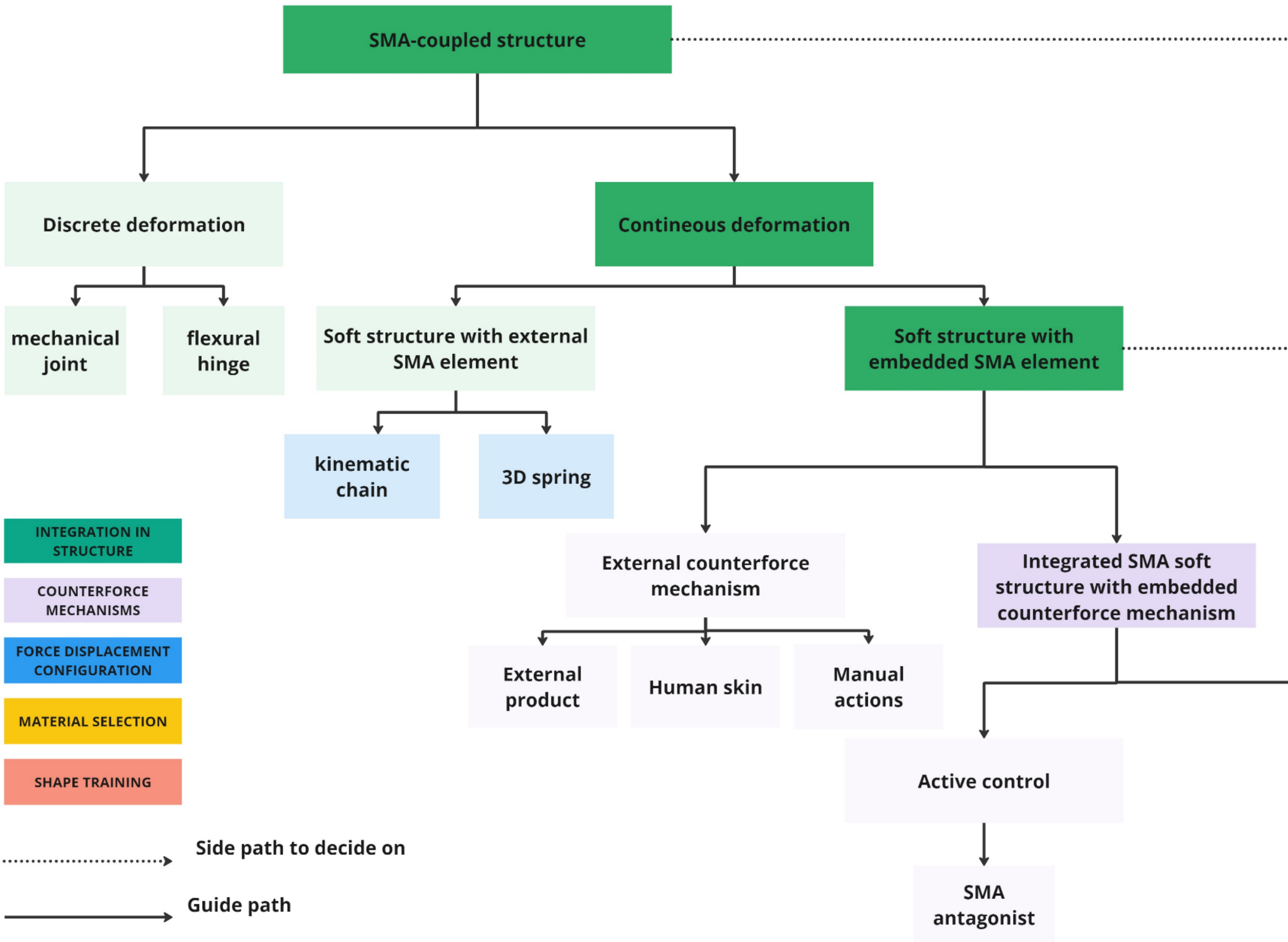
Figure 8.3.3 An overview of the classification of the proposed material system (dark-colored boxes) in relation to alternatives (light-colored boxes). The colors are associated with the steps that need to be considered and the dotted lines present segments to consider in parallel with the straight lines.

Green part

As the green part of figure 8.3.4 depicts, the one-way deformation of SMA wires can be implemented into different types of material systems creating three-dimensional deformations. Inspired by the overview of Rodrigue et al., (2017), these material systems can be classified based on how the SMA element has been implemented. Discrete deformations are enabled by rigid mechanical joints and semi-rigid flexural hinges. Continuous deformations on the other hand are enabled by a soft structure whereby the SMA wire is attached to or embedded into the soft structure. This project focuses on continuous deformation with an SMA wire embedded. This reflects the unique characteristics of a flexible organic movement of SMA wires which is new and desired as haptic feedback for VIPs (see conclusion Literature 2.4).

Purple segment

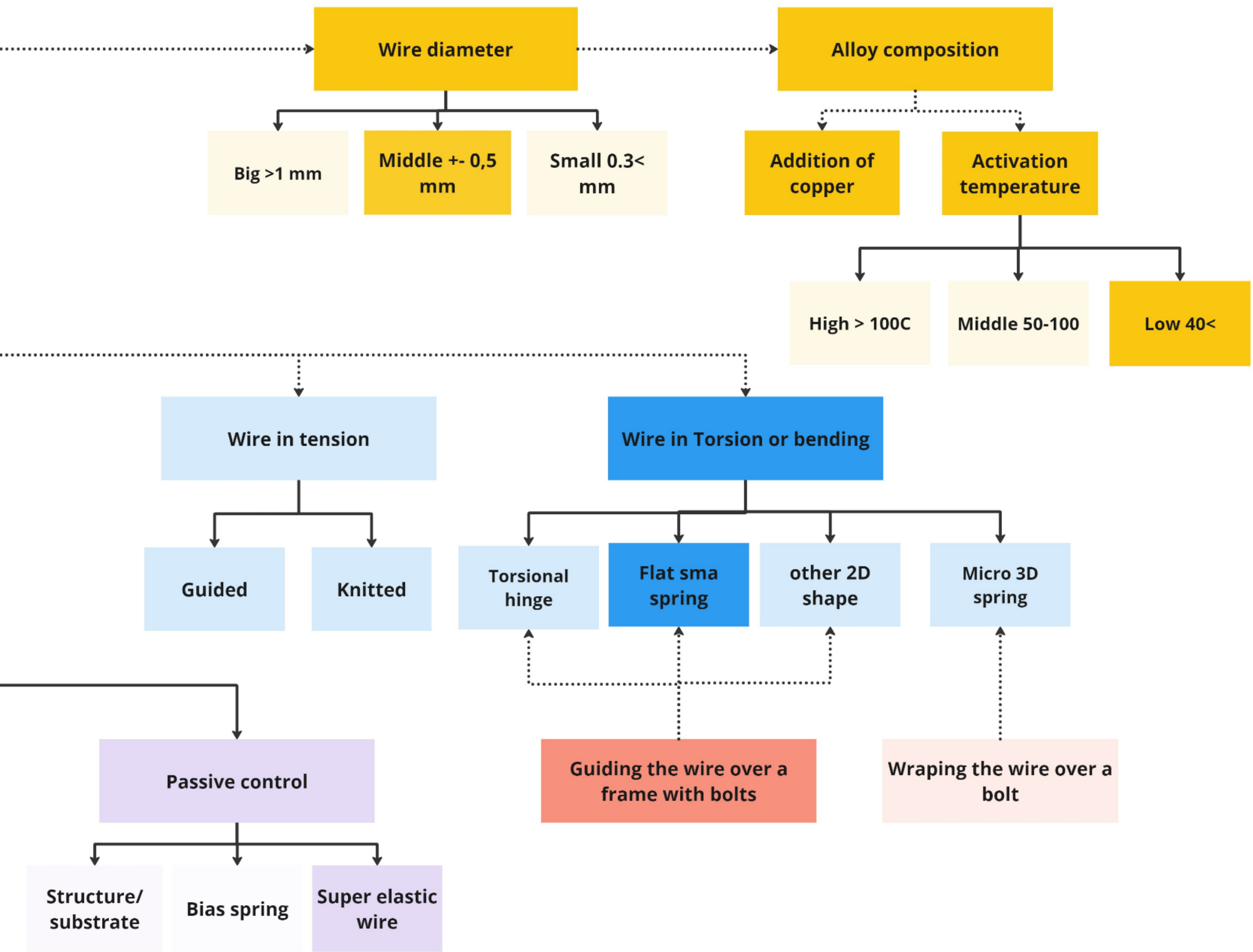
A soft structure with an embedded SMA wire can be classified based on how the counterforce is implemented into the system/structure, which is divided in two categories (shown in purple in Figure 8.3.3). An externally controlled counterforce applied from outside the material system (e.g human actions or skin or external product), or an integrated counterforce either actively controlled (e.g SMA antagonist) or passively controlled.



This passive control can be achieved by the material structure/substrate itself or a bias spring either externally attached to or embedded into the soft structure using a SE wire. This project focussed on integrating a passive counterforce using SE wires since this enables a fully integrated material system that could be used both as a wearable and touchable.

Yellow, blue and red segments (dotted lines)

The material selection (yellow) and load/displacement configuration (blue) of the SMA wire strongly influence the performance and design of the material system and determine the material properties and implementation requirements. As such, decisions need to be made on the type of material (e.g. activation temperature and wire dimensions), as well as in the load/displacement configuration, classified in using the wire in tension or in bending/torsion requiring to train a shape. In this project, the middle diameter (0.5mm) and low activation temperature wire were chosen in a flat spring shape as this enables an easy integration of the wire in the material system and creates a noticeable displacement within a reasonable response time that is safe to use.



MATERIAL SELECTION

To select a material, the alloy composition and the wire geometry are of importance.

i. Alloy composition

NiTi(Cu) alloys are the most popular alloy compositions due to their affordability and reliability (1,2). The exact alloy composition determines the transformation temperature (As-Af range) and the strength of the wire.

Transformation temperature

Adding 0.1 atomic % of Ni above the 50% Ni/Ti decreases the transformation temperature with 10C and increases the yield strength of the austenite phase (1). Higher transformation temperatures increase the response time due to the larger temperature distance to be bridged. For example, a flat spring wire (L=13cm) with 30C and 40C Af had a response time of respectively 4sec and 12sec with 1.3 Ampere (b). To achieve a faster response time, higher Amps need to be applied (in this case 1.8A to achieve 5 sec for a 40C wire).
Note: The As-Af range should be tested beforehand as it varies between manufacturers from 3 to 30 degrees (a).

High > 100C

Middle 50C-100C

Low <40C

Fast response time and no safety issues and possibility to react on body temperature

Strength

The addition of copper decreases the yield strength in martensite and hysteresis, resulting in more malleable wires in martensite and a shorter cycle time (1) and increases the generated force in austenite (3). For example, a 0.5mm wire zigzag with and without the addition of copper resulted in respectively around 2 and 3N of generated force when extended at 20% displacement (c).

+Cu

ii. Geometry

The geometry includes the wire length and diameter. These have an influence on the actuation force, cycle time and power consumption when electricity is used.

Wire length

When activated with electricity the following statement should be taken into account: the longer the wire the slower the response time. A way to increase the response time is to increase electrical power input (1).

Wire diameter

The bigger the diameter the slower the response and cooling time due to the decreased resistance and surface-to-volume ratio (4,5). In addition, the bigger the diameter the less flexible the wire is in martensite, limiting the shape complexity (for big diameters). However, small wires are very flexible to deform but fragile when used other than in wire tension or a micro spring (d).

Small 0.3< mm
+- 40C per sec (5)
F_pull: 12N (Af)-5N (Mf) (2)

Middle +- 0,5 mm
+- 10C per sec (5)
F_pull: 35N (Af)-14N (Mf) (2)

0.5mm wires are easy to shape in a spring and have an acceptable response time of 4-12 seconds with 13cm wire length (b)

Big >1 mm
+-3C per sec (5)
F_pull=115 (Af) (6)

Literature
1 Bengisu & Ferrara, 2018
2 Rao et al., 2015
3 Mail contact with Flexmet
4 Jani et al., 2014
5 Kelloggs nd
6 Shi et al., 2022

Tests
a As-Af testen Chapter 4.3
b Response time test Chapter 7.3
c Generated force is austenite Chapter 7.2
d Exploration of using small wires Chapter 4.2

FORCE DISPLACEMENT CONFIGURATION

To select a force/displacement configuration, the wire can be trained in tension, or any other shape using torsion or bending

Wire in tension/linear wire

Using the wire in tension is the common loading mode due to its reliable and strong force (energy density = 446 J/kg) (1,2). Two ways of designing are commonly used to enable a noticeable displacement with the limited strain of 4%: using a long wire or amplify the strain.

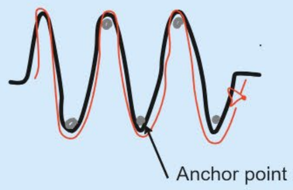
Long wire guidance

Using a long wire requires a controlled guidance of the wire in the material system. For example, to enable 2cm displacement one need 50cm of wire length. This can be done with anchor points in a zigzag shape or by using a knitted structure. Another option is to guide the wire in a tube system enabling to account for safety issues at the same time (3).
Using a long wire length increases the response time when electricity is used (4).

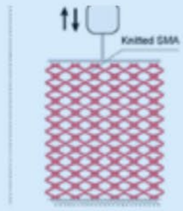
Amplified strain

To limit the wire length in a material system, the strain can be amplified to increase the ultimate displacement (4) by creating a lever system or integrate the wire in a material that could be bend. The downside is the increased complexity of the system. Another downside is that the higher the strain the closer you are to the limit of shape recovery

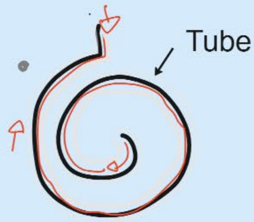
Zigzag guided



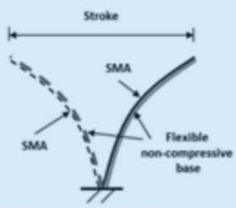
Knitting



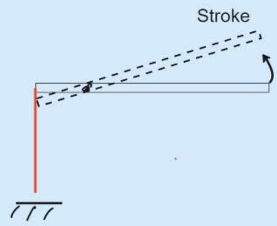
Tube guided



Curvuture



Lever system



Literature
1 Bengisu & Ferrara, 2018
2 Rao et al., 2015
3 Liu et al., 2022
4 Mohd Jani et al., 2017

Trained shapes/ torsion or bending

Torsion and bending loading modes are less used due to the reduced loading capabilities. However, the ultimate displacement can be bigger in a compact shape and more complex shapes/structures can be achieved as a specific shape can be trained (2).

Torsion

Torsion has around 10 times less energy density compared to tension and the most used configuration are springs (4). Micro springs are used for small wire diameters and can be integrated in textiles whereas for normal springs middle wire diameters are used.

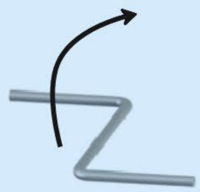
2D Bending

Bending has the least load bearing capacity, around 10-100 times less compared to tension (4). The advantage is the increased ultimate displacement and the ability to create more complex 2D structures which allows for easy integration.

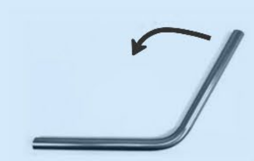
A 0.5mm flat spring with pitch/heigth 10/10mm can enable a displacement of 50-70% with +-100% shape recovery without a counterforce (a) using a force of 0.5-0.6N to deform the wire in martensite (b). In addition, it can generate around 2-3.5N of force in austenite when extended 50% of its initial length (b).

3D Spring

Torsion hinge



Bending bar



Roll up

Flat spring

Tests
a Extension rate Chapter 4.2
b Generated force in austenite and martensite Chapter 7.2

COUNTERFORCE MECHANISMS

A one-way SMA needs something to deform the system in cooled state to enable a shape change when heated.

External counterforce

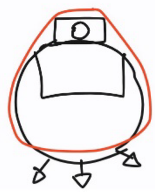
To keep the system simple without extra elements, the counterforce can be achieved by manual actions (1).

Human interference

A faster response time is enabled when no counterforce is incorporated as no pre-load needs to be overcome delaying the response time (3). The downside is that one is dependent on the human reset. When making a wearable, the flexibility of the skin can be used as a counterforce enabling a controlled and simple implementation. The downside is that every skin is different which requires personalized designs.

Human action

Human skin

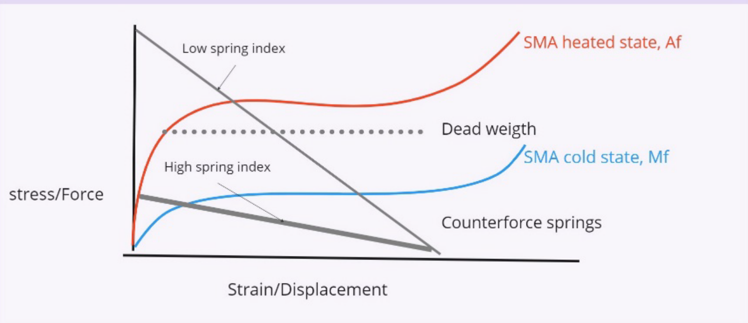


Embedded counterforce

An embedded counterforce enables a two-way material system actuation either actively or passively controlled, and increases the response (2) (a). For all, it is important to find a balance in the material system to create a two way movement:

F_SMA_Af > F_counterforce & F_SMA_Mf < F_counterforce

The graph below shows the arrangement consisting of the SMA wire and counterforce response overlap on a stress/strain plot (1).



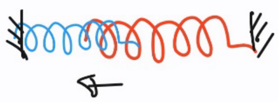
Literature
1 Rao et al., 2015
2 Ameduri, S. (2021)
3 Qamar et al. (2018)
4 Andani et al. (2015)

Tests
a Technical evaluation of structure Chapter 9.3
b Impression of force/displacement of SE wires Chapter 7.2
c Testing transformation temperatures

Actively controlled embedded counterforce

When an active control is desired, an SMA antagonist can be used. A SMA antagonist can only be used with electricity and it is important to incorporate the cycle time of the SMA before the counter SMA is activated (1). Besides, the wires need to be isolated from each other to prevent cross heating.

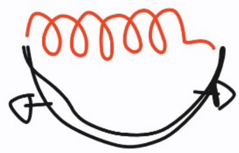
SMA



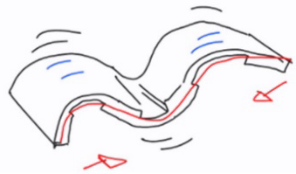
Passively controlled embedded counterforce

A passively controlled embedded counterforce means that the system automatically deforms the SMA wire in martensite. The most common way is using a bias spring, where the force increases when compressed more (see graph). Its slope is determined by the spring index (spring diameter/wire diameter) with smaller indices creating steeper slopes (1).
Another way is to use either the matrix material stiffness or the structure of the material system as a counterforce enabling an integrated material system (3).
Another form of bias spring is using a SE wires. These exhibit spring behaviour and can be shaped in any form due their SMA character, enabling complex movements and an integrated material system (4) (b).

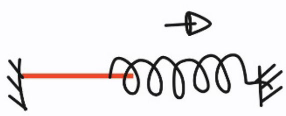
Structure



Material stiffness

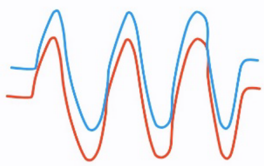


Bias spring



A 0.35mm SE shaped flat spring (H/P of 8/17 mm) is used to create a counterforce for a 0.5mm SMA flat spring wire, producing a force of around 0.5N when compressed 39% (b). As with 3D springs, the force seems to increase when more compressed.

SE



SHAPING SMA WIRES

To train a shape for SMA wires the wire need to be annealed in a ceramic oven in its ground shape

i. Annealing conditions

The annealing conditions are of crucial importance for the thermomechanical properties with the transformation temperature and strength being influenced the most (1).

Annealing conditions

The thermomechanical properties stay stable after 15 min of heat treatment and are strongly influenced by the annealing temperature using a 1 mm wire (1). The annealing time is influenced by the wire diameter (2) (the bigger the diameter the longer the annealing time)
Between 400-600C a SMA wire of 1mm shows a stable but linear increase in transformation temperature (1). Experimentally tests show that 0.3 and 0.5mm Nextmetal wires with transformation temperatures of 30C and 40C show around 1C increase of the intitial transformation temperature after annealing at 500C for 15 min (a). When annealed at 550 for 30 minutes, the increase was 10 and 20C for respectively 30C and 40C wires. To train SE wires, annealing conditions of 500C for 10-20 min are required.

Temperature
500C (1,2,a)

Time SMAs
15-30 min (2, a)

Time SE
10-20 min (2, a)

ii. Water quenching

After annealing the wire, it is water quenched together with the mould using a water bucket to cool the wire to ambient temperature.

Water quenching

Literature
1 Yoon and Yeo (2004)
2 Mail contact with Flexment
3 Rao et al., 2015

Tests
a Testing transformation temperatures (Chapter 7.1)
b Exploring wire detaching methods

iii. Wire shaping

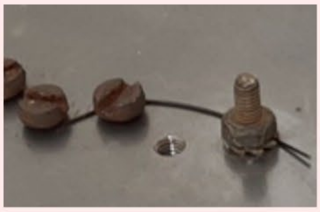
To create a desired trained shape the wire needs to be annealed in the deformed shape including two steps: attaching the wire to a mould for fixation while annealing and freeing the wire after annealing.

Attaching the wire to the mould

Guiding the wire involves guiding it over the bolts and fixate the wire only at the ends using nuts and bolts to enable a smooth and consistent shape repetition.
This can be done using a grid, which is especially desired for rapid shape explorations based on the predetermined holes. In this way, the bolts are fixated using nuts to the grid first and the wire is guided and fixated at the ends with an extra nut.
To create a more specific shape, a steel mould can be made using a milling machine to create screwdread holes. The bolts can be screwed in a mold and the wire can be guided over the bolts and fixated at the end using a smaller bolt and nut the other way around.
In both cases, a considerable thickness (>3mm) and equal geometry should be selected for the mould to prevent warping.

Grid

Mould



Freeing the wire from the mould

The wire needs to be carefully detached from the mould to prevent permanent deformation due to overstraining the wire. In this small diameter wires (<0.3mm) are more fragile (b).
For detaching 3D SMA spring wires, screwing the wire over the bolt is advised (b).

Screwing method

STRUCTURE INTEGRATION

To train a shape for SMA wires the wire need to be annealed in a ceramic oven in its ground shape

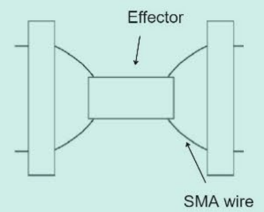
i. Shape changing mechanism

A material system based on SMAs can create a discrete or contineous movement. In this project the focus was on crearing a contineous movement to enable organic haptic feedback. This can be done using a soft structure with an embedded SMA of a structure with an external SMA.

Material system with external SMA

In a material system with an external SMA, several components are combined to create the shape change/movement that comes from the SMA wire, such as in exoskeletons. For example, it can be combined with an end effector to create a drag movement for one specific point.

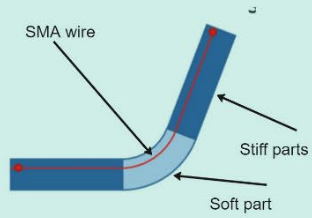
End effector



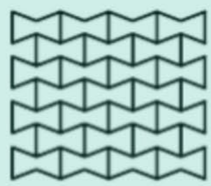
Soft structure with embedded SMA

In a soft structure with an embedded SMA, the SMA wire is fully integrated in the material system, creating a composite. In this, the substrate structure controls or guides the SMA shape change. This can be done using flexible polymers or textiles with different material stiffness or structures such as deployable or stretchable ones (1).

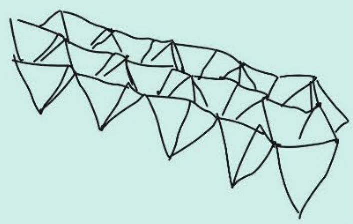
Variable stiffness



Stretchable



Deployable



A deployable structure such as origami, enables a specific shape change in multiple directions. When combined with textiles and SMA it becomes an integrated material system which may carry out both a movement as well as a shape change.

Literature
1 Rao et al., 2015
2 (Rao, & Reddy, 2015)
3 Nabil et al., 2019

ii. Wire integration

To create the material structure the SMA and SE wires need to be integrated into the material system and connected to electrical connections when electricity is desired. When the system reacts on body temperature, the wire should be tightly connected to the body.

Electrical connections

The best and most easy way to connect SMA wires to electrical wires are with crimps compared to soldering or wrapping the eletrical wire around the SMA wire (2, a). To protect the user from the heat build up in the crimps, isolation tape can be used. The power used for an integrated SMA spring (L=13cm) with 3 peaks (H/P=10/10mm) is around 1.3 V and 1.3 A to reach a response time below 10 sec (b).

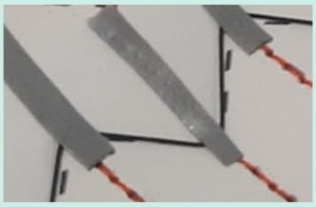
Crimps

Sewing/Textile integration

The SMA and SE wires can be sewn in fabric using a sewing machine. Loose threads and stitches minimize the shape recovery (3, c) The stitch is a zigzag with the stitch length 1 and width 1-1.5 depending on the wire diameter. The SE wire is sewn in first. The SMA wire is extended to its deformed length (the same as the SE trained shape) and sewn in next to the SE wire using 1.5 stich width. To hold the wire in place while sewing ductape can be used.

Stitch size (1.5-1)

Ductape



Tests
a Material exploration 4.3
b Technical evaluation Chapter 9.3
c Textile exploration Chapter 6.3

9 EXPERIENTIAL CHARACTERIZATION

9.0 INTRODUCTION

An experiential characterization has been done to understand the perception of the proposed material structures and the influence of fabric type length on the haptic sensation. This is researched using the four experiential levels from the Material Driven Design (MDD) method (Karana et al, 2015): the performative, sensorial, interpretive and emotional level, see paragraph 1.2 for the MDD method explanation. The main questions revolve around how people interact with the samples, which sensorial qualities are identified and what type of meanings, emotions and associations are evoked. It is hypothesized that all samples create the following qualities and haptic sensations:

1.Upward and contraction movement: a slow pressure increase from the upward 2D-to-3D transition and subtle stroke from the contraction of SMA wires which can be passively perceived when worn or touched by the cutaneous and kinesthetic system.

2.Texture difference through size and curvature (spatial property): the origami structure enables a shape change from a larger 2D surface to a smaller curved 3D surface. This can be actively explored by the cutaneous system by stroking the fingers around the created curves and size.

3.Coldness-warmth (material property): The SMA wires will heat up the surface to a maximum of 40 degrees which can be perceived passively by the cutaneous system.

9.1 METHOD

Participants
Eight participants (4 women and 4 men) aged between 26 and 70 years (the average is 55 years) joined the study. Participants were sighted and recruited via Dutch universities. One participant had earlier experience with SMAs and one participant was aware of the project content.

Stimuli & equipment
Three different samples were presented to evaluate two types of fabrics (sample A and B) and two types of sample length (sample B and C), see figure 10.2. Sample A has three peaks, is 35mm high and 50mm long and is made of textured synthetic double-knit fabric. Sample B has the same dimensions but is made of cotton/polyester satin weave fabric. The same fabric is used for sample C, is 35mm high and 70mm long and has 5 peaks. The samples were positioned on the table and connected with electrical wires to the power supply (1-1.3 A and V) and a camera was placed above the samples (see figure 10.1). The test was conducted in quiet locations either in the materials lab at the faculty or at home. Notes were taken using pen and paper and camera recording was done using a mobile phone.

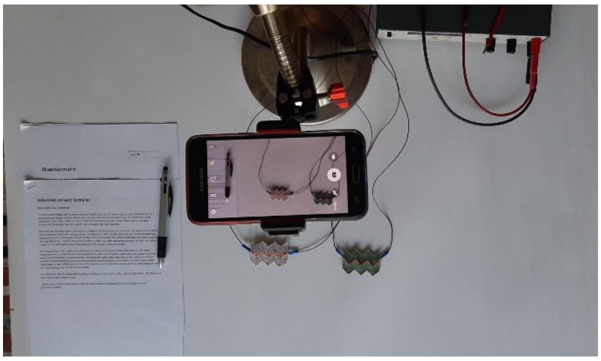


Figure 10.1 Test setup with camera recording

Procedure
The interview lasted 45-60 minutes and started with an introductory talk (see procedure of H3).

Phase 1, passive sample encounter (5 min) : The participant was asked to first interact with the two presented samples (A and B) on the table and express their first impression. If needed guided questions were asked such as '*How would you describe the material?'* and *'Could you describe the difference between the two samples?'*

Phase 2, active sample encounter (10 min): The participant was asked to position his/her hand on sample A and the sample was activated. Again it was asked to express their first expression and questions were asked such as '*How would you describe the behavior of the material?', 'Can you describe the type of sensation and how strong is that sensation?* The same was done for sample B and C and it was asked if they perceived any differences between the samples.

Phase 3, body location (10 min): The participant was asked to point out body locations where they would think it could be worn and felt. The reasons behind the locations were asked and it was asked if the sample fabric and length would influence their choice. Next, the sample was activated on the proposed body location and it was asked to describe the sensation. After the sample interactions the affective and interpretive level of the MMD method were elaborately discussed (15 minutes) using the questionnaire.

Data analysis
The research method was a semi-structured interview (Eelderink, 2016) to enable free exploration of the samples, guided using the levels from the MMD toolkit booklet (Karana et al, 2015) and questions from Parisi, Holzbach and Rognoli (2021). The performative and sensorial levels were analyzed based on observations made from the camera recordings. The interpretive and emotional level and a general reflection were analyzed using a questionnaire, see appendix F on experiential characterization. For the interpretive level, a rating scale was used from 1 to 5, distinguishing two contradictory words from the MDD vocabulary. For the affective level, a graph was used to rate the three most related emotions during the interaction on intensity (vertical axis) and pleasantness (horizontal axis). For both levels, the reason behind the choices was asked.

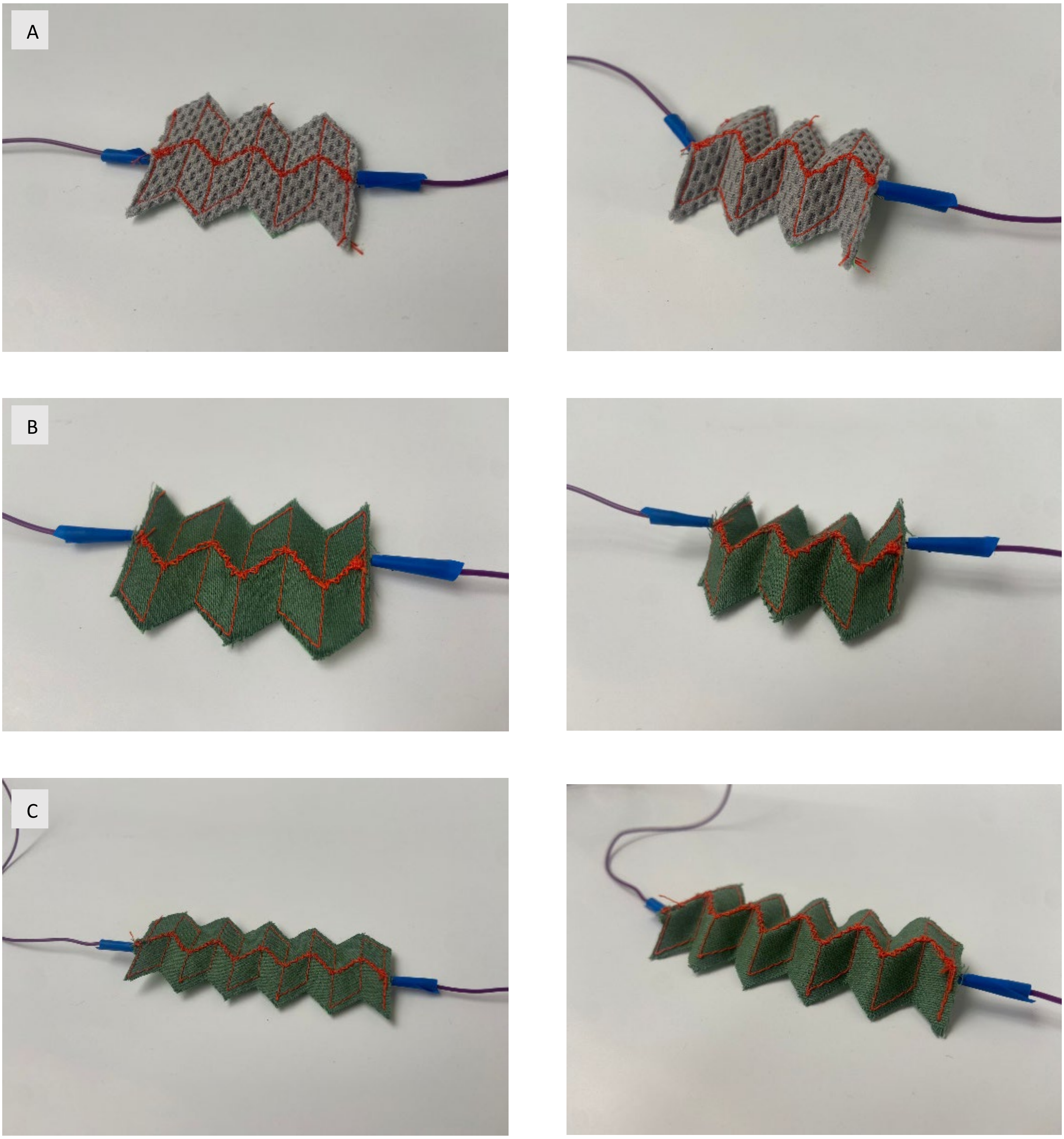


Figure 10.2 Samples

9.2 RESULTS PERFORMATIVE AND SENSORIAL LEVEL

A general observation was that all participants started by pressing and rubbing the samples following the zigzag line in the middle with their fingers (see figure xx for an overview).

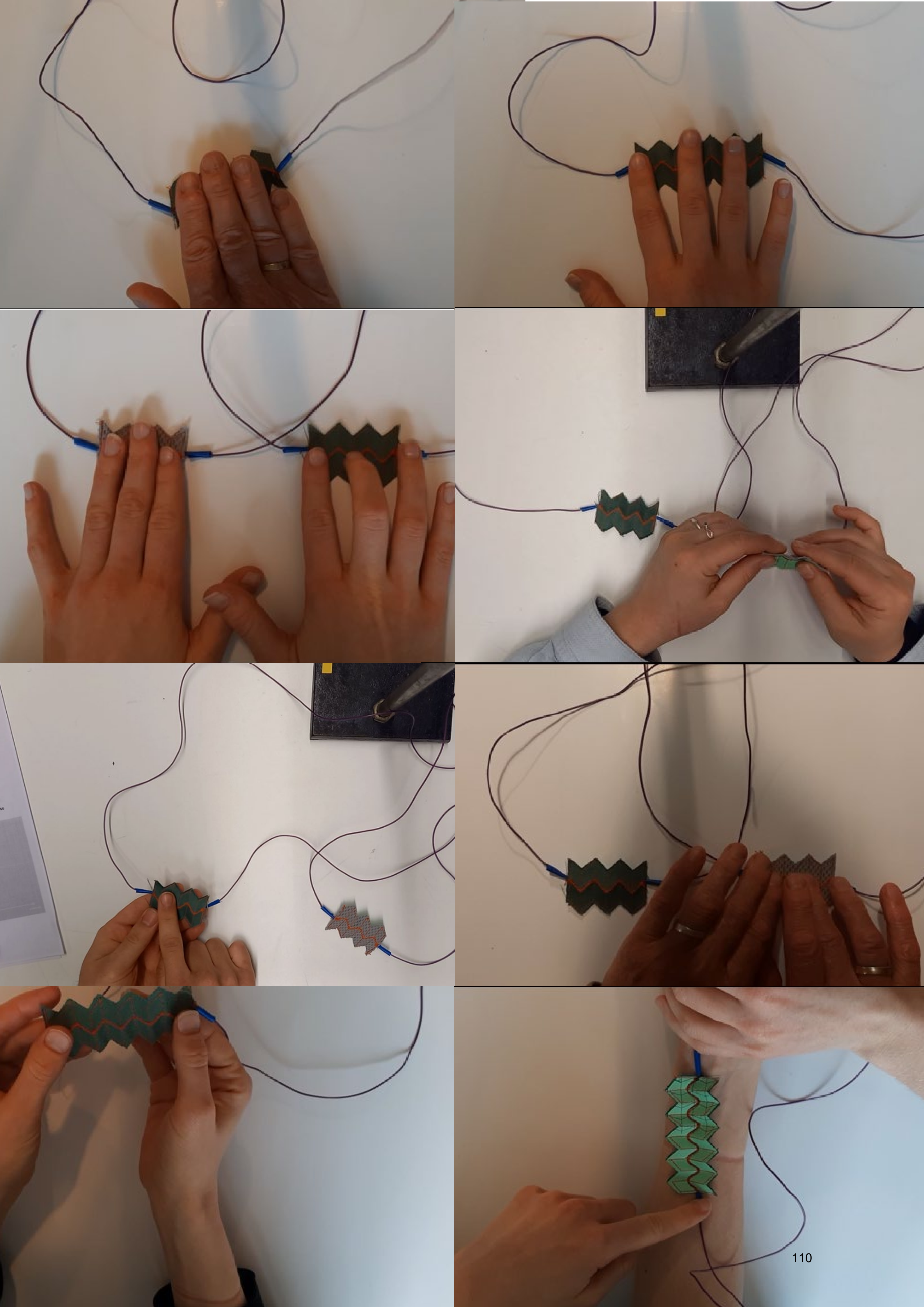
Perceived sensorial qualities
All participants notified an obvious shape change of the material structures from 2D to 3D when activated. Participants agreed on describing the samples in an active state as hard,textured, stiff and noticed a subtle change of coldness-warmth. However, two participants did not mention the change in coldness which probably has to do with the low SMA activation temperature (35C) and the activation time (1 min). Furthermore, all participants felt a subtle upward movement and almost all participants (7/8) identified both an upward and contracting movement at the same time. The combination of movements was also described as the most unique and pleasant quality of the material. Three participants referred to something that was *inflating* and two characterized the movement as *shrinking* and a *harmonica movement.* The identified haptic sensational qualities the change in texture, coldness and upward and contraction movement, are in line with the hypothesis.

Difference in texture
There was a preference towards the grey fabric (sample A) in terms of touching it. Reasons for that were the soft sensation as '*you can indent it'* and '*It feels more like a pillow'* whereas sample B was sensed as stiff, hard and rough with prominent noticeability of the zigzag wire and seams reminding them of *jeans* fabric. However, there was no clear distinction in the perceived intensity of motion.

Difference in length
The sample length had a subtle influence on the perceived intensity of the haptic sensation. 6/8 participants did perceive a more intense haptic sensation for Sample C (five peaks) compared to Sample B (three peaks) with reasons such as *'Now all my fingers are moving towards each other'*. However, two participants perceived no difference in haptic sensation regarding the sample length. One explanation was that when the sample was sensed by hand, he/she sensed the sample with three fingers which were enough to perceive both the contraction and upward movement for both samples.

Body locations and application areas
Most participants (6/8) agreed on using the longer sample when it was worn and all participants referred to the forearm and wrist as possible body locations. Reasons for that were '*the movement is more noticeable for the longer sample which is needed when you sense it other than with your fingers'* and '*You could make a bracelet with a longer sample to create a surrounding squeeze'*. Other locations that were mentioned at least twice were the belly, the chest and the neck (for example, integrated into a collar) with reasons that they were more hidden and you won't be distracted from other tactile information such as on the forearm. Other reasons mentioned for the chest were its high sensitivity, the appearance and that one can touch that place as well.

Based on these locations 6/8 participants suggested the material system to be used for signals such as a warning signal in traffic or healthcare, or as a navigating signal during sporting. It was suggested to integrate it into clothes and to multiply the unit to have diverse signals or to increase the sensation. Other participants referred to a mindfulness object to calm oneself and a shape-changing object that communicates its state.



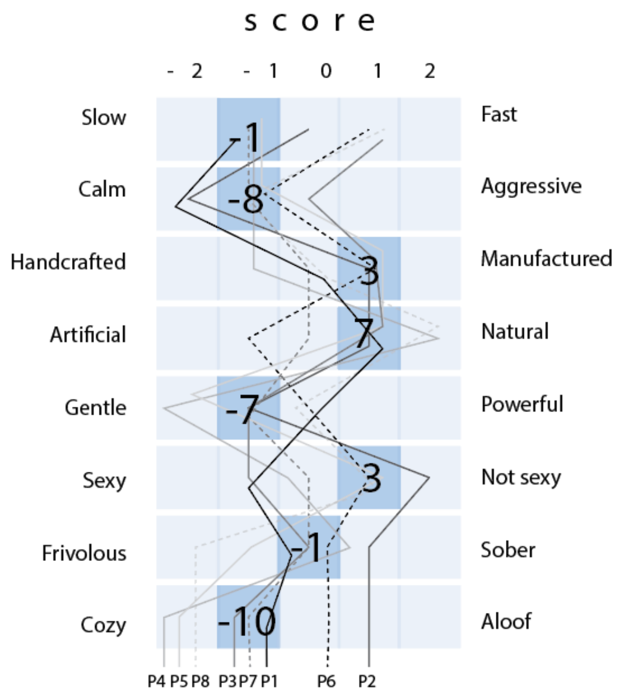
9.3 RESULTS INTERPRETIVE LEVEL

Figure XX illustrates the characterization of motion using antonymous terms. The lines represent the participants and the dark blue boxes denote the most frequently indicated positions, displaying the total score inside (a summation of the positions).

Cozy, Calm, Natural, and Gentle exhibit the highest scores, which is consistent with the hypothesis. Figure XX also reveals that after being asked to select three words from the list that best described the movement *calm, gentle, and natural* were chosen five times. Reasons for selecting these words included associations with natural phenomena, such as *It reminds me of an air mattress that inflates’ "It resembles a flower unfolding"* and *"It feels like a breath, oscillating back and forth so slowly."* The cozy characterization was explained due to the warmth and contraction motion.

Furthermore, the descriptors sexy-not sexy and frivolous-sober exhibit divergent descriptions (scores ranging from -2 to 1), with no clear rationale provided by participants. The slow-fast scores also show divergence, possibly due to differences in associations. Three participants likened the motion to a mechanical apparatus *"It is not as fast as a vibrating motor"* while others primarily associated it with the clarity of the movement *"You truly sense it emerging, and then it transforms"* and *"Indeed, you distinctly perceive its sudden, gradual motion."*

Remarkable is that the score for handcrafted-manufactured leans predominantly towards manufactured. Reasons included participants observing the crafted nature of the object and their unfamiliarity with such a movement as one participant commented *’Never experienced something like this before, it is a strange movement’*



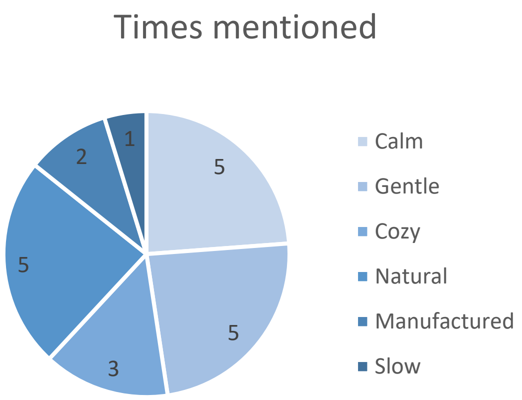


Figure XXX Overview of interpretive score according to MDD method; Figure XX Pie chart of descriptive words that were picked

9.4 RESULTS EMOTIONAL LEVEL

The results of the affective level are presented in a graph on a scale of intensity and pleasantness (figure XX).

As can be seen, the material system evokes predominantly positive emotions where *Curiosity* and *Surprise* were mentioned more than four times by the participants. Reasons for this were the unfamiliarity and strangeness of the movement *'It feels like spiders are crawling on my arm which is weird'* and *'The fact that you can actually feel the gradual movement is something I do not experience in daily life'.* Furthermore, the negative emotions were also related to unfamiliarity. For example, participant 8 referred to rejection with the reason '*It pulls you away which is a kind of rejection'*.

9.5 DISCUSSION

The aim of the study was to characterize the proposed material system on its experiential qualities on a sensorial, interpretive and emotional level. In sum, it seems that all hypothesized sensorial qualities were identified by most of the participants. The texture difference between the passive and active state was clearly noticed while the upward and contraction movement and the increase in warmth were more subtly perceived. The movement was characterized as natural, gentle and calm and evoked surprising and curious emotions due to its unfamiliar combination of qualities. Longer sample length influenced motion intensity perception and was deemed more suitable for wearables, such as wristbands and clothing integration. The activation of the sample on body locations other than the finger was difficult to examine as the sample was not fixated on the forearm but rather held there by their own hands. As this part was not the primary focus of this study it was purely purposed for giving an indication. In future research, this could be improved by using a compression bandage to fixate the sample as one of the participants mentioned. Furthermore, there was no clear difference between the fabric type on the motion intensity, although the elastic fabric was perceived as softer in the passive state. A more comprehensive study, specifically centered on the impact of fabric, could potentially be undertaken in the future to truly grasp its influence.

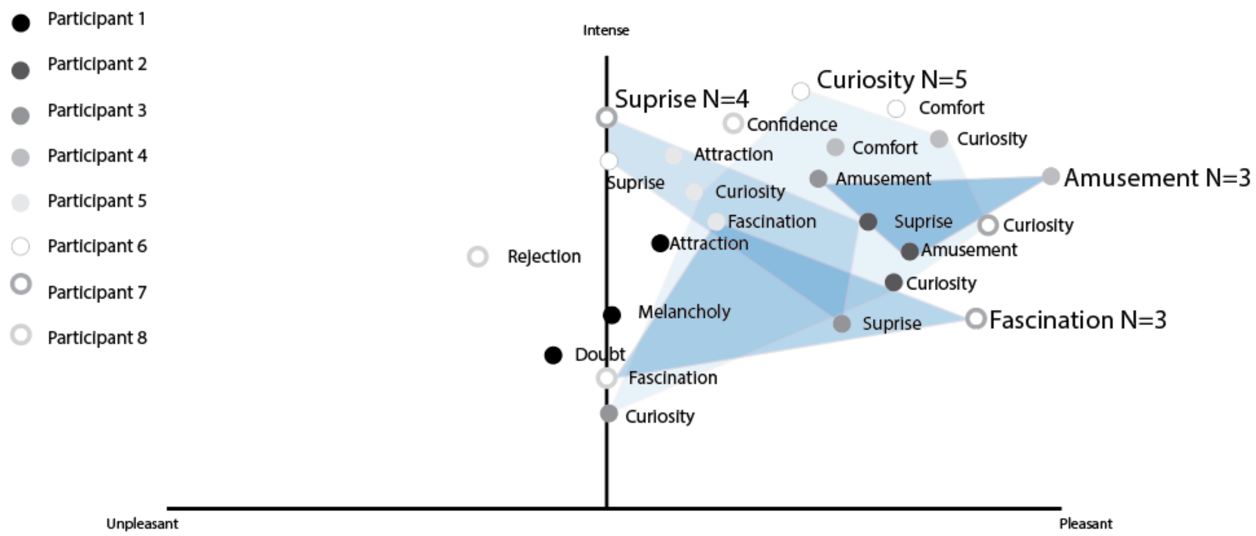


Figure XX

10 ADDED VALUE FOR VIPS

10.0 INTRODUCTION

This chapter describes the added value of the proposed material system based on SMAs for visually impaired people. As mentioned in the previous chapters, the focus was on designing a unit that can be used in multiple ways, being a wearable or touchable with or without electricity and including different types of tactile cues such as the upward and contraction movement, warmth-coldness and the difference in texture. To understand what the added value of such a system is and in what way it can be of value, the designed material system is evaluated with an expert on touch perception and visual impairment. Subsequently future directions are identified that show the potential of a material system based on SMAs for VIPs.

10.1 INTERVIEW WITH EXPERT

An interview was done with an expert on touch perception, in part because of her living with Usher syndrome. The aim of this interview is to evaluate the added value of the proposed structure and identify future application areas.

10.1.1 Method

Participant profile

The expert (female) was recruited through the Delft University and has Usher syndrome which is a rare genetic disorder characterized by a combination of progressive hearing and vision loss. Currently, has limited hearing capabilities and a tunnel sight of 8%. She did work as a Legal expert at the Supreme Court's research department. Currently is she working as a Shiatsu therapist and doing research about tactile perception for people that have limited sight and auditive capabilities.

Stimuli & equipment

Several samples were made to demonstrate the proposed haptic sensation including different fabrics, as shown in figure 10.1).

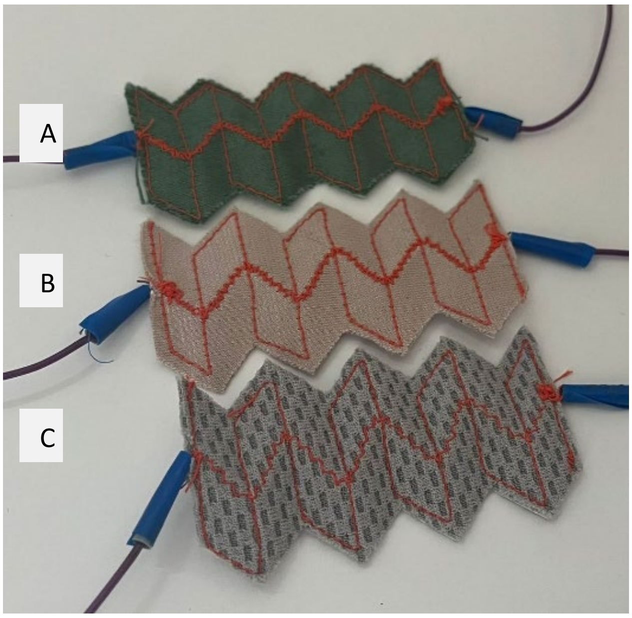


Figure 10.1 Sample overview

Procedure

The interview lasted 120 minutes and started with an introductory talk (see procedure of H3 Target group). First, the samples were evaluated (20 min) in the same way as described in the experiential characterization to evaluate the perceived sensations, without the additional questionnaire about the performative and emotional level. Second, a brainstorm (60 min) was started about the possible application directions taking four scenarios as starting points: the structure being wearable or graspable/touchable, and the activation with or without electricity. Each scenario was discussed one by one and relevant applications scenarios were evaluated.

10.1.2 Results on sample perception

Haptic sensation identification

The different states of shapes, as well as the upward and contraction movement, were easily noticed with the hands. The participant described the sensation as *'The shape transforms unrecognizable'* and *'Your fingers are really lifted and brought together'.* In this, the size of the zigzag did not matter. When discussing the pressure and contraction movement, it was mentioned that pressing the skin is probably more effective than a contraction movement resulting in a stroke/drag. It was brought up that pressing the skin involves the connective tissue whereas contracting/stroking the skin most likely only involves the skin surface resulting in less sensorial range.

When the sample tried on the upper arm the sensation was clearly less noticeable. This could be due to the improvised setup where she holds the sample to the upper arm herself: It was difficult to press the sample against the upper arm in such a way that the pressure created with the sample was noticeable.

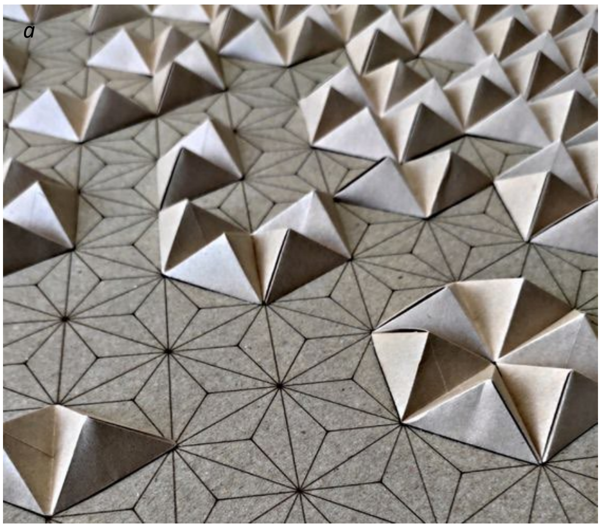
When comparing the three different fabrics, sample B evoked the most pleasant emotions as it felt soft and the zigzag line was subtly perceived. Sample A was perceived as stiffer and Sample C was perceived as one integrated fabric as the zigzag wire was least noticeable.9

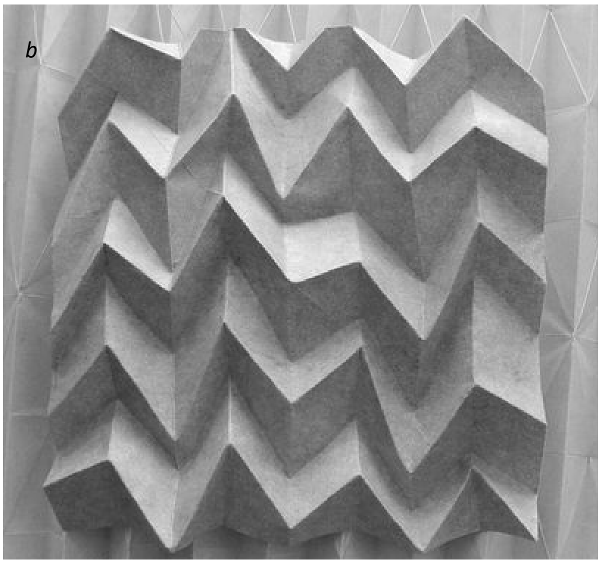
Tactile diversity and learning curve

Overall, the origami structure was perceived as inspiring and was seen as potential for conveying tactile information: *‘With this origami material, you could create a language in tactile information that can be much richer, more immerse and more dynamic versus vibration’*.

Especially when different tactile signs could be conveyed which was highlighted as an important requirement. A way to provide a variety of tactile feedback is by placing several units apart from each other in sequence or segregated (figure 10.2.a). In this way, patterns could be created by activating single units or sets of units for specific types of information. The advantage of separate activation is that you are not dependent on finishing the cycle time of each wire which could enhance the speed of usability. Another suggestion was to embed different wires in one big origami structure to activate specific wires resulting in specific patterns. In this, the type of fold (Figure 10.2.b) can be varied or different wire shapes in the same fold (Figure 10.2.c) can be applied to create different haptic sensations.

Another aspect that was mentioned is the learning curve of touch perception for VIPs that should be incorporated in the design. Every person has a different learning curve regards to how detailed they can sense tactile information. Someone, that does not have much experience with haptic devices could start with more obtrusive tactile information while others that have more experience prefer more subtle tactile information.





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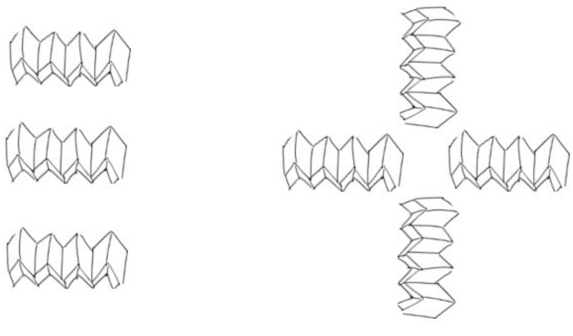


Figure 10.2 illustrative examples of the unit used in separate elements (a), in one structure with different origami folds (b) and in one structure with the same fold (c)

10.1.3 Discussion on future directions

Future application directions for the proposed material system were discussed for a wearable, touchable system with or without electricity.

Wearable system for non verbal communication
First Social haptics was mentioned as a relevant wearable application area for the proposed material due to the desire of noiseless and subtle feedback without interference of one's hearing. It was suggested to make an adjustable surrounding strap which could be placed around the upper arm or upper leg as these locations are less noticeable compared to the forearm which is preferred in social interaction. In specific she mentioned the importance of social haptic signs when giving a lecture:

When I give a lecture, I have little idea of my surroundings. I then often ask someone behind me who gives me basic information about whether people are paying attention, whether they like my joke, and what angle the question is coming from. It is very visible that someone is giving me that information. If I have such a strap on, then an interpreter can just sit down and give me that information passively.

The application area of getting more environmental cues in social interaction (either with giving a lecture or at a social event) is in line with the previous interview outcomes where nonverbal communication was identified as a daily obstacle (chapter 3). In addition, the information that is exchanged during a typical social interaction is for 65% nonverbal of which 72% is visual (Knap, Hall and Horgan, 2013). These non verbal visual communication encodes facial expressions, eye contact and body and hand gestures. According to a study from Krishna et al (2010) with 25 visually impaired, access to body mannerism, facial expression and eye contact are the most wanted needs for social interaction.

Wearable system for proprioception
Another wearable application that was suggested as relevant for the proposed material system is in assisting in orientation and the proprioception, the sensation of body position and movement (Tuthill & Azim, 2018). Unlike sighted people, VIPs cannot use their visual cues to maintain balance or have a sense of orientation:

'*I have to do a lot with my propioceptive because I cannot see if I am sitting straight, I cannot see if I am holding my cup straight or how I am bringing it to my mouth. All those things are not corrected with my vision.'*

This is also related to social haptics, as body mannerism in social interaction seems to be the most wanted need according to Krishna et al., 2010).

In addition, the outcomes from the interviews on identifying obstacles in daily life showed that a general sense of orientation was desired as an obstacle was the lack of orientation when for example distracted (see chapter 3).

Touchable application for education
A touchable system for the proposed material system that was mentioned as relevant, was in course material to learn visually impaired children abstract concepts such as depth and space. This seems to be difficult for children as it is hard to imagine a sense of depth and space without ever seeing it:

'That's where your material would be very interesting, precisely because it can be dynamic. It can be flat, and fluently it becomes 3D and can become 2D again. And that's how you develop a tactile perception of such concepts in the brain.'

Touchable system without electricity
When discussing application areas without the use of electricity, it was mentioned to apply the material for notifying the level of hot water in a cup or integrating it in a ceramic cooking plate as these lack buttons:

'These just don't have buttons anymore which is very convenient for cleaning and so on, but for a visually impaired person it's very inconvenient. So you can think of something that you can make the

knobs flat for cleaning, and become 3D when you want to use them.'

However, these were identified as nice-to-have devices rather than fulfilling a relevant need.

Future directions

Based on the interview results in chapter 3, the experiential characterization in chapter 8 and the material system evaluation with an expert on touch and visual impairment described above, three future directions are identified for the proposed material system for VIPs that match the SMA characteristics the most: Non verbal communication, proprioception and learning concepts. These areas benefit the noiseless and less intrusive unique characteristics of SMAs and will be explained in more detail in the next chapters.

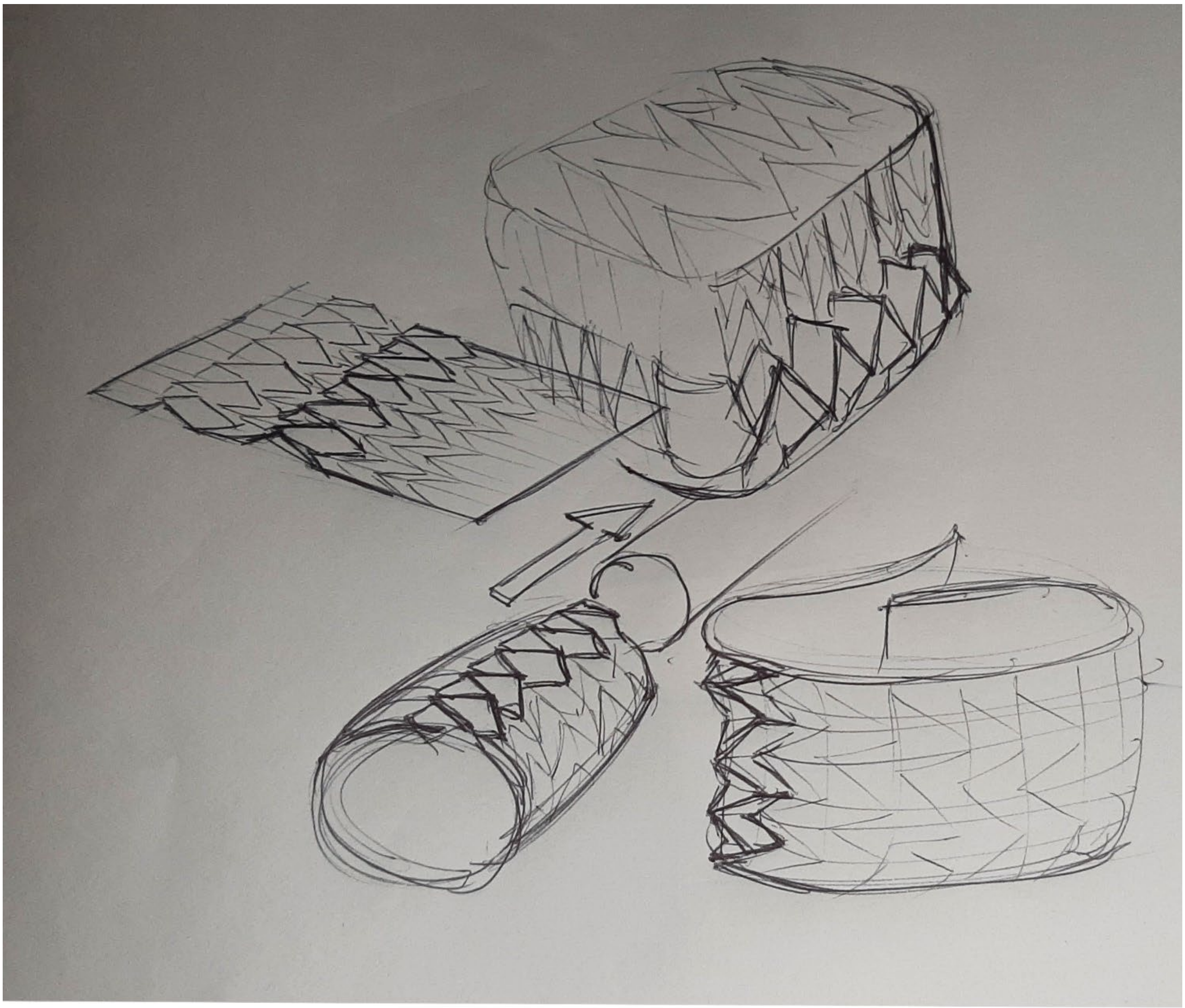


Figure 10.3.1 Material system integrations

10.2 NONVERBAL COMMUNICATOR

The proposed material systent could be relevant as a silent and subtle tactile communicator about facial expressions and eye contact while not hindering the conversation. The material could be integrated in two upper arm or leg sleeves connected to a camera through Bluetooth that detects facial expression and eyes contact from left or right and translate this to a pressure and warmth sensations. The choice of these areas are to free the hands while socially interacting (for social cues such as handshakes) and be not too visible which is desired by VIPs (Krishna et al., 2008). The advantage of placing it on the upper arm or legg is that the patterns are also actively perceivable with the hands if the pattern is unclear. The facial expressions can be translated to a symbolic level to translate the six basic emotions: happy, sad, surprise, anger, fear and disgust. In this way, the user can detect when and from where someone is making eye contact and get a global impression of their facial expression, see scenario 10.3).

The tactile information of the emotional state can be conveyed by using 7 discriminative points, making intuitive patterns that symbolizes the emotions, as researched by Krishna et al (2010) and Plaisier & Kappers (2021) who used vibrational patterns. These points should be placed 2-3cm from each other in order to be perceivable on the back (when integrated in the BiPed), legg or upper arm (Machnini et al., 2014) (see figure 10.4).

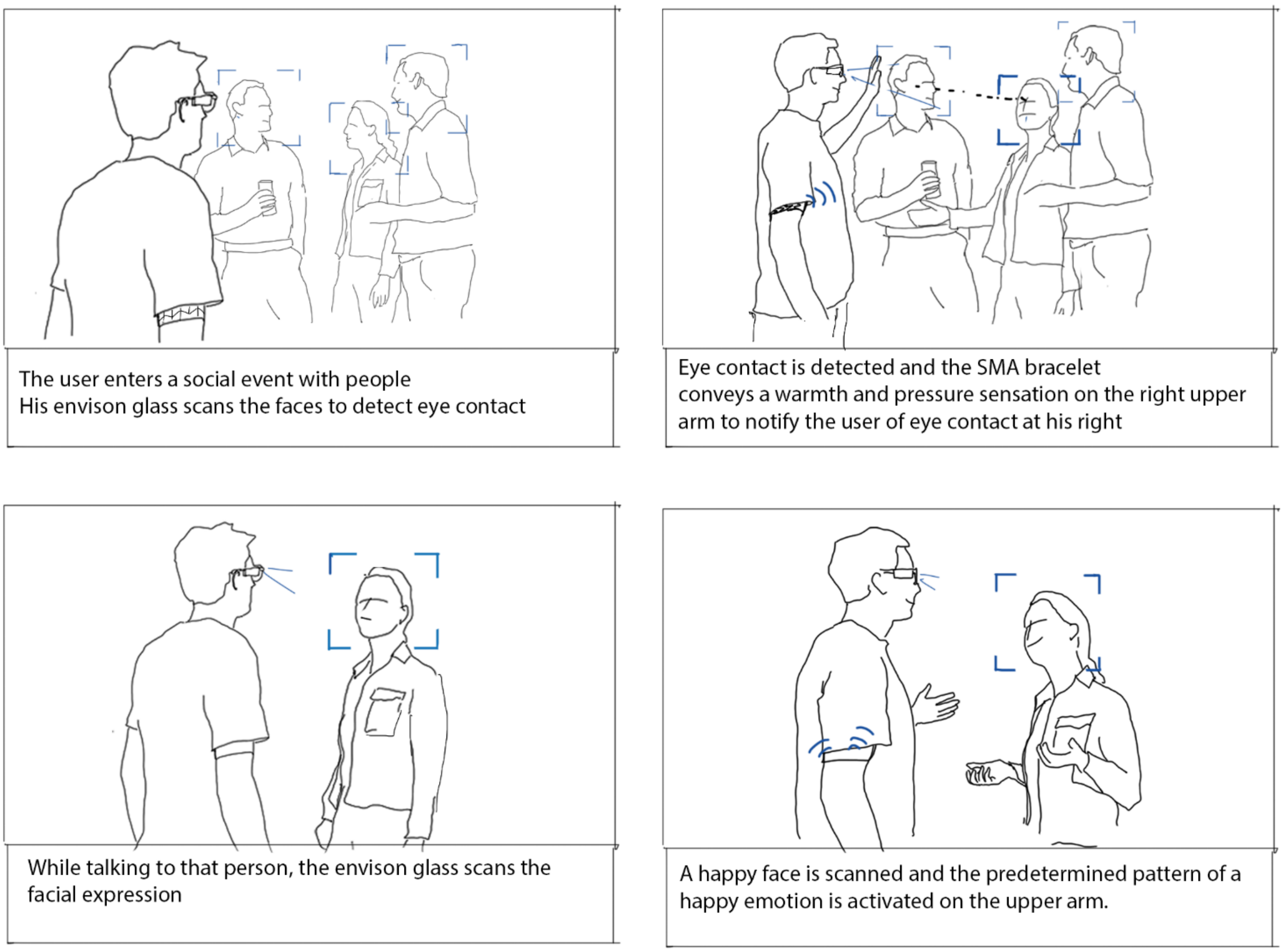


Figure 10.3 User scenario of implementing the material system in a wearable for non verbal communication

The activation temperature of the SMA wires should be slightly above body temperature, e.g. 43-45 degrees, so that less power is needed to activate the system like proposed in the previously discussed compression garment of Granberry and Holschuh (2017) (paragraph 2.4.3). The camera could be worn as a necklace or belt as suggested by the interviewee. Another option is to combine it with an already available assistive devices that include a camera such as the envision glass or Biped.

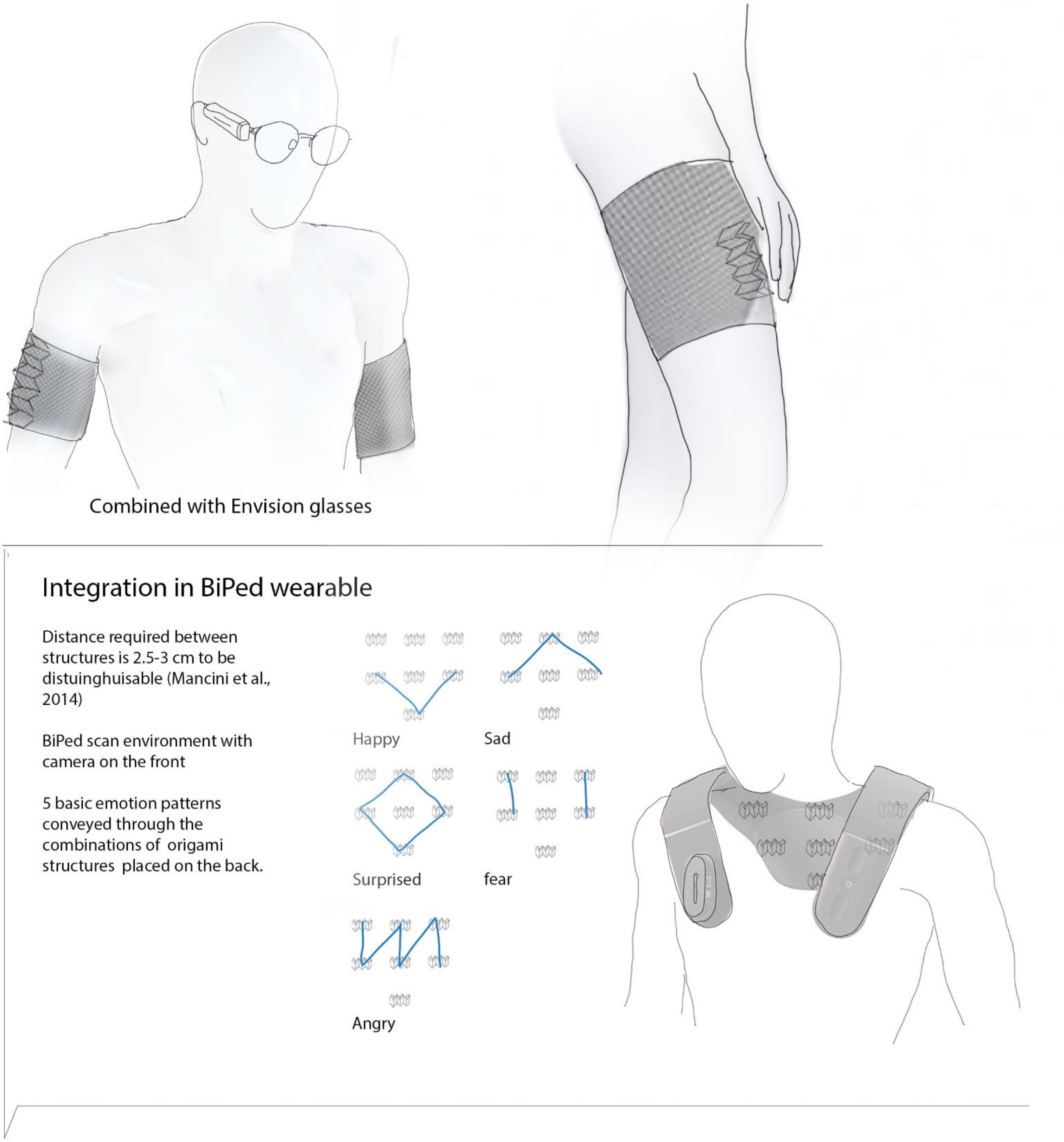


Figure 10.4 Detailed explanation of wearable system

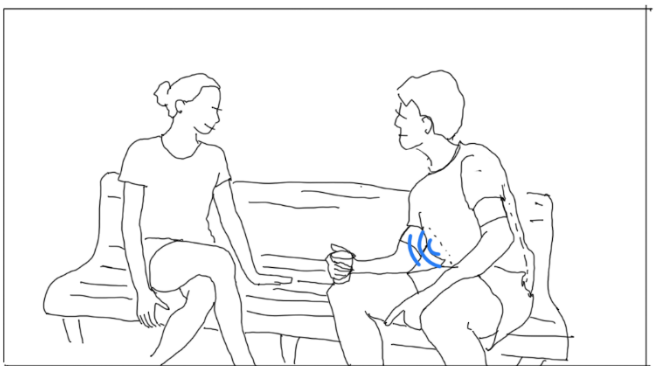
10.3 PROPIOCEPTION WEARABLE

The proposed material system based on SMAs could be beneficial in this area as it could convey subtle and silent information through a smart textile that could activate the propioception any time and moment. Visually impaired people have a poorer control of their postural performance, such as natural upright standing, compared to sighted persons due to the lack of visual cues (Ozdemir et al., 2013).

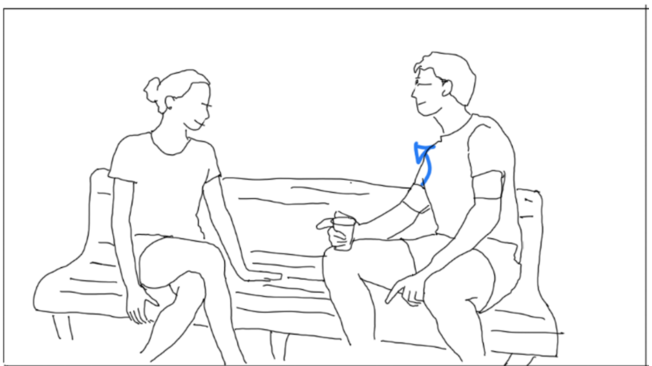
To improve this, a bundle of wires could be integrated in a smart textile t-shirt or belt and combined with muscle sensors to detect its body posture, specifically on the torso sides (as proposed by the interviewee). The aim of the smart textile would be to remind VIPs of being aware of their propioseption and notify the user about their balance or general orientation. This could be beneficial when overstimulated or having a conversation where a lot of concentration is required and the awareness of the proprioception could be forgotten. By notifying the user of his imbalanced posture or just sending a reminder of being aware of his/her proprioception could be helpful to generate socially acceptable body mannerisms.

In addition it could give a sense of orientation in relation to the environment such as notifying were North is, by connecting it to a smartphone app, like is done in the Feelspace assistive device. Using the proposed material system gives a more natural haptic sensation compared to vibrations, and could potentially feel like someone is correcting your posture by his hands.

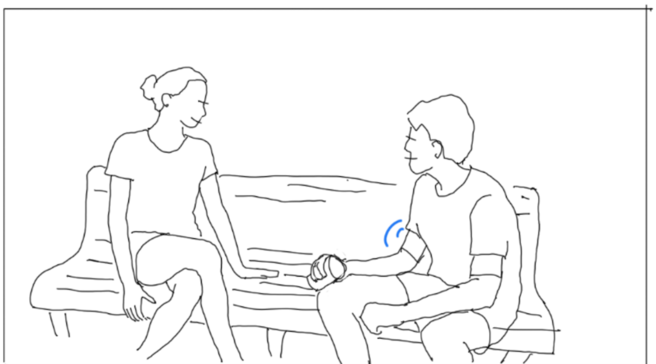
The embedded SMA wires should have an activation temperature above body temperature, e.g 45 degrees.



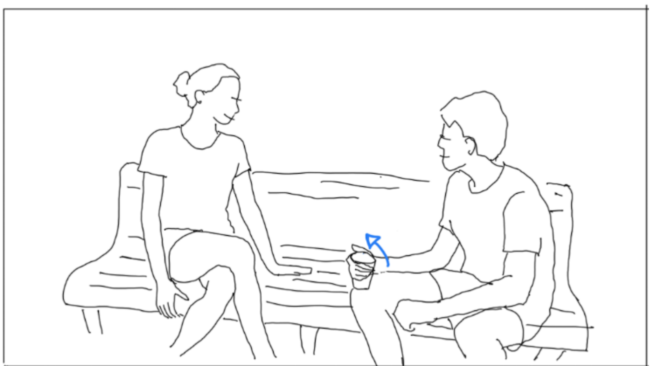
The user talks to someone and wears a smart t-shirt
The device detects that user is leaning towards one side and gives a pressure feedback on the the corresponding side



The user is subtly reminded of his propioceptic position in the interaction and corrects to a straight posture while talking



The smart shirt detects a slow rotation of the arm and gives a pressure sensation to the corresponding arm



Users is aware of holding his glass again

Figure 10.5 User scenario for implementing the material system in a wearable system for proprioception

10.4 LEARNING CONCEPTS

The proposed material system could be relevant to teach VI children abstract concepts due its dynamic shape change and possibilities in shape complexity. Education is highly dependent on visual representations and spatial concepts such as depth or occlusion are therefore difficult to learn for VIPs requiring adapted and accessible tools. Learning by touching tactile models significantly increase the ability to identify and understand certain terms and concepts (Jones et al., 2004). An interactive way of explaining such concepts with touch is proven to be even more efficient compared to explaining it with static objects such as the Raised Line Method (RLM) (Giraud et al.,2017).

By using the dynamic shape change of the proposed structure in a toy, children are interactively guided in the change of shape. For example, the concept of depth could be explained by a 2D plate that moves up while touching it and goes back to flat when releasing your hand. Or the term occlusion could be explained by an origami structure that slowly captures your hand.

Since the SMA and SE are trainable, a variety of shapes could be designed to explain certain concepts in combination with different origami folds. It also gives opportunities for teachers to modify different designs as it requires a simple integration of the wires in textile and paper using a sewing machine, something that is desired according to Giraud et la. (2017).

The system could work with or without electricity. The activation of the SMA wires should be between around 30-40 degrees which ensured a safe interaction. It can be activated using a heat blower to 30-40 degrees while the user is touching the toys, enabling a magic movement. Ideally, the toys react on body temperature allowing a very simple and intuitive interaction.

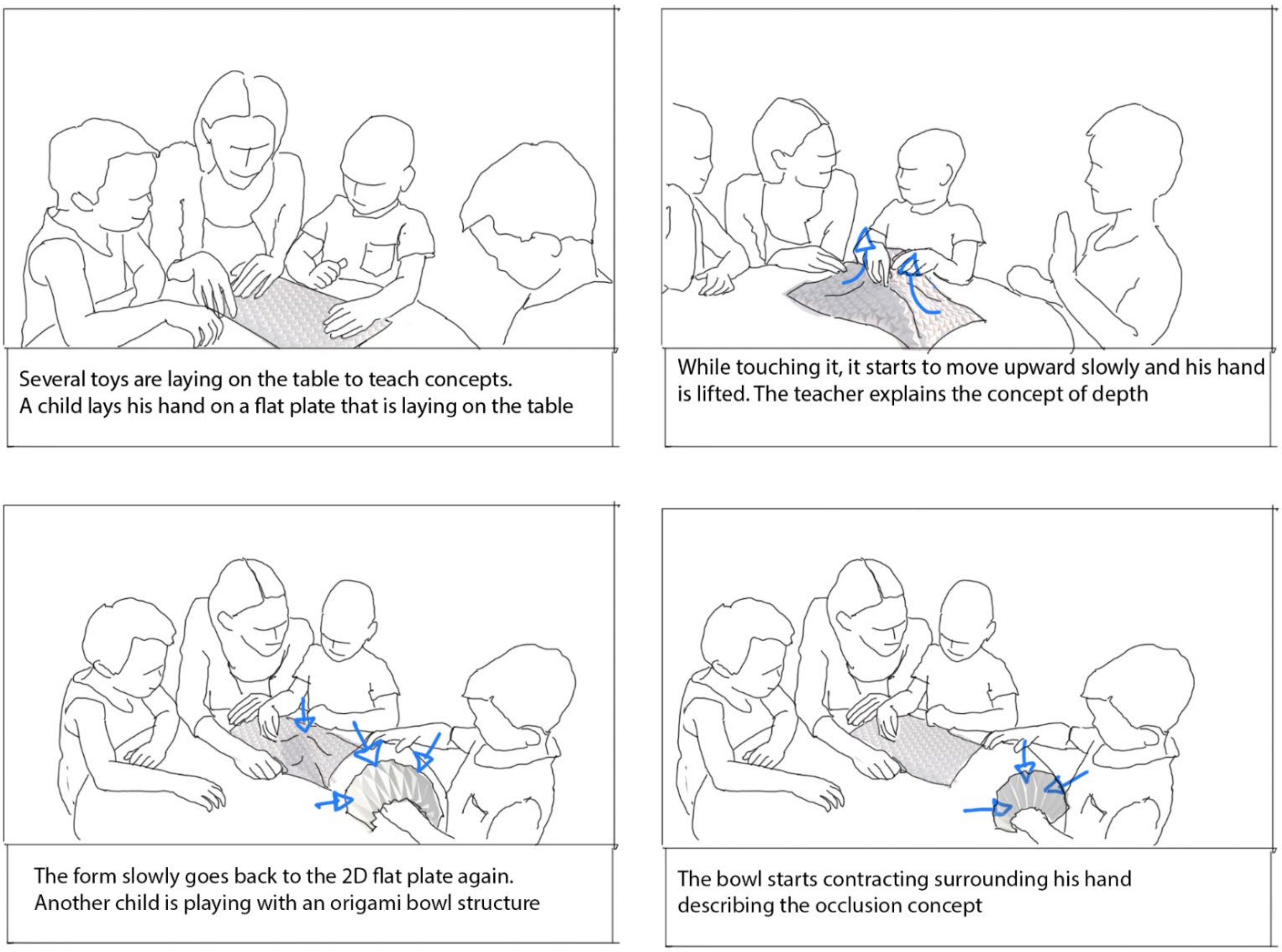


Figure 10.6 User scenario for implementing the material system in a touchable system for learning concepts for VIP children

11 DISCUSSION & RECOMMENDATIONS

11.0 INTRODUCTION

The aim of this graduation project was to explore the potential of a material system based on SMAs for visually impaired people. The focus was on showing the unique characteristics of SMAs and translating this into an integrated material system that could inspire designers to adopt these materials in future applications. The process had an explorative nature and included a research, form configuration and embodiment phase.

Based on the research phase it was concluded that many material systems based on SMAs for haptics were researched but none of these explored the possibilities of training a specific shape with the SMA in combination with SE wires as a counterforce, actually using the ability to design a 'memory'. In this way, more integrated complex shapes and displacements could be potentially achieved. Also, the integration of low temperature wires was represented limited in the literature. Secondly, the implementation of low temperature wires was explored, which could potentially solve safety issues that occur when using high temp wires. Additionally, they have the potential to be used without electricity and react on body temperatures.

Based on the form configuration phase, an integrated material system unit was made including a flat SMA and SE spring integrated in a textile and origami paper. The system aimed to change its shape back and forth generating three-dimensional haptic feedback. The usage of a 2d trained shape for the SMA and SE wires enabled an easy integration (of the SMA wire) in textile and an integrated counterforce (SE) at the same time. Combining this with an origami structure a three dimensional shape change is enabled from a 2D movement, providing rich tactile feedback. In addition, a guideline was developed for SMA wires based on all the research and explorative findings with the aim to give an overview of all steps involved when designing a material system based on SMAs. Overall, this project demonstrates that there is potential of creating an integrated material system based on SMAs, however, there is still a lot of room for improvement in order to verify its working principle.

This chapter aims to discuss the limitations, implications and recommendations of this project. First several discussion points are described for material system itself as well as the implementation possibilities for visually impaired people. Second, recommendations are outlined to improve the proposed material system and how to develop it further to be applicable for professional products. Finally, a reflection on the design process and outcomes is given.

11.1 DISCUSSION POINTS/LIMITATIONS

11.1.1 Material system unit

The advantage of using a combination of SMA and SE flat springs is to enlarge the displacement in a compact area (compared to SMA straight wires) while easing the integration in material systems (compared to 3D springs). The proposed material system manages to generate an initial displacement of 17.5% and return almost entirely to its deformed shape by the use of an SE wire enabling an ultimate displacement of 15.5%. This demonstrates the potential of using a trained SMA wire in addition to an SE wire as a counterforce. However, additional work needs to be done to verify the working concept of which the most relevant discussion points are listed below.

Small displacement and forces

The achieved displacement of the proposed system is bigger compared the tension strain (4%) but smaller compared to 3D springs (50-200%). An explanation for this amount of displacement in the is the small window of possible displacement that the SMA and SE flat springs are inherent to, due to their spring like behavior and their limiting produced force. Just like SMA 3D springs, it was discovered that the produced force of the SMA shape when heated, decreased when reaching its trained shape (see paragraph 7.2). At the same time, the produced counterforce of the SE shape increases when compressed more. The same principle is applied the other way around when the system is not activated and goes back to its deformed state. The combination of the two leaves a small window where the SMA-SE combination can work, in this case around 16%.

In addition, the absolute produced force difference between austenite and martensite for flat springs is small (respectively 3N vs 0.5N for a NiTiCu 0.5mm flat spring) compared to a wire in tension (respectively 35N vs 14N for a 0.5mm SMA wire (Rao et al, 2015). This is due to the fact that flat springs use a bending loading configuration which has less energy density compared to a tension loading condition (Rao et al., 2015, leaving a small window where the material system can function: F_counter>F_SMA_martensite & F_counter<F_SMA_austenite. However, this small displacement and force was not a big issue when evaluating the material system's haptic sensations with users. Using a three-dimensional shape change (upward movement due to the origami), the small displacement was easily noticed, as well as for demonstrators with less initial displacements. Based on this finding, it seems that the tactile sensation does not have to be very intense to sense it. Moreover, the origami structure accelerates the initial movement in three-dimensional way that is more noticeable.

Shape recovery

Another limitation/observation is that the SMA flat spring in the material system did not fully recover its initial (contracted) trained shape as the shape recovery is 80% whereas its shape recovery was 100% without embedding the wire in the material system. It seems that the counterforce created by the SE wire and the geometry of the paper limits the shape recovery of the SMA flat spring due to its spring like behavior as explained in the previous section (less force is produced when reaching its trained shape). It is not clear if the SMA spring also undergoes plastic deformation limiting the reliability of the material system, which is recommended to research before iterating more on the material system. Another observation was that the material system did not go fully back to its 2D flat shape as the SE shape recovery was 98-99%, which is desired to see a more drastic shape change. An explanation for this is the stiffness of paper fold lines preventing the system to go flat. A recommendation would be to iterate on making the fold lines as flexible as possible.

Finding the balance is time-consuming

The great advantage of using trained SMA and SE wires is the form freedom that is achieved as both wires can be trained in any shape. This enables the possibility of creating a fully integrated structure, like a composite in any form. A limitation with this approach is that finding the balance between the SMA and SE is difficult and requires a lot of testing. Besides, it will be different for every shape which makes it hard to rapidly prototype different structures. In addition, the flat springs require an additional manufacturing process compared to using the wire in tension. However, this project shows that the shaping process can be simplified to the same level as shaping springs with limited human interference (see paragraph 4.1).

Influence of low transformation wires

Using low temperature wires have the advantage of accounting for safety issues right away reducing the complexity of system and limiting the power input. Especially since it could react on body temperature the structure does not need bulky electrical connections and batteries which is a great progress in the field. In this project 35 and 45 degrees wires were used of which the 35C wire showed significantly faster response time. However, when cooling, it was noticed that the cooling time for the material system to deform back to its flattened shape took a considerable longer time than expected. This has probably to do with the low Martensite start (Ms) and finish (Mf) temperature of the wires. Only after reaching these temperatures, the system is able to go back to its deformed shape. Besides, the structure itself is also heated and need to cool down, slowing even more this process. A limitation with low temperature wires for haptic feedback is that these are too sensitive for small increases in temperature for example in summer, when temperature above 30C are common. This could result in a random stimulation and poor shape recovery of to the deformed state. When used as a wearable, it is advised to incorporate 40C wires (with the addition of copper).

11.1.2 haptic feedback for VIPs

The proposed material system was evaluated on its experiential qualities and the added value for VIPs. It was concluded that the system was easily perceiver with the hands and generated a gentle, natural and calm haptic sensation, which is in line with the SMA characteristics of generating a natural and organic movement.

Perception on other body locations than the hands

A limitation of the user test was that it did securely test other body locations than the hands it should be noted that the fingers have the highest spatial acuity in the body. When evaluating the haptic sensation on the forearm the results were less noticeable. This had partly to do with the improvised setup: the user had to hold the material system one his/her forearm which made it difficult to distinguish the pressure caused by the material system and the hand that was holding the material system. Based on this test setup, it is hard to say whether the proposed material system could generate haptic sensations on other body parts except from the hands which is relevant to know when giving passive feedback. In addition, a lot of steps still need to be taken to actually incorporate this material system unit in a workable prototype.

Non verbal communication accuracy

It was concluded that the proposed material system could be of value in the field of social haptics in the form of a wearable due to its noiseless and organic movement characteristics. A limitation using this system for this application area could be the temporality and accuracy of timing of the material system. As described, the material system had an response time of 10 seconds when 1.3A was used. This could be too slow in social interactions where a fast interpretation of social cues such as facial expressions and eye contact is needed. A way to improve this is to increase the power input to 2A, which will result in a faster response time. This power input of 2 Amps should be a short peak of timing to prevent the system from overheating and causing safety issues.

Overload with tactile cues

Furthermore, something to be attentive about is the extent of information conveyed for VIPs either auditive or haptically. When perceiving an overload of tactile information about the surroundings there is a possibility of becoming overstimulated.

11.2FUTURE RECOMMENDATIONS

Based on the discussion points recommendations are outlined and prioritized for this project.

11.2.1 Improving the unit

Technical aspects

The first recommendation is to look more into the technical characteristics of the proposed material system to verify its working principle before implementing it in applications. A better understanding of the reliability of the material system is recommended. As described in the material exploration the used SMA flat spring have a full shape recovery for 70% extension of its initial length over 10 cycles. However, in this measurement the influence of the counterforce is not taken into account. This could have a significant impact on the functional fatigue which highlights the relevance of testing this. A recommendation is therefore to examine the shape recovery over multiple cycles of SMA flat springs for a certain extension rate including a constrained force to get an idea of the functional fatigue. This can be done by extending the flat spring to a certain extension rate, subsequently connecting a weight that corresponds to the counterforce and measuring the length when the SMA wire is activated over 10 cycles (as was done for one cycle in the technical characterization paragraph 7.2). A more easy way to get an impression of the reliability of the material system (including the SMA and SE wire) is to measure its displacements using a video camera for 10 cycles.

Another recommendation is to understand the influence of the amount of peaks of the flat spring on the performance. This is relevant for the modularity of the material system, e.g. using 3 peaks or 5 peaks. Based on the technical characterization of the SE flat springs (paragraph 7.32), it was not clear what the exact influence of the addition of more peaks was on the produced force. It seems that the produced force increases slightly when more peaks are added. However, the exact influence was not clear and differed between wire diameters. Therefore, it is recommended to get a clear impression of the relation of peaks and produced force for both the SMA and SE flat springs to understand the modularity of this material system unit.

An additional recommendation is to develop a sort of spring index for flat springs meaning the ratio between the wire diameter, the height-pitch ratio and radius curve. It was noticed that smaller spring sizes (e.g. smaller height-pitch ratio) produced larger forces compared to larger spring sizes. For future research in this area, it is interesting to map out the influence of different parameters such as wire diameter, height and pitch on the force-displacement performance.

Transformation temperature

Something that was discovered in this project was the strong influence of the annealing conditions on the thermomechanical behaviour of wires. This is especially relevant in cases where a precise activation temperature is required like when body temperature is used as activation. There has been a study providing insights on the influence of annealing conditions (e.g. time and temperature) on thermomechanical behavior, using a 1mm wire (Yoon & Yeo, 2004). However, it would be relevant to get insights on the annealing conditions for different wire diameters and how the increase of activation temperature can be controlled to reach a specific activation temperature. In this way, it can be examined to what extent the wire can react on body temperature when used in a material system. In this would be recommended to further evaluate the stress-strain performance of low temperature wires as these seems to be influenced by the annealing conditions as well.

Another recommendation would be to evaluate different suppliers as their manufacturing processes can greatly influence the wire performance.

Origami structure

The proposed material system now consists of a combination of paper and textiles. To develop this further and implement it in real applications, it could be relevant to explore other options in which the paper is replaced. This is because paper is not water resistant and weakens when touched frequently which could degrade the performance of the material system over time.

As previous studies have shown, one way to do this is to knit or weave origami patterns into textiles. The advantage of using knitting is that the fold lines can be programmed to have the right direction (a valley or mountain fold). In this, the fold line needs to be as flexible as possible and the faces (the parts between the fold lines) need to be stiff in order to generate a subtle pressure on the skin. When using a knitting machine, the challenge is whether the faces can be created stiff enough to generate a subtle pressure on the skin.

Another way to create an origami pattern in textile is through 3D printing. In this, the faces could be 3D printed as figure XX shows while keeping the foldlines flexible. To give direction to the foldlines (either mountain or valley fold lines), the thickness of the 3D printed parts can vary like figure XX shows.

11.2.2 Integration in product for VIPs

Evaluation of wearability of Unit

The first recommendation for the material system when integrating it into a product for haptic feedback would be to examine the experiential characteristics of the material system for different body locations. As discussed in the discussion point, the haptic sensation of the proposed material system is easily perceived with the fingers. However, when integrated in a wearable, it should be evaluated if the proposed material system is still perceivable on other body locations. To do this, the material system should be designed in such a way that it is wearable without the user holding the material system, as was done in the experiential characterization of this project (chapter 9). Subsequently, a study could be executed that focuses on the perceivability of the material system on different body parts like the upper arm, neck, belt, back and upper leg (as proposed in the added value for VIPs in chapter 10).

An additional recommendation is to look into the zigzag size and length of the zigzags as well as the fabric used. As concluded in the evaluation with an expert, the current generated haptic sensation of the material system is rough and could be more subtle for VIPs that are better used to haptic feedback. Besides, there was a strong difference in the perception on the type of fabric. To really cater to the needs of VIPs, it is recommended to conduct a user study with VIPs on the influence of zigzag size, length and type of fabric.

Integrating the material system into a wearable (or touchable system) requires also to think about the electrical component integration, such as the battery, microcontroller and mosfets. In this, it is important to carefully consider the placement of the electrical parts as the characteristic of the proposed material system needs to be subtle. Second, the evaluation of using low temperature wires (e.g. 40-45 degrees) could be further explored as this could limit the battery size.

Diverse tactile output

Another important recommendation is to look into the possibilities of creating diverse tactile output with the proposed material system. As mentioned by the expert in chapter 10, it is important that the system can convey different messages using different tactile patterns: the use of multiple units in sequence to create several patterns and the integration of several wires in one origami fold. The workability of both methods should be further explored to understand to which extent this could be managed with the proposed material system.

In this it is important to include the target group in every design stage by organizing focus groups and creative sessions with the target group. Especially when designing for social haptics it is relevant to understand what type of information is desired and how fast this information needs to be perceivable.

11.4 REFLECTION

This project presented distinctive challenges, dealing with a novel material and a particular target group and managing the integration of the two which resulted in a explorative and complex project. The reason for choosing this project was driven by a fascination with shape-morphing objects and their potential to revolutionize current product offerings in haptics. Of particular interest was the prospect of adopting the material-driven design method, diverging from the conventional design process I have learned in my industrial design education in Delft. Together with the focus on technical aspects of the material, this new approach created a challenging and new learning environment.

Design process

Due to the explorative and multifaced nature of the project I tried to collect and analyze a variety of information from different perspectives in every phase. For example in the research phase I did an extensive literature research covering the market, a neuropsychological perspective on haptic feedback, SMA systems for haptics, analyzed the target group in depth and explored SMA materials. I believe that this interdisciplinary approach gave me a lot of new insights in how to deal with the complexity of the project. I tried to continue doing this in the form configuration and embodiment phase where I did a literature review for every parameter, tinkered with the materials and tried to analyze and evaluate both the technical details and the user experience for the proposed structure.

A struggle that I experienced was to hold on to the MMD method and connect the unique characteristics of SMAs to a valuable need for VIPs. To cater more to the needs of VIPs, more involvement of VIPs in different stages of the project would be relevant.

Encountering a novel material

One of my personal ambitions was to gain experience with SMAs. Utilizing the Material Driven Design (MDD) approach, I was engaged extensively in training Shape Memory Alloy (SMA) wires, even to the point of physical discomfort (blisters on my fingers). Driven by curiosity, I found myself persistently probing various aspects to better comprehend SMAs. During this process, I encountered difficulties attributed to the influences of both the training method and the type of wire used. This dual-factor influence posed challenges in discerning the root cause of issues encountered.

Initially perceived as obstacles, these seemingly minor elements have, upon reflection, provided valuable lessons. They facilitated the development of my ability to independently make active decisions—an essential component of the learning process. Through engaging with these challenges, I have gained a more profound understanding of the complexities involved in SMA manipulation and have developed a deeper appreciation for the experiential learning it offers.

Familiarize with the target group

A specific learning objective was to get involved with an unfamiliar target group, visually impaired people. This offered valuable insight on how to establish well-structured in-depth interviews, go through the ethical approval comission, and the importance of providing a comprehensive introduction during the interview process. It was particularly inspiring to visit participants in their home environments which learned me the value of familiarizing with a target group.

This, in turn, necessitates a more professional disposition which, I surmise, will be of great value in my future professional career.

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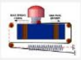
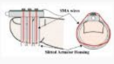
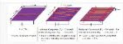
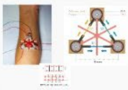
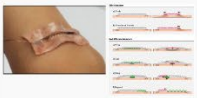
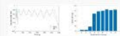
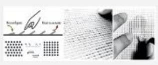
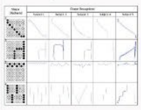
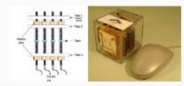
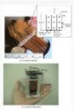
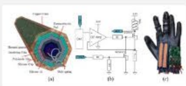
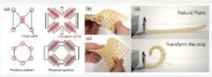
APPENDICES

APPENDIX A: OVERVIEW OF SMA SYSTEMS FOR HAPTICS

SMA systems devices for haptics

Product	Picture	Reference	Goal	Location	Haptic type	Haptic generator	Type of wire	Wire construction	Counter force	remarks
Tangential skin		(Solazzi, Provancher, Frisoli, & Bergamasco, 2011) Solazzi, M., Provancher, W. R., Frisoli, A., & Bergamasco, M. (2011, June). Design of a SMA actuated 2-DoF tactile device for displaying tangential skin displacement. In *2011 IEEE World Haptics Conference* (pp. 31-36). IEEE.		Finger tip	stretching	round effector	Flexinol, 0.076 mm, 90C Ttrans	guided: 75 mm wire for 0.5 mm displ	bias spring	
Tactile feedback at fingertip		(Scheibe, Moehring, & Froehlich, 2007) Scheibe, R., Moehring, M., & Froehlich, B. (2007, March). Tactile feedback at the finger tips for improved direct interaction in immersive environments. In *2007 IEEE Symposium on 3D User Interfaces*. IEEE.	VR experience	Fingertip	press + heat	wire	Memory metalle, 0.001 mm, 65C Ttrans	50mm wire for 0.5 mm displac	relaxation of wire + finger	
Touch me gentle		(Muthukumarana et al., 2020) Muthukumarana, S., Elvitigala, D. S., Forero Cortes, J. P., Matthies, D. J., & Nanayakkara, S. (2020, April). Touch me gently: recreating the perception of touch using a shape-memory alloy matrix. In Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (pp. 1-12). Muthukumarana, S., Elvitigala, D. S., Cortes, J. P. F., Matthies, D. J., & Nanayakkara, S. (2019). PhantomTouch: Creating an extended reality by the illusion of touch using a shape-memory alloy matrix. In *SIGGRAPH Asia 2019 XR* (pp. 29-30).	VR experience	forearm	squeezing, by shear force	fabric	BMF150 SMA wire, 70C Ttrans,	guided wire in 2d zigzag: 4% contraction 1.44N	relaxation, skin as restoration force	 U forms for evenly distribution
In contact		Simons, M. F., Haynes, A. C., Gao, Y., Zhu, Y., & Rossiter, J. (2020, April). In contact: Pinching, squeezing and twisting for mediated social touch. In Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems (pp. 1-9).		forearm	pinch	skin actuator	BioMetal Helix, BMX series 15000)	coiled micro wire	structure that is sticked to the skin	
Scweecs		Haynes, A., Simons, M. F., Helps, T., Nakamura, Y., & Rossiter, J. (2019). A wearable skin-stretching tactile interface for Human–Robot and Human–Human communication. IEEE Robotics and Automation Letters, 4(2), 1641-1646.		forearm	stretching and squeezing	fabric	Toki Biometals, 70C	two coils, 5 mm discpl	The diamond structure couples the two actuators such that contraction of one SMA extends the counter SMA as shown in Figure 2	the SMA coils are suspended on raised pins 4 mm above the skin, minimising any risk of harm to the user or interference of the tactile sensation that could occur from the heat of the activated SMA wire
Springlets		Hamdan, N. A. H., Wagner, A., Voelker, S., Borchers, J., & Steimle, J. (2019, May). Demonstration of Springlets: Expressive, Flexible and Silent On-Skin Tactile Interfaces. In Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems (pp. 1-4).				end effector skin actuator		3.5 mm thick Springlet embedding a 0.62 mm diameter SMA spring 50% deformation wire diameter dependent on skin type and location, not specified	bias force: skin elastic resistance	
tactile vest		Jones, L. A., Nakamura, M., & Lockyer, B. (2004, March). Development of a tactile vest. In 12th International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2004. HAPTICS'04. Proceedings. (pp. 82-89). IEEE.	navigation	back	press	skin actuator	0.254mm	100 mm long wire for 3.9 mm displacement, strain 4 %, force 7N. 0.254 mm diameter Current applied across the SMA wire causes the fiber to contract, rotating the pin around the pivot rod which presses against the skin when worn	The superelastic wire resets the system without the need for activation energy	The tactile sensations elicited by stimulation were not well localized, and felt as firm pressure, as if the skin was being prodded by a finger. Stimulation of the fleshier areas of the back was easier to detect than when the tactors were positioned close to the spinal cord. A
Skin+		Cao, F., Saraiji, M. Y., & Minamizawa, K. (2018). Skin+ programmable skin as a visuo-tactile interface. In *ACM SIGGRAPH 2018 Posters* (pp. 1-2).		hand	squeeze friction	skin actuator	BioMetal Fiber, 70C	0.15 mm wire, twisted in a double-wire in order to increase the contraction force.	auxetic physical structure	
Haptic SMA ring		Chernyshov, G., Tag, B., Caremel, C., Cao, F., Liu, G., & Kunze, K. (2018, October). Shape memory alloy wire actuators for soft, wearable haptic devices. In Proceedings of the 2018 ACM International Symposium on Wearable Computers (pp. 112-119).		finger	squeeze		Biometal® Fiber BMF150, D=150 microns, Toki corp.	0.15mm , wire with silicon tube to protect and guide	relaxation by tube and finger force	 gevarieerde displac en tijd
SMA pen		Takeda, Y., & Sawada, H. (2013, November). Tactile actuators using SMA micro-wires and the generation of texture sensation from images. In *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems* (pp. 2017-2022). IEEE.		finger, touchable	micro-vibration actuator for presenting mechanical vibratory stimuli to human skin.		68 and 73C	0.075mm	relaxation, cooled	
Tactilia external force of heat		Bhatnagar, T., Marquardt, N., Miodownik, M., & Holloway, C. (2021, July). Transforming a Monolithic Sheet of Nitinol into a Passive Reconfigurable Tactile Pixel Array Display at Braille Resolution. In *2021 IEEE World Haptics Conference (WHC)* (pp. 409-414). IEEE.	braille	fingers, touchable	press		Nitinol from Fuxus® with 51% Ni, an activation temperature of 40±5oC	dimensions of 100 x 100 x 0.3 mm sheet, 0.4mm discplacement	manually	
tactile display prototype		Velazquez, R., Pissaloux, E., Hafez, M., & Szewczyk, J. (2005, July). A low-cost highly-portable tactile display based on shape memory alloy micro-actuators. In *IEEE Symposium on Virtual Environments, Human-Computer Interfaces and Measurement Systems, 2005.* (pp. 6-pp). IEEE.	braille	fingers, touchables	press, patterns	effector	FLEXINOL2 wire with the following geometric characteristics: 1.5 mm of spring outer diameter and 12 active coils. Its weight is 30 mg.	0.2 mm coiled wire 45mm lentgh with 1.4mm displacement 320 mN force is needed to retract the taxel to surface level	antagonist SMA springs with forced air	form recognition 
Improved version		Velazquez, R., Pissaloux, E. E., Hafez, M., & Szewczyk, J. (2008). Tactile rendering with shape-memory-alloy pin-matrix. *IEEE Transactions on Instrumentation and Measurement, 57*(5), 1051-1057.								
tactile interface		Matsunaga, T., et al., Tactile display using shape memory alloy micro-coil actuator and magnetic latch mechanism. Displays, 2013. 34(2): p. 89-94. Taylor, P. M., Moser, A., & Creed, A. (1998). A sixty-four element tactile display using shape memory alloy wires. *Displays, 18*(3), 163-168.					BMX-50, TOKI Co., Japan)	0.05mm coiled wire of 0.2mm external diameter, 1 mm displacement with 0.1-0.15N, response time was 0.3 s in the case of a supplied current of 120 mA.	two polymer parts that extend the coil on both sides, hold in place by magnets	
fingerflex			pressing a button	hand	a resistive kinesthetic actuation		45C	tensile springs with a mean diameter of 5mm, a wire diameter of 0.8mm, and a maximum compression force of up to 3N	forced air in guided tubes	Yet, it takes about 500 ms to cool the spring down again for another activation. This time gets longer the more often the system is used and is a limitation of FingerFlex. The prototype will not work for touch typing or other applications that require fast feedback

hapticube		Lim, B., Kim, K., Oh, S. R., & Hwang, D. (2019, November). Hapticube: A compact 5-DOF finger-wearable tactile interface. In *2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)* (pp. 5094-5100). IEEE.	press and shear	fingertip	press and shear		Flexinol® ctuator Wire, DYNALLOY Inc (wires) and BioMetal Helix, TOKI Corp (for springs)	0.15mm spring, 12N	bias spring	In general, when the diameter of the SMA wire is doubled, the output force capacity is increased four times.
squeezebands		Yarosh, S., et al., SqueezeBands: Mediated Social Touch Using Shape Memory Alloy Actuation. Proceedings of the ACM on Human-Computer Interaction, 2017. 1(CSCW): p. 1-18. Yarosh, S., X. Wang, and Y. Yao, Perceptions of visual and multimodal symbolic mediated social touch: Role of technology modality, relationship, and task emotional salience. International Journal of Human-Computer Studies, 2022. 159: p. 102757.	VR	hand back	squeeze		off-the-shelf Flexinol SMA wire2 (0.012" diameter, 70°C nominal activation temperature)	spring		
Tickler		Knoop, E., & Rossiter, J. (2015, April). The tickler: a compliant wearable tactile display for stroking and tickling. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems* (pp. 1133-1138).		wrist	stroking			1mm discplacement of each bar, 5% contraction		
Compression garmet		Foo, E. W., Lee, J. W., Ozbek, S., Compton, C., & Holschuh, B. (2019, September). Iterative design and development of remotely-controllable, dynamic compression garment for novel haptic experiences. In *Proceedings of the 23rd International Symposium on Wearable Computers* (pp. 267-273).		torso, shoulder, back	squeezing		Flexinol® wire of 0.012" diameter, 70C	SMA coil actuators (coil outer diameter of 0.048")	use of braids as a coaxial (external) sheath forms an antagonistic system that allows the SMAs to automatically re-expand when unpowered (due to elastic energy stored in braids as they are compressed during SMA constriction).	
second skin		Sun, R., Onose, R., Dunne, M., Ling, A., Denham, A., & Kao, H. L. (2020, July). Weaving a second skin: exploring opportunities for crafting on-skin interfaces through weaving. In *Proceedings of the 2020 ACM Designing Interactive Systems Conference* (pp. 365-377).		all positions	squeezing		ngs (Toki BioMetalHelix BM 2.75 V used	0.15mm wire diameter, 0.62mm spring diameter		
Eyes free device		Wang, H., Kaleas, D., Ruuspakka, R., & Tartz, R. (2012, March). Haptics using a smart material for eyes free interaction in mobile devices. In *2012 IEEE Haptics Symposium (HAPTICS)* (pp. 523-526). IEEE.	t	touchable, press				SMA spring with 0.5 millimeter (mm) diameter can be in the maximum strain of 4% strain. The martensite temperature is 25o C degree and the austenite temperature is 55o C degree.	two way SMA	
HapticClench		Gupta, A., Irudayaraj, A. A. R., & Balakrishnan, R. (2017, October). HapticClench: Investigating squeeze sensations using memory alloys. In Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology (pp. 109-117).		wrist	squeezinf		flexinol, 70C	The final HapticClench prototype (Figure 2f) uses 30-coil Flexinol® springs with a 0.5mm wire diameter and a 3.45mm span (outer diameter) that has a load capacity of 1.63kg	4x12mm extension spring (Figure 2b), to the ends of the wire which was enough for restoration.	
sprout		Coelho, M., & Maes, P. (2008, February). Sprout I/O: a texturally rich interface. In *Proceedings of the 2nd international conference on Tangible and embedded interaction* (pp. 221-222).		touchable	passive, stroke				teflon, two wires --> antagonist	
Surflex		Coelho, M., Ishii, H., & Maes, P. (2008). Surflex: a programmable surface for the design of tangible interfaces. In *CHI'08 extended abstracts on Human factors in computing systems* (pp. 3429-3434).							counteracting the contraction force of the SMA strands with the ability of the foam to return to its original shape	
Weaving tentacles		Nakayasu, A. (2015). Waving Tentacles 8× 8: Controlling a SMA actuator by optical flow. In *SIGGRAPH Asia 2015 Posters* (pp. 1-1).								
Affective sleeve		Papadopoulou, A., Berry, J., Knight, T., & Picard, R. (2019). Affective sleeve: Wearable materials with haptic action for promoting calmness. In *Distributed, Ambient and Pervasive Interactions: 7th International Conference, DAPI 2019, Held as Part of the 21st HCI International Conference, HCII 2019, Orlando, FL, USA, July 26–31, 2019, Proceedings 21* (pp. 304-319). Springer International Publishing.	reduction of anxiety and promotion of calmness	warmth and slight pressure					arm, manual force	
Knitdermis		Kim, J. H., Huang, K., White, S., Conroy, M., & Kao, C. H. L. (2021, June). KnitDermis: Fabricating tactile on-body interfaces through machine knitting. In Designing Interactive Systems Conference 2021 (pp. 1183-1200).	Not specified	several locations	compression/press			SMA micro-spring (internal diameter: 0.5mm, Kellogg Research Labs, 45-C, activated at 38C)	manual force	
Haptic kinestic device		Seo, S. W., & Kwon, S. (2022, November). Finger Kinesthetic Haptic Feedback Device Using Shape Memory Alloy-based High-Speed Actuation Technique. In *Proceedings of the 28th ACM Symposium on Virtual Reality Software and Technology* (pp. 1-2).								
Bendi		Park, Y. W., Park, J., & Nam, T. J. (2015, April). The trial of bendi in a coffeehouse: use of a shape-changing device for a tactile-visual phone conversation. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (pp. 2181-2190).								
Coded Skeleton		Iwafune, M., Ohshima, T., & Ochiai, Y. (2016). Coded skeleton: programmable bodies for shape changing user interfaces. In ACM SIGGRAPH 2016 Posters (pp. 1-2). Iwafune, M., Ohshima, T., & Ochiai, Y. (2018). Coded skeleton: shape changing user interface with mechanical metamaterial. In *SIGGRAPH Asia 2018 Technical Briefs* (pp. 1-4).	unspecified	Touchable				straight wire in silicon tube, diameter not specified	flexible polymer skeleton with negative poisson ratio	

APPENDIX B: TARGET GROUP

Questionnaire

This questionnaire serves as a guideline rather than a strict followed questionnaire. Therefore, not all questions will be asked.

General - 15 min

1. Consent
    1. Ik heb een informed consent opgesteld, zou je deze willen doorlezen/aanhoren en willen tekenen?
2. Personal information
    1. Wat is je naam en leeftijd?
    2. Hoe is jou visuele beperking op het moment? mild, moderate, severe, blind?
    3. Waardoor komt jou visuele beperking en hoe evalueert deze?
    4. Heb je een baan en mag ik vragen welke wat voor een functie je hebt?
    5. Met wie leef je op dit moment? Heb je kinderen?

Part 1 - 30 min

3. Ochtend: 8-12 (opstaan, aankleden, opfrissen)
    1. Wat is een specifieke activiteit/moment bij het opstaan waar je moeite mee hebt?
    2. Wat is een moment dat eigenlijk heel goed gaat en waar je voorheen moeite mee had?
    3. Kun je mij beschrijven hoe je je ontbijt klaarmaakt en Wat zijn moeilijkheden daarbij? Bv hoe onderscheid je verschillende onderdelen? Zijn er wel eens dingen die gevaarlijk zijn?
4. Middag: 12-16 (iets doen/werk)
    1. Wat doe je in de middag? Hoe ziet jou middag doordeweeks eruit?
        1. Hoe is jou werkplek ingericht?
            1. Wat voor activiteiten heb je op werk?
            2. Wat zijn hindernissen die je tegenkomt op je werk?
            3. Kun je alles makkelijk vinden? zo ja/nee, hoe ga je daarmee om?
        2. Kun je beschrijven hoe jou lunch moment is?
    2. Kun je een activiteit beschrijven die je wel eens in de middag hebt gedaan?
        1. In het weekend? hoe is dat?
        2. Sport je?
    3. Hoe verplaats je je meestal? en waarom?
        1. Hoe orienteert je je?
        2. Ben je beperkt in de mogelijkheden die je kunt doen? kun je overal zo naartoe?
        3. Kun je beschrijven hoe je naar een winkel gaat die je niet kent? wat zijn aspecten die daar moeilijk bij zijn?
    4. Hoe is het voor jou om in een onbekende ruimte te zijn?
        1. Kun je beschrijven hoe dat voelt?
        2. Welke elementen zijn lastig aan een onbekende ruimte?
        3. Wat zijn nou dingen waar je tegenaan loopt letterlijk en figuurlijk in een onbekende ruimte?
            1. licht?

        2. mensen?
5. Vroege avond: 16-20 (avondeten)
    1. Hoe ziet de dag/het moment eruit als je thuiskom? Wat doe je op je vroege avond?
    2. Kook je wel eens? zo ja, hoelaat begin je met koken en hoeveel tijd besteed je aan koken?
        1. Doe je dat vaak alleen of met iemand?
        2. Kun je beschrijven hoe je dat doet? Welke elementen vind je moeilijk hierbij en welke gaan juist hele goed?
        3. Ervaar je dingen die te warm zijn?
6. Late avond: 20-23
    1. Hoe ziet jou late avond eruit na het eten totdat je gaat slapen?
        1. Wat doe je meestal?
        2. Welk moment kan wel eens lastig zijn tijdens deze periode?
7. Nacht: 23-8
    1. Lukt het goed om in te slapen? Wat doe je daarvoor?
    2. Welke elementen zijn voor jou belangrijk om een goede nachtrust te hebben?
8. Algemeen
    1. Welk deel van de dag ervaar je als het lastig en waardoor komt dat?
    2. Kun je een moment in je leven beschrijven dat je het heel lastig vond dat je minder zag? Hoe ging dat?
        1. hitte en kou?
    3. Welk seizoen is voor jou het fijnst? hoezo is dat? Hebben de seizoenen invloed op jou beperking?
    4. Hoe deel je je tijd in ? Hoe duid je tijd?

Part 1 - 30 min

1. Huidige producten
    1. Welke producten gebruik je allemaal?
    2. Welk product vind jij het fijnst om te gebruiken en waarom?
    3. Heb je een voorbeeld van een product dat je niet fijn vind?
        1. Op welke aspecten oordeel jij of een product fijn in gebruik is ?
        2.
    4. Bij welk product is het voelen belangrijk? Vind je dat product fijn, waarom wel/niet?
        1. Heb je een product dat enkel haptische feedback geeft?
        2. Kun je voordoen hoe je met dit product omgaat?
        3. Zijn haptische cues belangrijk voor het gebruik? zo ja hoe doe je dat, volg je lijnen, hoogte verschillen?
    5. Welk product zou je willen aanschaffen en waarom?

APPENDIX C: MATERIAL EXPLORATION

4.3 Influence of shape

To understand SMA wires, different 3D (springs) and 2D (zigzags) shapes were explored. The focus is laid on exploring 2D zigzag shapes as no literature is found about testing and exploring this shape.

4.3.1 Spring forms

The first shape that was made from SMA wires were spring forms from a Flexmet wire in diameters 1mm and 0.5mm. After playing with these springs, it was noticed that the springs showed a spring-like effect. When deforming the springs by hand, putting them in hot water and cooling them, the length of the spring differed between the heated and cooled state. This was for both the 1mm and the 0.5mm diameter spring, respectively a difference of approximately 5 and 10 mm in length. This effect was further explored in a more systematic way, as described in the following paragraph.

Spring effect

A spring from a Nextmetal wire was made and tested on its shape recovery for 10%, 50% and 100% deformation, heated to its Af (65C) using an electrical current (V=1.7, A=1.85). ***The initial dimensions of the spring were 0.5 mm diameter, 18 [mm] length, XXX.*** The deformation was created by stretching the wire by hand alongside a ruler to determine the extension percentage, see picture 4.5.

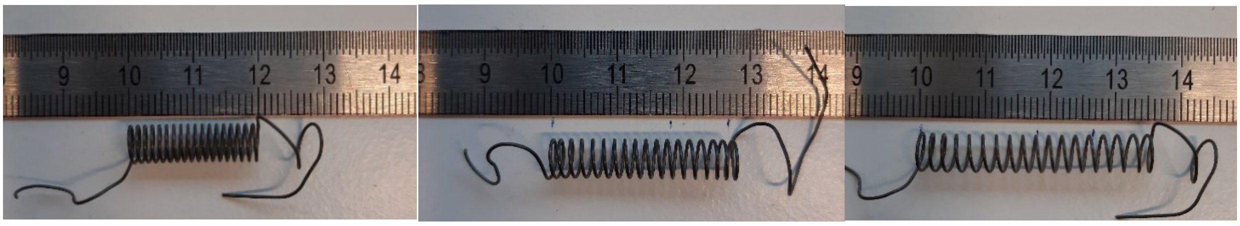


Figure 4.5 The spring forms with 10% deformation (left), 50% deformation (middle), 100% deformation (right).

The length of the spring was measured 1 second after the wire was heated to its Af (Hn) and after 60 seconds, representing its cooled state (Cn). The results are shown in figure 4.6, for 10%, 50% and 100% deformation of its total length over 10 cycles.

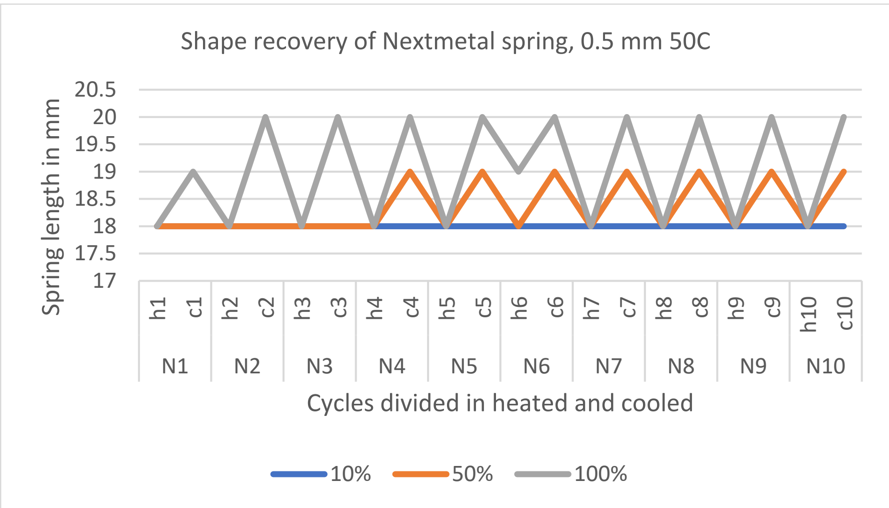


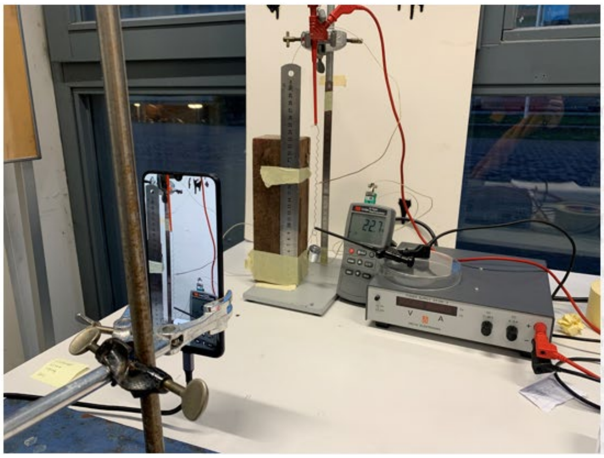
Figure 4.6. Graph of the measured length of spring wires in a heated state (65C) and cooled state (20C) over 10 cycles.

As shown in the figure, it seems that the length for all deformations stays the same in the heated state, namely 18 mm. However, when the spring is deformed 50% or 100% of its initial length, the spring retains its shape when heated but extends when cooled respectively 1 and 2 mm. Besides, this extension seems to be larger for larger deformations. Since both the Flexmet wire springs and Nextmetal spring show this kind of behavior, it suggests that SMA springs are inherent to a kind of spring or two-way effect. However, this effect does not need to affect the design when a counterforce is used since then the cooled state will be determined by the deformation.

It should be noted that these results are part of a tinkering session and serve only as an indication rather than objective and scientific results. For example, the deformations were created using a human hand which could have resulted in various deformations within the spring influencing the outcomes. To ensure an objective result, one should take out human actions in all stages of the test. An improvement and next step could be to use a force meter to both deform the wires and measure the needed force for a certain deformation.

4.3.2 Zigzag forms

An interesting 2D shape are zigzagged shapes as these are flat and therefore can be smoothly integrated into structures such as textiles. Besides, almost no literature is found on zigzagged trained shapes. Therefore, the influence of force on shape recovery and the influence of height-pinch ratio on displacement is explored for zigzagged shapes. Three zigzags were made with a Flexmet wire (65) of 0.5mm diameter with different sizes in height-pinch ratio, 0.5-1[cm], 1-2[cm] and 2-4[cm] with an approximate length of 10 cm. The zigzags were deformed using a weight, heated using electric current, and tested by measuring the lengths with a ruler after it was recorded. Figures 4.7 and 4.8 describe the dimensions of the zigzag form and the test setup.



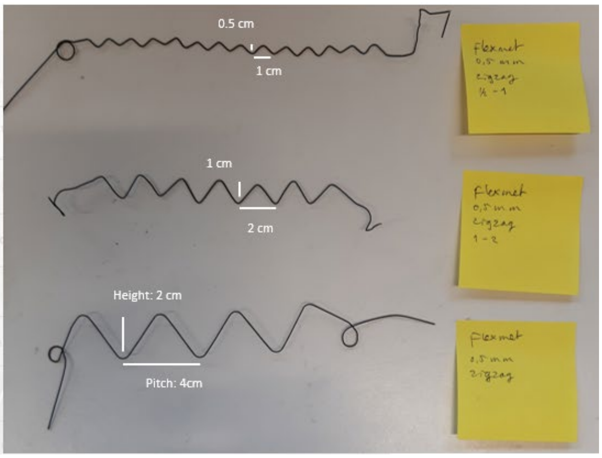


Figure 4.7 Created and tested zigzag shapes

Figure 4.8 Test setup

More displacement with a larger height-pitch size

The displacement of three zigzag shapes of different sizes with the same pitch-height ratio is tested over 10 cycles with 0.1N and 0.2N, see figure 4.9.

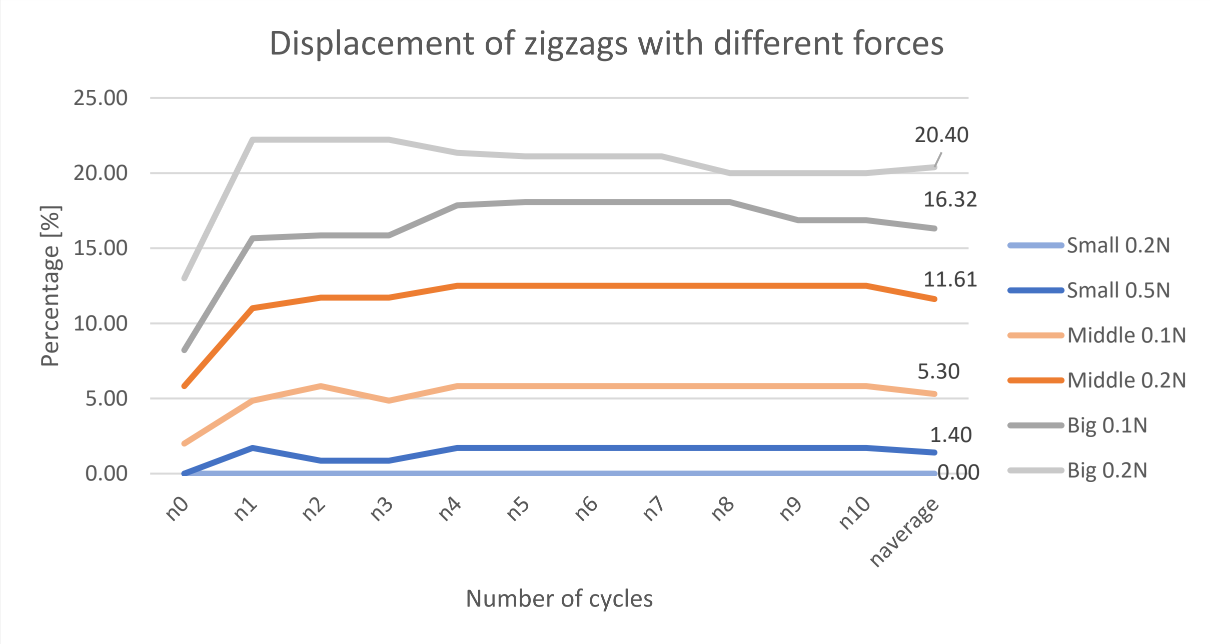


Figure 4.9 Displacement over 10 cycles for 0.1N, 0.2N and 0.5N for three different zigzag pitch-height sizes: small=0.1-1cm, middle=1-2cm, big=2-4cm.

A general observation shown in figure 4.9 is that it seems that all zigzags show less displacement in the first cycle, N0. This is mainly due to the measured length of the cooled state which is smaller compared to the cooled length in the following cycles. An explanation for this occurrence can be due to residual stresses in the wire preventing the wire from deforming when force is applied.

Another observation is that there is a considerable difference in displacement percentage for the small, middle and big zigzags when the same force is applied. For example, when 0.2N was applied the small zigzag showed no displacement versus the middle wire showing an average displacement of 12.2% and the big zigzag 21.1%. The displacement of the small wire was 1.7% on average when 0.5N was applied, which is still small compared to the displacement of the middle and big zigzags when 0.1N was applied, respectively 5.5% and 16.3%. Furthermore, it was noticed that the displacement graph line of the big zigzag is fluctuating over the cycles while the lines of the small and middle zigzags are more constant. This could mean that a bigger zigzag is less reliable in general or that the applied forces are too high to enable a reliable displacement.

4.2 Material properties

The solution space for this project revolves around SMA wires that react to low temperatures through for example body temperature and/or electrical current for low-temperature wires such as 40/50 degrees. Different NiTi alloy compositions (referring to its transition temperature) from different manufacturers are explored to get a sense of SMA wires in relation to their material properties. The ultimate goal of this tinker session is to determine a reliable wire to proceed with, which is defined to have a workable As-Af range and a reliable shape recovery.

4.2.1 Importance of determining As-Af range

A general observation was that SMA wires show a considerable difference in the austenite start temperature (As) and finish temperature (Af). As explained in paragraph 2.2, the As refers to the temperature when the SMA wire starts to show a shape memory effect and the Af refers to the temperature when the shape memory effect is fully finished. Most transition temperatures reported by manufacturers correspond to the Af, they do not mention the As. For example, the Flexinol and Flexmet wires showed an As around 30-35 degrees while its Af was reported at respectively 70 and 65 degrees (see table 4.1).

4.2.2 Nextmetal wires have the most suitable As-Af range

Another observation was that based on the tinkering with available wires, the wires from Nextmetal had the most suitable and reliable low transition temperatures (around 30-40C). Table 4.1 shows an overview of the tested wires and observed As and Af.

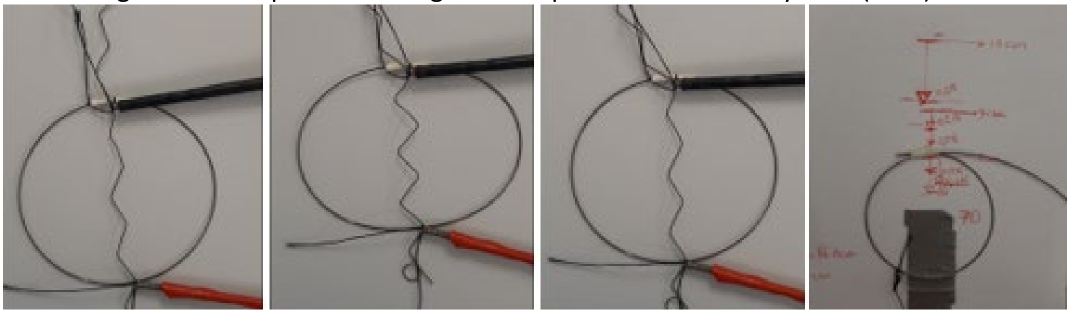
	As [C]	Af (reported) [C]	Strain [%] (with 30 cm straight wire and 0.5N force)
Kelloggs 0.25 mm, 35C	Between -20 and 0 C	20 C	-
Kelloggs 0.25mm, 45C	Superelastic	Superelastic	-
Nextmetal 0.5mm 40C	35	45	0.2
Nextmetal 0.5mm 50C	35	50	0.7
Flexinol 0.3 mm 70C	29	70	5
Flexinol 0.5mm 70C	30	70	2.4
Flexmet 0.5 mm 65C	35	65	4.2

As shown in table 4.1, the Kelloggs wire with 0.25mm diameter that should react on body temp (35C) seems to have a big As-Af range or a lower As and Af temperature than expected. The wire showed super elastic behaviour both at room temperature (20C) and in the fridge (4C), meaning that the wire immediately went back to its 'trained' shape after deformation. The wire only showed a shape memory effect (SME) when it was put in a freezer of -20 degrees, meaning that the wire could be deformed at minus 20C and went back to its trained spring shape at room temperature (20C). Besides, the Kelloggs wire that should react at standard temperature (45C) showed super elastic behaviour for all temperatures. Based on these results, it seems that the Kellogg's wires with 0.25mm diameter are not suitable to react at body temperature in the desired way.

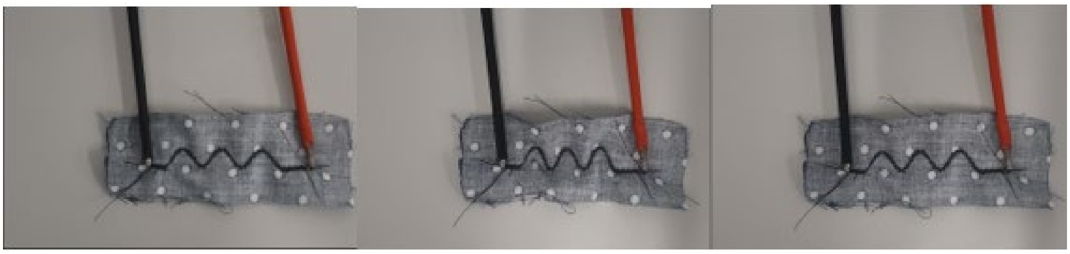
The tested Nextmetal wires showed a coherent and relatively small As-Af range. However, the difference in the As-Af range of 40C and 50C wires is rather small. Therefore, 30C Nextmetal wires will also be purchased to test the As-Af range.

APPENDIX D: STRUCTURE EXPLORATION

Interesting material explorations to give an impression of all the system (+-30) that were tested



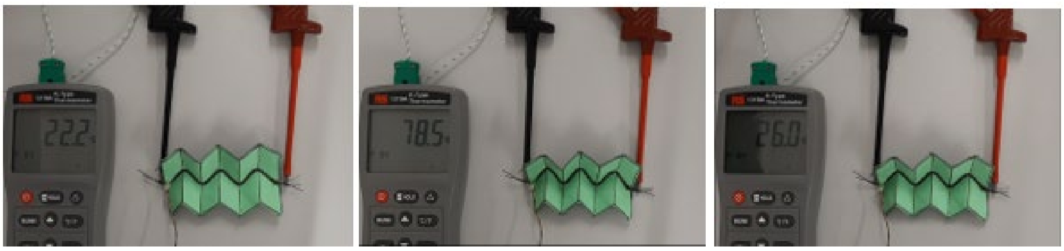
Loose fabric:



0.25mm in compression:

Too many extension:

Big zigza in origami paper structure:



Without paper fold lines

APPENDIX E: TECHNICAL CHARACTERIZATION

The green dots represent a full shape recovery at a certain temperature, the grey dots represent a half shape recovery at a certain temperature and the red dots show no shape recovery at all. An estimation of the austenite starting (As) and finishing temperatures (Af) has been made, taking the first temperature where the wire showed a full recovery for Af (lowest green dot) and the first temperature where the wire showed movement for As (lowest grey dot), an overviewed of these are showed in figure 7.2.

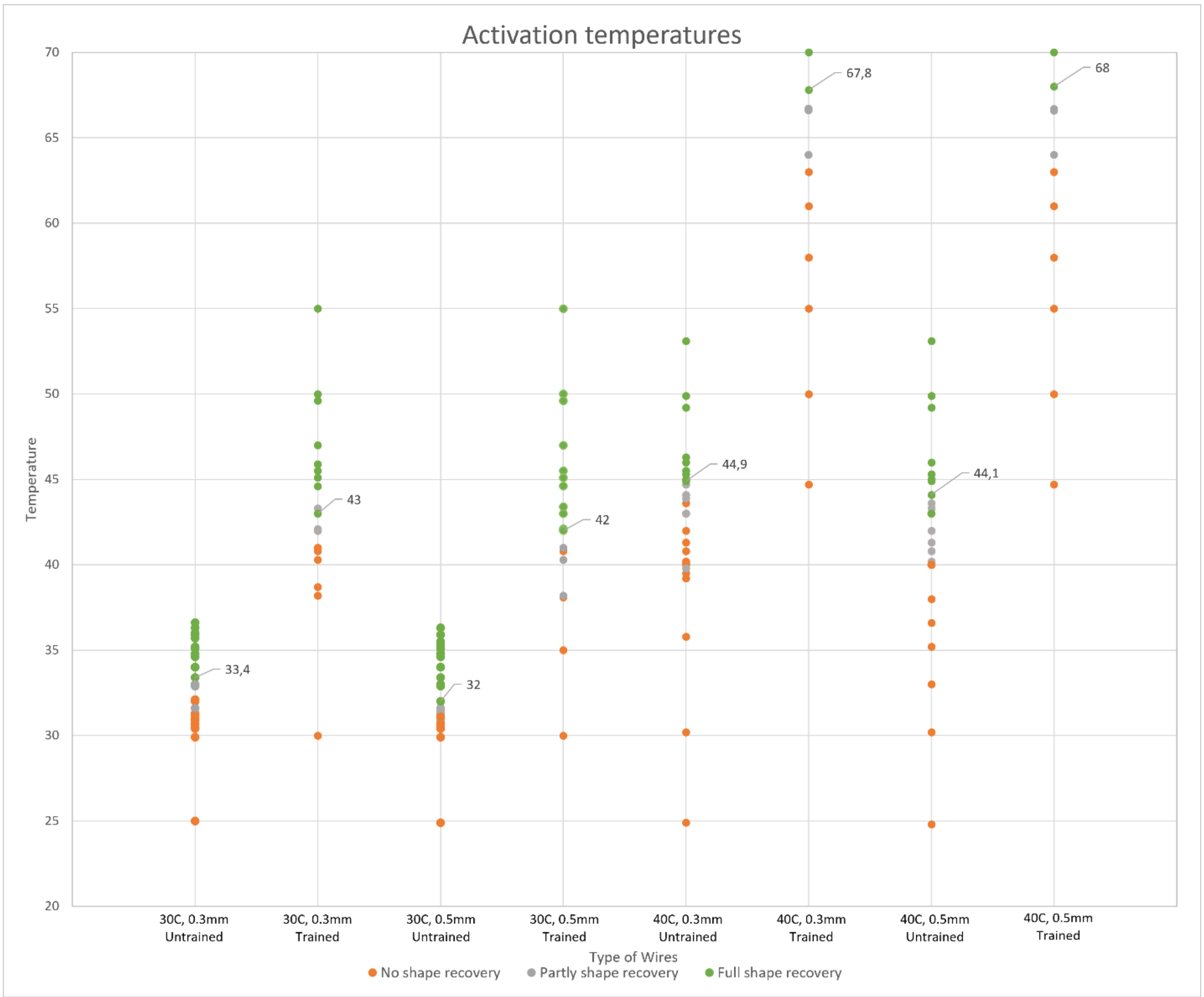
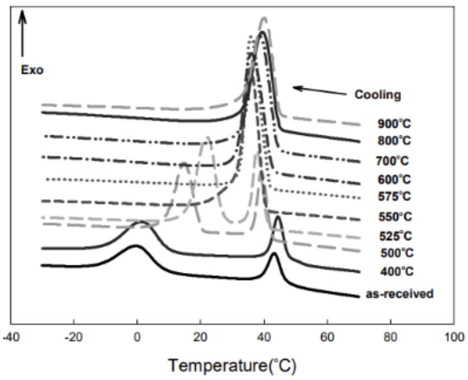


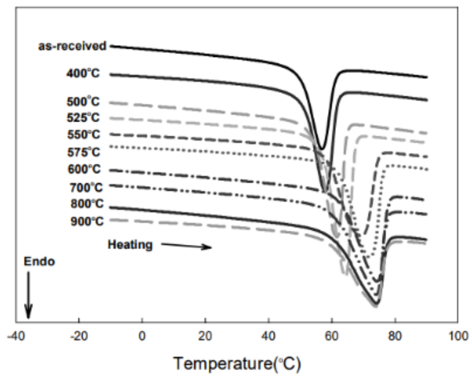
Figure 7.2

Explanation annealing conditions

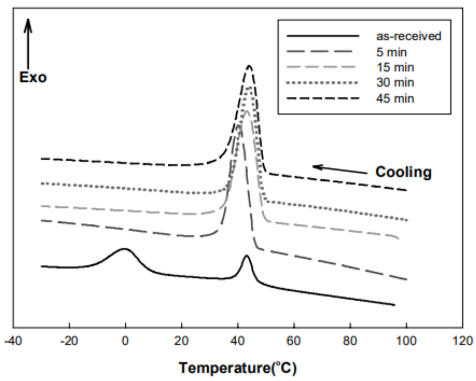
Yoon en Yeo (2004) tested a NiTi (*54.5Ni-45.5Ti%)* wire of 1 mm on the following temperatures and times: 700C heat treatment for 5min, 15min, 30min, 45min and heat treated temperatures of 400℃, 500℃, 525℃, 550℃, 575℃, 600℃, 700℃, 800℃, 900℃ 30 minutes treatment time (see figures below). The results show that the thermomechanical behavior strongly depends on heat treatment temperatures. As, Af, Ms and Mf of heat treated samples between 400-600 C tend to linearly increase. Above 600C there is no significant result and below 400C, the phase transformation ℃ temperatures are the same as those of the received wires. This is in line with Kus and Breczko (2010) findings who tested a sheet of 2x2mm with 0.5 thickness on various annealing temperatures: 400, 450, 500, 550 and 600 for 30 minutes. They found that the phase transformation temperatures show an obvious increase and a better defined phase transformation from annealing temperatures above 500 degrees. In addition, Yoon and Yeo (2004) found that more than 15 minutes of annealing is advised to get a stable result for heat treatment at 700C. In short, these results seem to clarify the change in transformation temperatures in the experiment. Furthermore, after email contact with Flexmet (see next page) it became clear that SMA wires should undergo a heat treatment of around 10-15 minutes with 500-510 annealing temperature. It should be noted that the type of manufacturer and alloy geometry might affect the results. Therefore, 500 degrees at 15 minutes should serve as a guide and has to be experimentally verfified and checked by the manufacturer if possible.



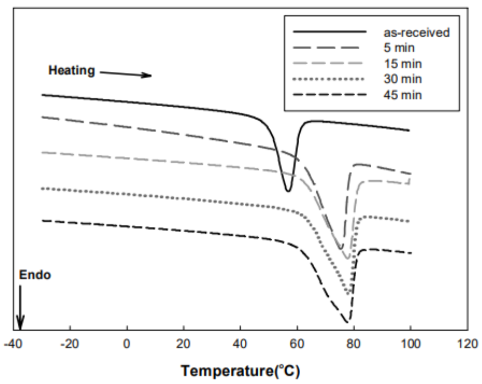
(a) In case of cooling



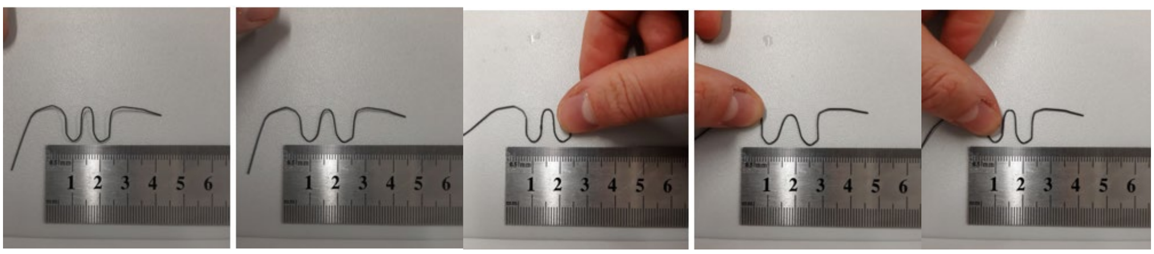
(b) In case of heating



(a) In case of cooling



(b) In case of heating



Mail contact with flextmet about annealing conditions for SMA and SE wires

[redacted]

Subject: Re: vragen over SMA wires

Beste,
Als je die kort (<15') op 500-510°C warmtebehandelt, dan zal die draad zeker nog superelastisch zijn bij kamertemperatuur.
Als die warmtebehandeling langer duurt zullen de transformatietemperaturen langzaam opschuiven naar hogere temperaturen, en kan het dus zijn dat d
draden bij kamertemperatuur niet meer superelastisch zijn.
Mvg,
Rudy
Op 21/02/2023 om 18:29 schreef Mila Lücker:

[redacted]

Subject: Re: bestellen super elastische draad

Beste,
Die 500-510°C zal altijd wel werken. Voor NiTi met een wat hogere activatietemperatuur mag het eventueel iets lager, maar echt relevant lijkt me dat hier niet te zijn. Voor NiTiCu zou ik eerder 480°C aanraden, maar ook daar zal 510°C een mooi resultaat geven.
Langer dan 10' is af te raden, zeker voor superelastische draden.
Mvg,
Rudy
Op 10/03/2023 om 15:43 schreef Mila Lücker:

> Beste Rudy,
>
> Ik heb de draden goed ontvangen! Bedankt daarvoor!
>
> Nog een kleine vraag over SMA wires en hun warmtebehandeling.
>
> Voor superelastische draden raadde je aan om een warmte behandeling te doen op: 500 graden voor 10 minuten
> Zou je hetzelfde adviseren voor geheugen draden van NiTi?
>
> Stel ik heb NiTi draden met transformatie temperaturen van 30 graden, 40 graden en 65 graden.
> Kunnen deze allemaal een warmte behandeling krijgen van 500 graden voor 10 minuten? Of zou je langer aanraden?
> Of is de warmte behandeling verschillend voor verschillende temperaturen? Zo ja, welke zou u aanraden bij 30C, 40C en 65C draden?
>
> Ik hoor uw antwoord graag tegemoet!
>
> Vriendelijke groet,
>
> Mila

RE: Question about flat spring capabilities

[redacted]

To Mila L?cker

Reply | Reply All | Forward | ...

Wed 08/03/2023 11:26

Start your reply all with: It does. Thank you! | Thank you so much for the info! | Thank you! | Feedback

Hi Mila,

A 0.5mm wire with 1cm amplitude produces around 3-5N of force. I hope this helps! Flat springs are an excellent solution because they have little to no thickness. An equivalent helical actuator would be about 5mm thick. This really opens the door for some new hardware technologies.

[redacted]

Kellogg's Research Labs

[redacted]

KRL KELLOGG'S RESEARCH LABS

[redacted]

Subject: Question about flat spring capabilities

Dear contact from Kelloggsresearchlabs,

I am doing a graduation project at TuDelft on SMAs and might want to use flat springs. You indicate the flat spring has the same actuation capabilities as a helical spring. What exactly do you mean by that?

For example, say I would like a NiTi SMA flat spring with 0.5 mm wire diameter and spring amplitude of 1 or 2 cm, how much force and displacement could it generate in martensite and austenite state? Is there available test data conducted with flat springs or a formula that could predict the displacement and force?

Re: bestellen super elastische draad

[redacted]

To Mila Lücker

Reply

Mila

[redacted]

>En kan een NiTiCu draad meer of minder kracht leveren in austenite (warme) toestand?
Eerder meer.

Op 15/03/2023 om 16:24 schreef Mila Lücker:

Beste Rudy,

Bedankt voor het snelle antwoord. En kan een NiTiCu draad meer of minder kracht leveren in austenite (warme) toestand?

Vrijdag versturen is goed! Dan hoop ik dat het er maandag is :).

Vriendelijke groet,

Mila

[redacted]

Goeiedag,
>Ik heb namelijk het vermoeden dat de toevoeging van Cu ervoor zorgt dat de draad makkelijker te vervormen is.
De NiTiCu draad is inderdaad makkelijker te vervormen in de koude (martensietische) toestand

>Zou ik nog meer draad kunnen bestellen? Dit keer 5 meter van de 'as drawn' 0.25 mm voor 20 euro?
Dat kan maar ik kan het wel pas vrijdag versturen.

Mvg,
Rudy

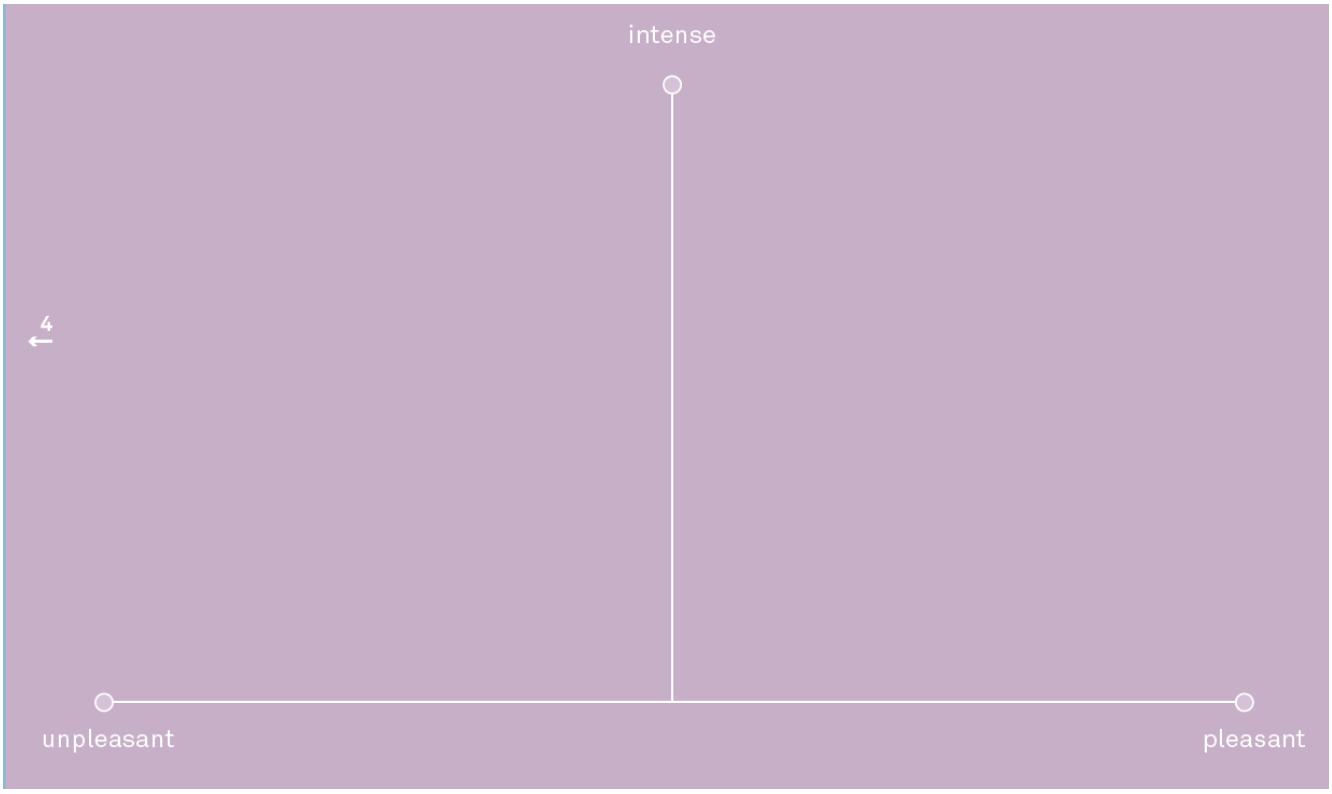
Form NO.	

Questionnaire

1. How do you describe the movement of the sample?

Slow	◯ 1	◯ 2	◯ 3	◯ 4	◯ 5	Fast
Calm	◯ 1	◯ 2	◯ 3	◯ 4	◯ 5	Aggressive
Handcrafted	◯ 1	◯ 2	◯ 3	◯ 4	◯ 5	Manufactured
Artificial	◯ 1	◯ 2	◯ 3	◯ 4	◯ 5	Natural
Gentle	◯ 1	◯ 2	◯ 3	◯ 4	◯ 5	Powerful
Sexy	◯ 1	◯ 2	◯ 3	◯ 4	◯ 5	Not sexy
Frivolous	◯ 1	◯ 2	◯ 3	◯ 4	◯ 5	Sober
Cozy	◯ 1	◯ 2	◯ 3	◯ 4	◯ 5	Aloof

2. Which emotions, feelings and memories does the material elicit in you? Please pick the three most related words and position those in the graph.



3. Reflection: What do you think the material is?

The most pleasant quality, why? ______________________________

____

The most unpleasant quality, why? ______________________________

____

The most unique quality, why? ______________________________

____

Reference Vocabulary: Ease to Use, Modular, Expressive, Reconfigurable, Noiseless, Unreliable Connection, Complicated, Limited Application Scenarios, etc.

4. Which body location do you find most applicable for the demonstrator and why? If there is a difference between the two demonstrators, please explain.

____

5. In what application field do you see this demonstrator operating?

____

6. Could you think of an improvement for the demonstrator?

____

Guided questions during sample interaction

First encounter

- How would you describe the material?
- How would you think it would change in time?
- Which meanings would you use to describe the material? Why?
- Is there a difference for the two samples?

Second encounter: when activated

- How would you describe the behaviour of the material? What are the inputs?
- What are the qualities of the behaviour?
- Which emotions, feeling and memories does the behaviour elicit in you? Why?
- Which adjective/meanings would you use to describe the behaviour? Why?
- Look at the previous paper (paper A): is the experience elicited by the material changed? What in particular? Think about the sensorial qualities, emotions,meanings, way of interacting or approaching the materials. Would you change the nickname of the material?
- Describe the different experiences resulting from the materials and related behaviours?
- Put the different experiences in order of preferences and explain why?

Third encounter: body locations

- Why did you choose this body location?
- How is the sensation on that precise body location?
- Is there a difference for the two samples?

APPENDIX F : PROJECT BRIEF

DESIGN FOR our future

TU Delft

IDE Master Graduation

Project team, Procedural checks and personal Project brief

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

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

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

STUDENT DATA & MASTER PROGRAMME

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

family name
initials   given name
student number
street & no.
zipcode & city
country
phone
email

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

SUPERVISORY TEAM **

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

** chair Gijs Huisman   dept. / section: HCD
** mentor Sepideh Ghodrat   dept. / section: SDE
2nd mentor Qiang Liu
organisation: Phd student at TuDelft
city: country:

comments (optional)

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

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

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

APPROVAL PROJECT BRIEF

To be filled in by the chair of the supervisory team.

chair Gijs Huisman date 10 - 11 - 2022 signature

CHECK STUDY PROGRESS

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

Master electives no. of EC accumulated in total: ______ EC

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

List of electives obtained before the third semester without approval of the BoE ______

YES all 1st year master courses passed

NO missing 1st year master courses are:

name ______ date - - signature ______

FORMAL APPROVAL GRADUATION PROJECT

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

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

Content: APPROVED NOT APPROVED

Procedure: APPROVED NOT APPROVED

comments

name ______ date - - signature ______

Initials & Name M.E.K. Lucker Student number 4401719

Title of Project The potential of smart material systems for visually impaired people

The potential of smart material systems for visually impaired people

project title

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

start date 28 - 10 - 2022 10 - 05 - 2023 end date

INTRODUCTION **

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

What if products could adapt to the environment, just like nature? Like a pine cone that folds together to protect its seeds from rain, and reopens when it is dry. Products around us are defined by the materials that they are made of. Imagine that these products are not just static objects but display dynamic behavior instead as a result of surrounding stimuli.

That is what Shape memory materials (SMMs) do. They change shape in a programmed way due to external stimuli such as heat (Bengisu & Ferrara, 2018). As such, these materials have the ability to simplify systems that are used in products: instead of having to use complex electronics that rely on electric power they engage with and react to their environment in a natural way. A good example of a shape memory product is the self-extendable stent implant made from a shape memory alloy (SMA) for narrowing veins. Currently, these materials are mainly used in the aerospace and medical fields. However, one can imagine that these materials as well can be used for other purposes on different scales.

An increasing group that might benefit from material systems based on SMAs are people with visual impairment (VI), through haptic feedback. This group is increasing due to ageing population and diabetes, including approximately 378 800 visually impaired and blind in the Netherlands (Keunen et al., 2011). Consequently, the market for assistive devices is growing (Fact.mr, 2021) with the main focus on improving vision or translating vision to audio feedback (Personal visit to Ziezo fair). Although haptic feedback has gained popularity for VI assistive devices, it remains underexposed while it can offer great opportunities for VI people to conduct tasks, navigate and communicate (Sorgini et al., 2018).

Materials systems based on SMAs can be used for haptic feedback (Cruz et al., 2018). Given that SMAs are not necessarily dependent on electronic actuators and sensors, they can have a great potential for simple tactile assistive devices for VI people. This project focuses on exploring the potential of a material system based on SMAs for a haptic feedback device for visually impaired people. The purpose is to showcase the possibilities of these materials by using its core strengths; reacting to an natural environmental stimulus.

Bengisu, M., & Ferrara, M. (2018). Materials that move: smart materials, intelligent design. Springer.

Keunen, J. E., Verezen, C. A., Imhof, S. M., Van Rens, G. H. M. B., Asselbergs, M. B., & Limburg, J. J. (2011). Toename in de vraag naar oogzorg in Nederland 2010–2020. Ned Tijdschr Geneeskd, 155(41), 1828-33.

Fact.mr (2021). Assistive Technologies Demand for Visually Impaired Market forecast, trend analysis & competition tracking - global market insights 2020 to 2026,"

Cruz, M., Kyung, K. U., Shea, H., Böse, H., & Graz, I. (2018). Applications of smart materials to haptics. IEEE Transactions on Haptics, 11(1), 2-4.

Sorgini, F., Caliò, R., Carrozza, M. C., & Oddo, C. M. (2018). Haptic-assistive technologies for audition and vision sensory disabilities. Disability and Rehabilitation: Assistive Technology, 13(4), 394-421.

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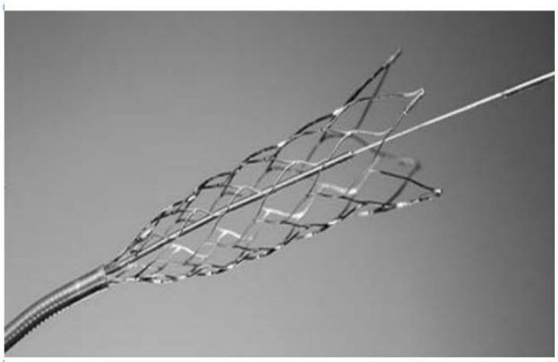
introduction (continued): space for images



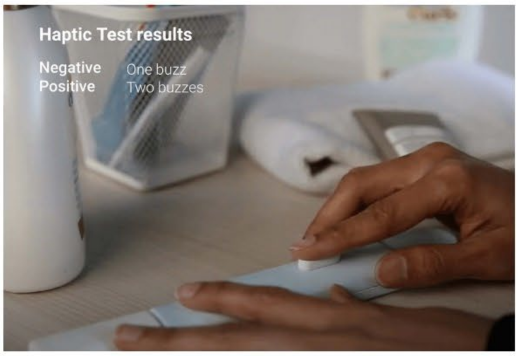


image / figure 1: Left: NiTi self-expandable neurosurgical stent; Right: Haptic pregnancy test for VI people

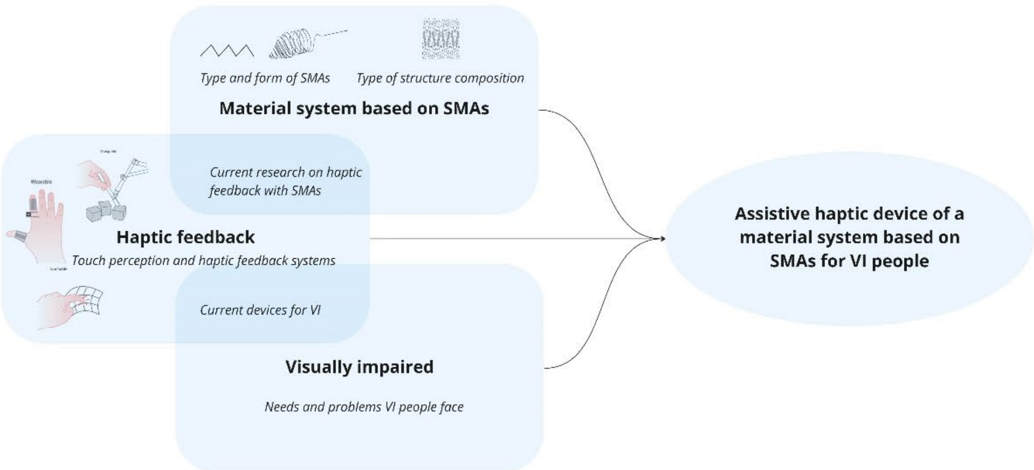


image / figure 2: Project overview

Initials & Name M.E.K. Lucker Student number 4401719

Title of Project The potential of smart material systems for visually impaired people

PROBLEM DEFINITION **

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

Research has been done on haptic feedback using SMAs. However, no concrete applications have been designed for Visually Impaired people yet while haptic feedback can be an essential tool for VI people. Sandhir's master thesis (2021) explores the possibilities of incorporating SMAs into haptic technology for VI people, using an Arduino to actuate the SMA. It has not yet been explored, however, if these systems may add value for VI people too in cases where a natural environmental stimulus is used. Therefore, the main question is: How can a material system based on SMAs react to a natural environmental stimulus and provide haptic feedback for visually impaired people?

Questions that need to be addressed:
- What specific needs do VI people have and is there a need where the potential of SMAs can be shown?
- What are the advantages and disadvantages of current assistive devices for VI people?
- What types of haptic feedback exist and how are current haptic feedback techniques with SMAs perceived?
- What types of SMMs exist and what types of SMA and structure is suitable to generate haptic feedback for visually impaired people?

ASSIGNMENT **

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

I am going to explore the potential of SMAs and what value they can add for visually impaired people. The outcome will be a prototype of an material system based on SMAs that reacts to a natural environmental stimulus and generates haptic feedback for visually impaired.

- The first objective of this project is to explore the potential SMAs, the influence of different patterns and structures on these materials and how they can provide haptic feedback, inspired by the Material driven design method.

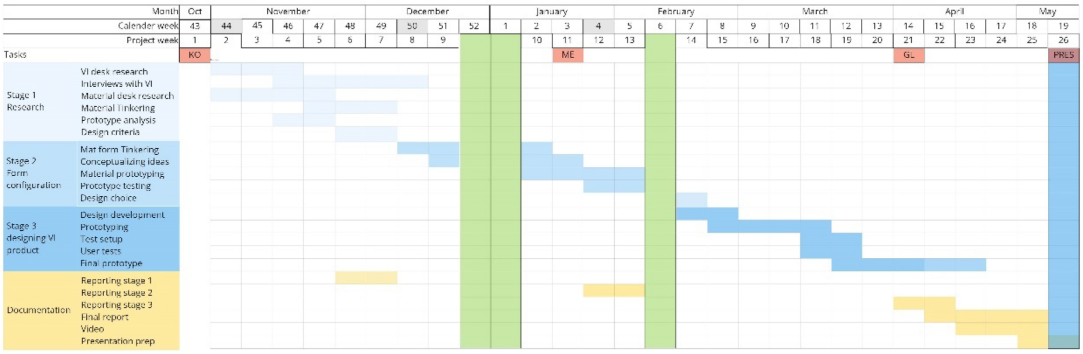
-The second objective is to identify a specific need for VI people where haptic feedback can assist them to better understand the world around them. This is done by involving the target group in the design process.

- The third objective is to develop a prototype from a material system based on SMAs that reacts to an natural environmental stimuli and generates haptic feedback that creates value for VI people.

PLANNING AND APPROACH **

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

start date 28 - 10 - 2022 10 - 5 - 2023 end date



The project is divided into three stages consisting of six weeks and a documentation stage.

Stage 1: research.
In this stage, both the target group and SMMs will be researched in parallel, in order to formulate design criteria and identify several needs to focus on.
The material desk research consist of researching all SMMs and the material tinkering will focus only on SMAs due to the limited time and available SMMs at TuDelft.

Stage 2: Form configuration.
In this stage, the type and form of SMAs will be further investigated in relation to different structures and shapes that can generate haptic feedback. From this tinkering, a number of prototypes will be created and tested.

Stage 3: Designing VI assistive device.
In this stage, one prototype will be taken as a starting point and will be further iterated on to see how it can create value for VI people.

I will work 4 days a week (monday-thursday) because I have another job one day a week.

Important dates: Kickoff: 28-10-2023, Midterm: 18-01-2023, Green light: 05-04-2023, End: 10-05-2023

MOTIVATION AND PERSONAL AMBITIONS

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

The reason I chose this thesis project is because I am very intrigued by shape memory materials. The fact that these materials change over time challenges you to design something dynamic rather than static. This sheds a different light on designing objects which I find fascinating and like to explore.

We, as IO students, are used to start from a problem and choosing a material that matches the design we have come up with. I find it challenging to partly turn this around: to design from a material and see what possibilities it offers for a target group. By taking the Msc course, material driven design, I am familiar with designing from a material as a starting point and I will use some parts of this method, such as material tinkering, in my graduation project.

Furthermore, I am not very familiar with VI people and find it hard to imagine having reduced vision. For that reason I find it all the more interesting to delve into this world and unravel their needs. Considering I did a previous study in brain and cognitive science, I find it interesting to look into haptic perception and how SMAs can play a role in this. Something I would like to learn is how to actually test a working prototype with a target group and then make improvements based on my findings.

Personal learning goals:

- Improve technical and scientific debate and presentation skills
- Gaining experience with SMAs
- Learn how to use software to program/ produce these SMAs
- Prototype testing with users
- Doing interviews with an unfamiliar target group

FINAL COMMENTS

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